Subcommission on
Silurian
Stratigraphy in
Sardinia

Fieldmeeting
4 - 11 June 2009

Time and life in the Silurian: a multidisciplinary approach

Rendiconti
della Società Paleontologica Italiana

THE SILURIAN OF SARDINIA

Supplemento al Bollettino della Società Paleontologica Italiana, Vol.48, n.1

Società Paleontologica Italiana
Modena - 2009

Rendiconti della Società Paleontologica Italiana

3

(1)

The Silurian of Sardinia

volume in honour of
Enrico Serpagli

Edited by
Carlo Corradini
Annalisa Ferretti
Petr Storch

Società Paleontologica Italiana
2009

REFERENCES TO THIS VOLUME

It is recommended that reference to the whole or part of this volume be made in one of the following forms, as appropriate:

Corradini C., Ferretti A. & Storch P., eds. (2009). The Silurian of Sardinia. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 170 pp.

Barca S. (2009). The Silurian of Sardinia (Italy): more than one and half century of researches. *In* Corradini C., Ferretti A. & Storch P. (eds.), The Silurian of Sardinia. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 11-22.

EDITORS' ADDRESSES

Carlo Corradini
Dipartimento di Scienze della Terra, Università di Cagliari
via Trentino 51, I-09127 Cagliari (Italy); corradin@unica.it

Annalisa Ferretti
Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia
largo Sant'Eufemia 19, I-41100 Modena (Italy); ferretti@unimore.it

Petr Storch
Institute of Geology, Academy of Sciences of the Czech Republic
Rozvojova 269, 165 02 Praha 6 (Czech Republic); storch@gli.cas.cz

THE ITALIAN PALAEONTOLOGICAL SOCIETY

The Association named *Società Paleontologica Italiana* was founded in 1948 to promote research in palaeontology and related sciences. Membership is open to institution and to anyone is interested in palaeontology, wheather as a professional scientist or as amateur. Membership fees for year 2009 are:

Ordinary membership (European Union)	35 Euro
Ordinary membership (extra E.U.)	45 Euro
Junior membership (under 30)	21 Euro
Istitutional membership	70 Euro

Since 1960 the Society publishes the *Bollettino della Società Paleontologica Italiana*, an international journal with scientific papers dealing on any branch of palaeontology. In year 2000, it also started to publish *PaleoItalia*, a half-yearly booklet written in Italian, mainly addressed to amateur palaeontologists.

The *Rendiconti della Società Paleontologica Italiana* is a series of volumes grouping documents of scientific meetings (abstracts and proceedings) and field trips guidebooks.

For further informations: www.spi.unimo.it

Subcommission on
Silurian
Stratigraphy in
Sardinia
Fieldmeeting
4 - 11 June 2009
Time and life in the Silurian: a multidisciplinary approach

Time and life in the Silurian: a multidisciplinary approach

Subcommission on Silurian Stratigraphy field meeting 2009
Sardinia, June 4-11, 2009

ORGANIZING COMMITTEE

Carlo Corradini	*Università di Cagliari, Italy*
Annalisa Ferretti	*Università di Modena e Reggio Emilia, Italy*
Petr Storch	*Czech Academy of Sciences, Czech Republic*
Sebastiano Barca	*Università di Cagliari, Italy*
Maria G. Corriga	*Università di Cagliari, Italy*
Myriam Del Rio	*Università di Cagliari, Italy*
Maurizio Gnoli	*Università di Modena e Reggio Emilia, Italy*
Kathleen Histon	*Università di Modena e Reggio Emilia, Italy*
Francesco Leone	*Università di Cagliari, Italy*
Alfredo Loi	*Università di Cagliari, Italy*
Gian Luigi Pillola	*Università di Cagliari, Italy*
Sergio Piras	*Università di Cagliari, Italy*
Paola Pittau	*Università di Cagliari, Italy*
Paolo Serventi	*Università di Modena e Reggio Emilia, Italy*

SCIENTIFIC COMMITTEE

Stanley Finney	*California State University Long Beach, Long Beach, CA, U.S.A.*
Michael J. Melchin	*St. Francis Xavier University, Antigonish, Canada*
Juan Carlos Gutiérrez-Marco	*Universidad Complutense de Madrid, Madrid, Spain*
Charles H. Holland	*Trinity College, Dublin, Ireland*
Jiri Kriz	*Czech Geological Survey, Prague, Czech Republic*
Peep Männik	*Tallinn Technical University, Tallin, Estonia*
Florentin Paris	*Université de Rennes 1, Rennes, France*
Jiayu Rong	*Chinese Academy of Sciences, Nanjing, China*
Hans Peter Schönlaub	*Austrian Academy of Sciences, Vienna, Austria*
Enrico Serpagli	*Università di Modena e Reggio Emilia, Modena, Italy*
Jacques Verniers	*Ghent University, Ghent, Belgium*

Contributors

Sebastiano Barca	Università di Cagliari, Italy Dipartimento di Scienze della Terra, via Trentino 51, I-09127 Cagliari
Carlo Corradini	Università di Cagliari, Italy Dipartimento di Scienze della Terra, via Trentino 51, I-09127 Cagliari
Maria G. Corriga	Università di Cagliari, Italy Dipartimento di Scienze della Terra, via Trentino 51, I-09127 Cagliari
Myriam Del Rio	Università di Cagliari, Italy Dipartimento di Scienze della Terra, via Trentino 51, I-09127 Cagliari
Annalisa Ferretti	Università di Modena e Reggio Emilia, Italy Dipartimento di Scienze della Terra, largo Sant'Eufemia 19, I-41100 Modena
Antonio Funedda	Università di Cagliari, Italy Dipartimento di Scienze della Terra, via Trentino 51, I-09127 Cagliari
Maurizio Gnoli	Università di Modena e Reggio Emilia, Italy Dipartimento di Scienze della Terra, largo Sant'Eufemia 19, I-41100 Modena
Jiri Kriz	Czech Geological Survey, Prague, Czech Republic Division of Regional Geology of Sedimentary Formations, P. O. Box 85, Praha 011
Francesco Leone	Università di Cagliari, Italy Dipartimento di Scienze della Terra, via Trentino 51, I-09127 Cagliari
Alfredo Loi	Università di Cagliari, Italy Dipartimento di Scienze della Terra, via Trentino 51, I-09127 Cagliari
Paola Mameli	Università di Sassari, Italy Dipartimento di Scienze Botaniche Ecologiche e Geologiche, Via Muroni 25, I-07100 Sassari
Giacomo Oggiano	Università di Sassari, Italy Dipartimento di Scienze Botaniche Ecologiche e Geologiche, Via Muroni 25, I-07100 Sassari
Vincent Perrier	Université de Lyon 1, France UMR CNRS 5125 PEPS, 2 rue R. Dubois, F-69622 Villeurbanne cedex
Sergio Piras	Università di Cagliari, Italy Dipartimento di Scienze della Terra, via Trentino 51, I-09127 Cagliari
Paola Pittau	Università di Cagliari, Italy Dipartimento di Scienze della Terra, via Trentino 51, I-09127 Cagliari
Paolo Serventi	Università di Modena e Reggio Emilia, Italy Dipartimento del Museo di Paleobiologia e dell'Orto Botanico, via Università 4, I-41100 Modena
Petr Storch	Czech Academy of Sciences, Czech Republic Institute of Geology, Rozvojova 269, 165 02 Praha 6

Università degli Studi
di Cagliari

Università degli Studi
di Modena e Reggio Emilia

UNDER THE PATRONAGE OF

Il Magnifico Rettore dell’Università degli Studi di Cagliari
Il Magnifico Rettore dell’Università degli Studi di Modena e Reggio Emilia
Il Preside della Facoltà di Scienze MM.FF.NN., Università di Cagliari
Il Presidente della Società Paleontologica Italiana

SPONSORING INSTITUTIONS

Università di Cagliari
Università di Modena e Reggio Emilia
Facoltà di Scienze MM.FF.NN., Università di Cagliari
Comune di Goni
Comune di Silius

ACKNOWLEDGEMENTS

A special acknowledgement goes to the International Subcommission on Silurian Stratigraphy and to its Chairman, Mike Melchin, for having accepted our invitation to visit Sardinia.

Thanks are due to the authors of the individual research papers for their hard work and for their efforts to meet the generally stringent time tables we imposed on them.

Finally we thank Ruggero Matteucci, President of the Società Paleontologica Italiana, who invited us to publish this volume within the “Rendiconti della Società Paleontologica Italiana” and allowed us complete freedom in acting as guest-editors of the volume.

Foreword

“Les terrains siluriens occupent une partie remarquable de la surface de la Sardaigne, mais les gisements fossilifères découverts jusq’ici sont peu nombreaux”.

With these words, Giovanni Meneghini in 1857 started his study on the Silurian fossil faunas of Sardinia that became a classical reference for the Italian Palaeozoic and palaeontology in general. More than 150 years later, we are back in Sardinia to host the International Subcommission on Silurian Stratigraphy together with other Silurian workers with the aim to reconstruct “Time and Life in the Silurian” *and to test multidisciplinary approaches suitable for future investigations. In other words, a starting point from which to summarize research and focus on future strategies with regard to facing the remaining challenges for a better comprehension of the Silurian world.*

Sardinian outcrops have offered important biostratigraphical data both on graptolites and conodonts - the two fossil groups depicted in the congress logo. Sardinia is also the place where many other fossil groups have been investigated and have contributed to the present state of knowledge on Silurian life in the Sardinian sea. Sardinia represents also an example of a long-term and fruitful cooperation between two universities, the University of Cagliari and the University of Modena, as testified by a long list of joint papers, co-organized meetings and joint projects. Sardinia is and has also been a place in which many non-Italian specialists have worked and studied the sections. Colleagues from the Czech Republic, Germany, Ireland, Sweden, United Kingdom, etc. have shared their expertise and data in a common effort to study more in detail the Silurian, its environmental settings and biota.

The present volume “The Silurian of Sardinia” is composed of two related components. The first part comprises seven contributions introduced by an historical overview on the studies already carried out on the Silurian faunas of Sardinia. It aims to delineate a comprehensive scenario of the Silurian of Sardinia within a proper geological setting. A global overview regarding the palaeoenvironment and palaeogeography is also provided. The second part of the volume consists of seven research papers that illustrate actual knowledge on major fossil groups encountered in the Silurian limestones and shales of southern Sardinia.

Finally, the meeting is also the appropriate occasion to celebrate a first-class Silurian palaeontologist, Enrico Serpagli, and his more than 40 years of activity in the Lower Palaeozoic of Sardinia. The volume is dedicated to him with a special acknowledgment for what he has given to Silurian research and, for two of us, for having introduced us to Silurian palaeontology and biostratigraphy. Thanks, Prof.

The Editors

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 1-10

Enrico Serpagli, celebrating his 44th Silurian-research birthday

Petr Storch, Annalisa Ferretti, Carlo Corradini

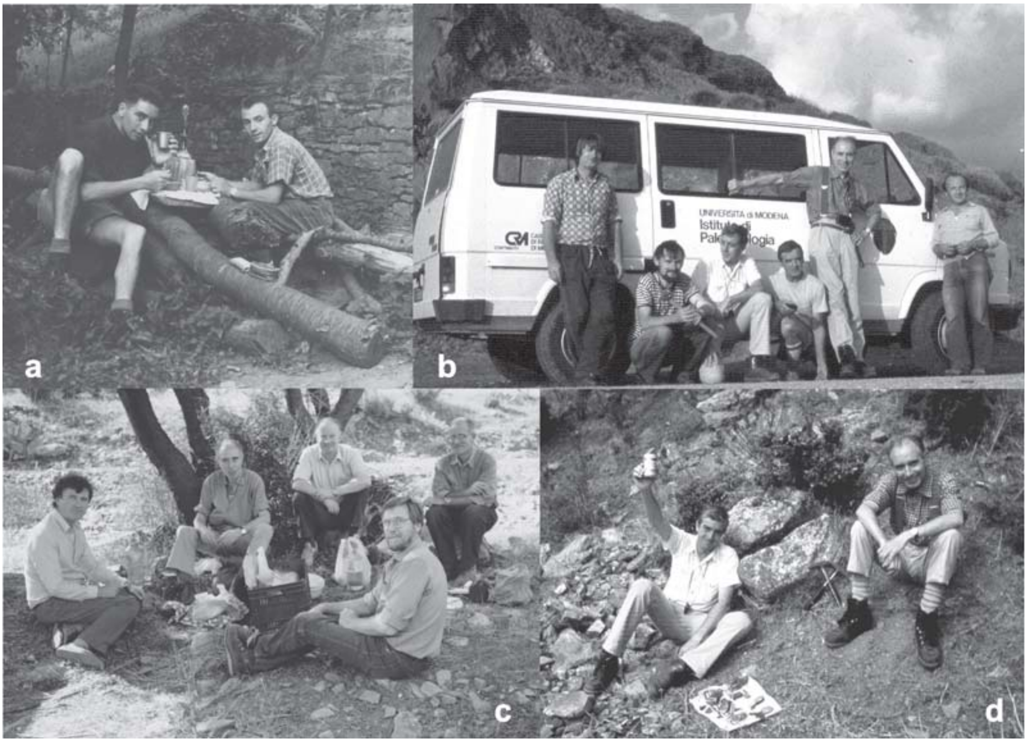
P. Storch - Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojova 269, 165 02 Praha 6 (Czech Republic); Storch@gli.cas.cz
A. Ferretti - Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia, largo S. Eufemia 19, I-41100 Modena (Italy); ferretti@unimore.it
C. Corradini - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); corradin@unica.it

The editors are pleased to dedicate this volume on the Silurian of Sardinia to Enrico Serpagli, an outstanding personality of Italian palaeontology, who devoted substantial part of his professional life to marine faunas and biostratigraphy of Ordovician and Silurian sedimentary formations mostly of southern Sardinia. Two of the editors are former doctoral students of Enrico Serpagli and PS has been collaborating with him since his first, early postgradual visit to Sardinia in 1982.

Enrico Serpagli was born in 1936 in the small town Borgo Val di Taro in district of Parma, northern Italy. His interest in geology led him to the university studies in Modena where he graduated from geology in 1960, with a special mention (110/110 with honours). His long and fruitful scientific career started in Italian Geological Survey with detailed geological mapping in Northern Apennines (1961-1962). In 1962 the young and enthusiastic scientist was appointed an Assistant Professor at the Institute of Palaeontology of the University of Modena, though, between 1964 and 1975, he also acted as a lecturer in geomorphology. Those years, however, his research work has already focussed on micropalaeontology.

In 1963, Serpagli underwent some research training on dinoflagellate cysts in the laboratory of A. Eisenack at the University of Tübingen. The first study visit was followed by training on conodonts in the laboratory of M. Lindström, University of Lund in 1965. In May 1969, Enrico Serpagli was appointed a "*Libero Docente*" in Palaeontology. A postdoctoral stay at the Department of Geology, Ohio State University in Columbus, Ohio (1971-1972) may be considered another milestone that influenced further scientific specialization of the young micropalaeontologist. Since then, Early Palaeozoic conodonts became his principal field of research.

In 1975 Serpagli achieved a full-professor status in Palaeontology at the University of Turin and, two year later, he became a Professor of Palaeontology at his *alma mater*. Upon the retirement of Eugenia Montanaro Gallitelli in 1977, Serpagli was elected to the directorship of the Institute of Palaeontology and remained in this office, with some breaks, until 1995. Under his directorship the Institute has developed in one of the most respected palaeontological research centers in Italy and also gained a considerable international reputation. A large collection of early Palaeozoic faunas (conodonts, graptolites, bivalves, brachiopods, trilobites, echinoderms, ostracodes, etc.) was at the same time deposited in the Institute of Modena, thanks to a fruitful collaboration of Enrico Serpagli with major specialists of the diverse fossil groups.

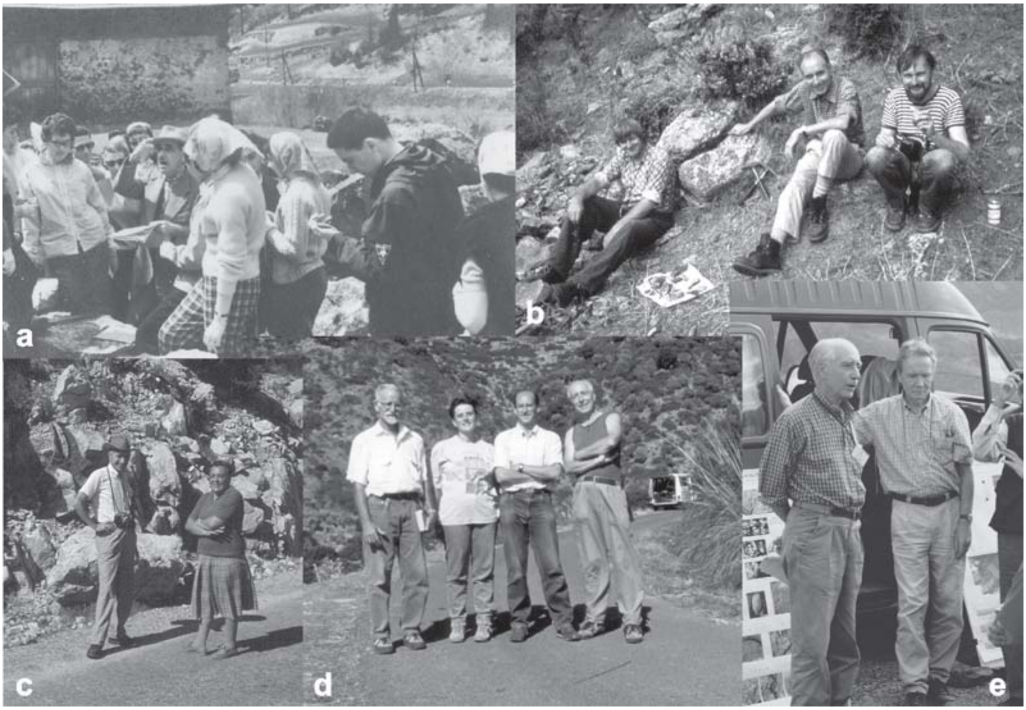


a) Enrico Serpagli and Pietro Rompianesi during field work in the Northern Apennines in 1958. b) Jiri Kriz, Petr Storch, Maurizio Gnoli, Roberto Ferraresi, Enrico Serpagli and Pietro Rompianesi at Portixeddu in 1982. c) Richard Fortey, Enrico Serpagli, Robin Cocks, Wolfgang Hammann and Francesco Leone at Rio San Marco in 1989. d) Maurizio Gnoli and Enrico Serpagli at the Mason Porcus Section in 1982.

Enrico Serpagli is a co-author of the only Italian text-book on palaeontology (*Introduzione alla Paleontologia*, 650 pp.) published in 1993. From 1984 to 2008 E. Serpagli acted as a state coordinator of Joint Doctoral Study Program in Palaeontology run by the universities of Modena, Roma, Bologna and Firenze. His former students and present collaborators (M. Gnoli, S. Conti, A. Ferretti, C. Corradini a.o.) successfully develop his research on conodonts and other topics of palaeontology and stratigraphy.

Apart from the University of Modena and Reggio Emilia, was Enrico Serpagli teaching at the University of Mogadishu, Somalia, in 1982 and the University of Addis Ababa, Ethiopia, in 1985.

Enrico Serpagli is the author or co-author of over 130 publications. In sixties, Serpagli studied mainly Caenozoic forams and dinoflagellata but in 1965 he published his first report on Late Ordovician and Silurian conodonts of the Carnic Alps and, in 1967, the first paper on Silurian conodonts in southern Sardinia. In seventies he started with more systematic conodont research. Since then, he worked, for the most part, on conodont taxonomy and biostratigraphy though some of his papers, largely those co-authored with students and fellow workers, were devoted also to conularids, scolecodonts, nautiloid cephalopods, graptolites, bivalves, algae, ostracodes, problematics and ichnofossils. His extensive collaboration with universities and research institutions in Italy, namely the



a) Enrico Serpagli (first from the right) at a student field trip in the Dolomites, guided by Prof. Paolo Montanaro in 1956. b) Jiri Kriz, Enrico Serpagli and Petr Storch at the Mason Porcus Section in 1982. c) Enrico Serpagli and Renata Olivieri at Capo Caccia, during the 19th European Micropalaeontological Colloquium Field Trip, Sardinia 1985. d) Francesco Leone, Annalisa Ferretti, Carlo Corradini and Enrico Serpagli at Cea Brabetza Section in 1997, during the preparation of the ECOS VII Field Trip. e) Enrico Serpagli and Rolf Schroeder at Punta Pedrona at the Società Paleontologica Italiana field trip 2002.

University of Cagliari, and abroad (*e.g*. Argentina, Germany, Spain, Ireland, United Kingdom, Czech Republic) gave the research team working on the Silurian System of Sardinia an international dimension. In 1998 Serpagli organised the Seventh European Conodont Symposium (ECOS VII) and successful pre-symposium excursion across the Palaeozoic formations of southern Sardinia.

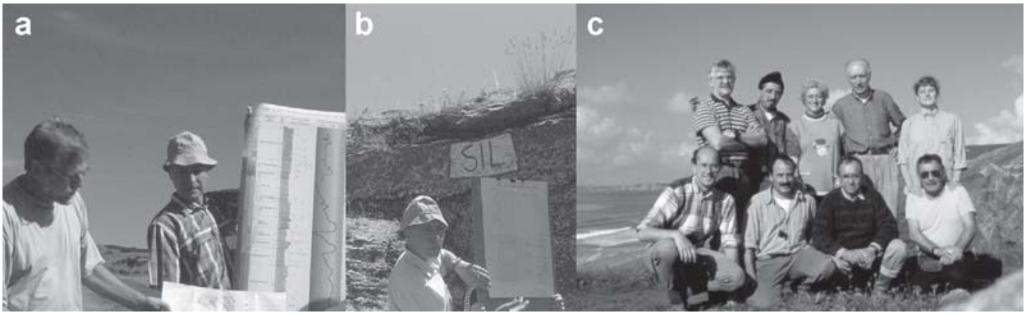
For many years, Enrico Serpagli has been an active member of *Società Paleontologica Italiana*, *Società Geologica Italiana* and *Società dei Naturalisti e Matematici di Modena*, and he has also served to palaeontological community as editor in chief of the *Bollettino della Società Paleontologica Italiana* (from 1978 to present). His work was recognized by Italian *Accademia Nazionale di Scienze, Lettere ed Arti di Modena* who elected him a member in 1995. In 1990 he became a titular member of the International Subcommission on Silurian Stratigraphy IUGS. Further international enrollments of Enrico Serpagli involved Palaeontological Association, European Palaeontological Association and *Sociedad Espanola de Paleontologia*.

Since 2006 Enrico Serpagli retired from his full-time teaching and research duties, moved to his belowed country house in Sassuolo, and acquired more time for his long-time passion for photography to accompany his continuing palaeontological investigations and editorship of *Bollettino della Società Paleontologica Italiana*. Photography became

a) Wolfgang Hammann, Enrique Villas, Enrico Serpagli and Francesco Leone at Argiola in 1991. b) Enrico Serpagli during the 19th European Micropalaeontological Colloquium Field Trip, Sardinia 1985. c) Francesco Leone, Wolfgang Hammann and Enrico Serpagli in central Spain in 1992. d) Enrico Serpagli and Antonio Russo at the "Giornate di Paleontologia 2004" field trip at Butterloch. e) Charles Holland, Francesco Leone, Enrico Serpagli, Annalisa Ferretti, Pietro Rompianesi, Matthew Parkes, Douglas Palmer and George Sevastopulo at Monte Padenteddu in 1990.

an integral part of his geological profession. Just family, friends and some collaborators know that Enrico "Giulio" Serpagli became a respected artistic photographer during the past ten years. First public exhibition of his sensitive artistic photographs was in 1999 in Modena and since that time, at least 6 more exhibitions were housed in other Italian cities. In 2007 a book of art photographs *Il senso dell`Ordine* (Sense of Order) came to light.

While reading through manuscript papers submitted for publication in this volume, one has to recall once again the substantial contribution of Enrico Serpagli to the present, advanced state of knowledge on Silurian sedimentary successions and fossil faunas preserved in southern Sardinia. For conodont people, his monographs represent true milestones both for future taxonomic and biostratigraphic studies. In all his papers it is greatly appreciated the exactness of the scientific presentation of the facts and of the problems and the solidity of the conclusions.



a) Wolfgang Hammann and Enrico Serpagli at Cannemenda, during the ECOS VII field trip, 1998. b) Enrico Serpagli illustrating the Silius Section during the ECOS VII field trip, 1998. c) Florentin Paris, Alfredo Loi, Sofia "Giovanna" Serpagli, Enrico Serpagli, Annalisa Ferretti, Carlo Corradini, Gian Luigi Pillola, Michel Robardet and Jean-Jacques Chauvel at Lostmarc'h, Brittany, in 1999.

Acknowledgments

Pictures were kindly provided by Maurizio Gnoli, Angelo Ibba, Jiri Kriz, Francesco Leone, Gian Luigi Pillola, Sergio Piras, Pietro Rompianesi and Claudia Spalletta.

Papers by Enrico Serpagli, ordered by year of publication

Serpagli E. (1961). Contributo alla conoscenza dei terreni oligo-miocenici nel Subappennino modenense. *Bollettino della Società Geologica Italiana*, 80(2):127-134.

Serpagli E. & Reutter K.J. (1962). Micropaleontologia stratigrafica sulla "Scaglia rossa" di Val Gordana (Pontremoli-Appennino Settentrionale). *Bollettino della Società Paleontologica Italiana*. 1 (2):10-30.

Serpagli E. (1962). Età paleogenica e non miocenica della Formazione di Rio Giordano tra Pavullo e Lama Mocogno (Appennino Settentrionale modenese). *Accademia Nazionale dei Lincei. Rendiconti Classe Scienze Fisiche Matematiche e Naturali*, s. 8, 33 (3-4): 153-157.

Serpagli E. (1963). Carta Geologica d'Italia, Foglio 86 (Modena), rilevamento delle tavolette I SO, II NO, II SO, II SE e II NE(quest'ultima fino al limite col Pliocene). Litografia Artistica Cartografica. Firenze.

Serpagli E. (1964). Livello ad "Argille variegate" del Cenomaniano sup.-Turoniano alla base del Flysch ad Elmintoidi (Appennino Settentrionale). *Rendiconti dell'Accademia Nazionale dei Lincei. Classe Scienze Fisiche Matematiche e Naturali*, s. 8, 35 (6): 1-10.

Serpagli E. (1964). Ritrovamento di Flysch tipo M. Sporno nell'Appennino modenese: osservazioni geopaleontologiche. *Bollettino della Società Paleontologica Italiana*, 3 (1): 20-37.

Serpagli E. (1964). Primo studio di dinoflagellati e istricosferidi del Mesozoico italiano (Cretaceo superiore-Appennino Settentrionale). *Bollettino della Società Paleontologica Italiana*, 3 (1): 89-109,tav.18,19.

Serpagli E. & Greco A. (1965). Documentazione paleontologica di Ashgilliano nel versante Sud del M. Zermula (Alpi Carniche italiane). *Atti e Memorie dell'Accademia Nazionale di Scienze Lettere e Arti di Modena*, s. VI, 7: 3-12.

Serpagli E. & Greco A. (1965). Osservazioni preliminari su alcuni Conodonti ordoviciani e siluriani delle Alpi Carniche italiane. *Bollettino della Società Paleontologica Italiana*, 3(2): 192-211.

Serpagli E. & Sirotti A. (1966). Growth anomalies in *Lepidocyclina (Nephrolepidina) morgani* Lemoine & R.Douvillè. *Bollettino della Società Paleontologica Italiana*, 5 (1): 58-61.

Serpagli E. & Sirotti A. (1966). Gli strati a *Lepidocyclina* e *Miogypsina* ai Sassi di Rocca Malatina e a Montegibbio (Appennino Settentrionale modenese). *Bollettino della Società Paleontologica Italiana*, 5 (1): 79-91.

Serpagli E. (1967). Prima segnalazione di conodonti del Siluriano della Sardegna e relative osservazioni stratigrafiche. *Rendiconti dell'Accademia Nazionale dei Lincei. Classe Scienze Fisiche Matematiche e Naturali*, s. 8, 42 (6): 856-858.

Serpagli E. & Sirotti A. (1967). Additional remarks on growth anomalies in *Lepidocyclina (Nephrolepidina) morgani* Lemoine & R.Douvillè. *Bollettino della Società Paleontologica Italiana*, 5 (1) (1966): 99-100.

Serpagli E. & Sirotti A. (1967). Età aquitaniana delle brecciole a lepidocicline e miogipsine delle "Arenarie del M.Cervarola" (Appennino Settentrionale). *Bollettino della Società Paleontologica Italiana*, 6 (1): 1-29.

Serpagli E. (1967). I conodonti dell'Ordoviciano superiore (Ashgilliano) delle Alpi Carniche. *Bollettino della Società Paleontologica Italiana*, 6 (2): 30-111.

Fuganti A. & Serpagli E. (1968). Geological remarks on Urbana limestone and evidence for its Upper Ordovician by means of Conodonts (Eastern Sierra Morena, South Spain). *Bollettino della Società Geologica Italiana*, 87 (2): 511-521.

Corradini D. & Serpagli E. (1968). Preliminary report on the discovery and initial study of large amount of scolecodonts and polychaete jaw apparatuses from Mesozoic formations. *Bollettino della Società Paleontologica Italiana*, 7(1): 3-5.

Serpagli E. & Sirotti A. (1969). L'età della base del Macigno in Val Gordana (Pontremoli, Appennino Settentrionale) dallo studio biometrico delle lepidocicline. *Atti della Società dei Naturalisti e Matematici di Modena*, 100: 3-12.

Serpagli E. (1970). Ordovician conularids of Sardinia. *Bollettino della Società Paleontologica Italiana*, 8 (1): 1-8.

Serpagli E. (1971). Uppermost Wenlockian-Upper Ludlowian (Silurian) Conodonts from Western Sardinia. *Bollettino della Società Paleontologica Italiana*, 9 (1): 76-96.

Serpagli E. (1973). Carbonati di tipo bahamitico nell'Ordoviciano inferiore della Precordillera argentina e relative osservazioni paleoclimatologiche: *Atti della Società dei Naturalisti e Matematici di Modena*, 104: 239-245.

Serpagli E. (1974). Un momento della storia geologica dell'Ordoviciano atlantico: Conodonti baltici nella Precordillera argentina. *Rendiconti dell'Accademia Nazionale dei Lincei. Classe Scienze Fisiche Matematiche e Naturali*, s. 8, 40 (5): 1-6.

Serpagli E. (1974). Lower Ordovician Conodonts from Precordilleran Argentina (Province of San Juan). *Bollettino della Società Paleontologica Italiana*, 13 (1-2): 17-98.

Serpagli E., Corradini D. & Russo F. (1974). L'importanza del SEM nello studio di microstrutture di scolecodonti. *Bollettino del Servizio Geologico d'Italia*, 95: 182

Serpagli E., Corradini D. & Russo F. (1975). Ultrastructure of some fossil and recent polychaete jaws (scolecodonts). *Bollettino della Società Paleontologica Italiana*, 23 (1-2) (1974): 122-134.

Serpagli E. (1977). I Conodonti. *Le Scienze*, 116: 26-35.

Serpagli E. & Gnoli M. (1977). Silurian cephalopods of the Meneghini collection (1857) with the reproduction of the original plate. *Bollettino della Società Paleontologica Italiana*, 16 (2):137-142.

Serpagli E. & Gnoli M. (1977). Upper Silurian cephalopods from southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 16 (2): 153-195.

Serpagli E., Gnoli M., Mastandrea A. & Olivieri R. (1978). Paleontological evidence of the Gedinnian (Lower Devonian) in southwestern Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 84: 305-312.

Gelmini R., Lorenzoni, S. , Mastandrea A., Orsi G., Serpagli E., Vai G.B., Zanettin & Lorenzoni E. (1978), Rinvenimento di fossili devoniani nel cristallino dell'Aspromonte (Calabria). *Rendiconti della Società Geologica Italiana*, 1: 45-47.

Gnoli M., Parea G.C., Russo F. & Serpagli E. (1980). Palaeoecological remarks on the "*Orthoceras* limestone" of Southwestern Sardinia (M.-U. Silurian). *Memorie della Società Geologica Italiana*, 20 (1979): 405-423.

Serpagli E. & Mastandrea A. (1980). Conodont assemblages from the Silurian-Devonian boundary beds of southwestern Sardinia (Italy). *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1980-H.1: 37-42.

Serpagli E. (1980). Il "coccodrillo" del Modenese. *In* I Vertebrati fossili italiani:135.

Gnoli M. & Serpagli E. (1980). A sponge spicule assemblage from Ordovician of Precordilleran Argentina. *Rivista Italiana di Paleontologia e Stratigrafia*, 86 (2): 267-272.

Gnoli M. & Serpagli E. (1980). The problematic microorganism *Nuia* in the Lower Ordovician of Precordilleran Argentina. *Journal of Paleontology*, 54(6): 1245-1251.

Olivieri R., Mastandrea A. & Serpagli E. (1980). Riconoscimento di alcune zone a conodonti del Devoniano inferiore nei calcari di Monte Padenteddu nella Sardegna meridionale. *Atti della Società dei Naturalisti e Matematici di Modena*, 111: 1-12.

Gnoli M., Jaanusson V., Leone F., Serpagli E. (1981). A Lower Devonian *Stromatactis* -bearing carbonate mound from Southern Sardinia: *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1981-H.6: 339-345.

Serpagli E. (1982). Le conoscenze paleontologiche del Paleozoico sardo (Rassegna dei dati). *In* Guida alla geologia del Paleozoico sardo. Guide Geologiche Regionali. Società Geologica Italiana, 4: 25-32.

Serpagli E. & Conti S. (1982). A new morphological structure in some Ordovician Bryozoans from Sardinia. Paleontological Contribution of University of Oslo, 280: 47.

Serpagli E. (1982). Remarks on the apparatus of *Icriodus w. woschmidti* Ziegler (Conodonta). *In* Jeppsson L. & Lofgren A. (Eds.), 3rd European Conodont Symposium (ECOS III) Abstracts. *Publications from the Institute of Mineralogy, Palaeontology and Quaternary Geology of Lund, Sweden*, 238: 31.

Serpagli E. (1983). The conodont apparatus of *Icriodus woschmidti woschmidti* Ziegler. *Fossils and Strata*, 15: 155-161.

Conti S. & Serpagli E. (1984). A new interpretation of the antozoan *Septodaeum* Bishoff, 1978 as a bryozoan. *Bollettino della Società Paleontologica Italiana*, 23 (1): 3-20.

Gnoli M. & Serpagli E. (1984). Evidence of phyllocarid remains from Silurian- Devonian boundary beds in southwestern Sardinia. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1984-H.5: 257-268.

Serpagli E. & Gnoli M. (1984). Palaeozoic Palaeontology in Sardina: a review (1857-1983). *Bollettino del Museo Regionale di Scienze Naturali di Torino*, 2 (1): 163-180.

Gnoli M. & Serpagli E. (1985). An unusual preserved foraminiferal association from the Upper Silurian-Lower Devonian beds in southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 23 (2) (1984): 211-220.

Gnoli M. & Serpagli E. (1985). Palaeozoic of Southwestern Sardinia. *In* Cherchi A. (ed.), 19th European Micropaleontological Colloquium, Sardinia, October 1-10, 1985: 33-43.

Gnoli M. & Serpagli E. (1985). Silurian of Fluminimaggiore. *In* Cherchi A. (ed.), 19th European Micropaleontological Colloquium, Sardinia, October 1-10, 1985: 121-124.

Gnoli M., Mastandrea A. & Serpagli E. (1985). Lower Devonian of Fluminimaggiore. *In* Cherchi A. (ed.), 19th European Micropaleontological Colloquium, Sardinia, October 1-10, 1985: 124-129.

Barca, S., Gnoli M., Olivieri, R., Serpagli E. (1986). New stratigraphic data and evidence of Lower and Upper Devonian based on conodonts in Sarrabus area (Southwestern Sardinia). *Rivista Italiana di Paleontologia e Stratigrafia*, 92 (3): 299-320.

Conti S. & Serpagli E. (1987). Functional morphology of the cap-like apparatus in autozooids of a Palaeozoic trepostome bryozoan. *Lethaia*, 20:1-20.

Havlicek V., Kriz J. & Serpagli E. (1987). Upper Ordovician brachiopods assemblages of the Carnic Alps, Middle Carinthia and Sardinia. *Bollettino della Società Paleontologica Italiana*, 25 (3): 277-322.

Conti S. & Serpagli E. (1988). Biomineralic (calcareous and phosphatic) skeleton in Late Ordovician Bryozoa from Sardinia: geological implications. *Bollettino della Società Paleontologica Italiana*, 27 (2): 129-162.

Gnoli M., Leone F., Olivieri R. & Serpagli E. (1988).The Mason Porcus Section as reference section for Uppermost Silurian-Lowermost Devonian in SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 27(3), 323-334.

Gnoli M., Kriz J., Leone F., Olivieri R., Serpagli E. & Storch P. (1990). Lithostratigraphic units and biostratigraphy of the Silurian and early Devonian of Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 11-23.

Olivieri R. & Serpagli E. (1990). Latest Silurian-early Devonian conodonts from Mason Porcus Section near Fluminimaggiore, Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 59-76.

Ferretti A. & Serpagli E. (1991). First record of Ordovician conodonts from Southwestern Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 97 (1): 27-34.

Gnoli M. & Serpagli E. (1991). Nautiloid assemblages from Middle-Late Silurian of Southwestern Sardinia: a proposal. *Bollettino della Società Paleontologica Italiana*, 30 (2): 187-195.

Leone F., Hamman W., Laske R., Serpagli E. & Villas E. (1991). Lithostratigraphic units and biostratigraphy of post sardic Ordovician sequence in South-West Sardinia. *Bollettino della Società Paleontologica Italiana*, 30 (3): 201-235.

Barca S., Ferretti A., Massa P. & Serpagli E. (1992). The Hercynian Arburese Tectonic Unit of SW Sardinia. New stratigraphic and structural data. *Rivista Italiana di Paleontologia e Stratigrafia*, 98 (2): 119-136.

Barca S., Ferretti A., Massa P. & Serpagli E. (1992). Minor tectonic units within the Hercynian Arburese Nappe in Southwestern Sardinia. New structural and stratigraphic evidence. *In* Carmignani L. & Sassi F.P. (eds.), Contribution to the Geology of Italy with special regard to the Paleozoic basement. A volume dedicated to Tommaso Cocozza. *IGCP Project No 276 Newsletter*, 5: 51-55.

Raffi S. & Serpagli E. (1993). Introduzione alla Paleontologia. U.T.E.T.,1-650, Torino.

Storch P. & Serpagli E. (1993). Lower Silurian Graptolites from SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 32 (1): 3-57.

Serpagli E. (1993). I documenti fossili della vita primordiale (L'evoluzione della vita nel Precambriano). *In* Tugnoli C.(Ed.), I segni del tempo: 167-207.

Kriz J. & Serpagli E. (1994). Upper Silurian and Lowermost Devonian Bivalvia of Bohemian type from Western Sardinia. *Bollettino della Società Paleontologica Italiana*, 32 (3) (1993): 289-347.

Leone F., Menghi L., Serpagli E. & Storch P. (1994). Late Ordovician Graptolites from Sardinia: a preliminary record. *Bollettino della Società Paleontologica Italiana*, 32 (3) (1993), 411-414.

Barca S., Corradini C., Ferretti A., Olivieri R. & Serpagli E. (1994). Conodont evidences from the "Ockerkalk" of Southeastern Sardinia (Silurian, Silius area). *In* Schönlaub H.P. & Kreutzer L.H. (eds.), IUGS Subcommission on Silurian Stratigraphy. Field Meeting Eastern+Southern Alps. *Berichte der Geologischen Bundesanstal*t, 30/1994, 30: 126.

Barca S., Corradini C., Ferretti A., Olivieri R. & Serpagli E. (1995). Conodont biostratigraphy of the "Ockerkalk" (Silurian) from southeastern Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 100 (4) (1994): 459-476.

Rickards R.B., Holland C.H & Serpagli E. (1995). Aspects of Silurian and Lower Devonian graptolite faunas and stratigraphy in southern Sardinia. *Bollettino della Società Paleontologica Italiana*, 34 (1): 67-80.

Ferretti A., Gnoli M., Kriz J. & Serpagli E. (1995). The Silurian and early Devonian in south-west Sardinia. In Paleobenthos Guidebook. *Rendiconti del Seminario della Facoltà di Scienze dell'Università di Cagliari*, 65, suppl.: 106-117.

Ferretti A. & Serpagli E. (1996). Unusual graptolitic limestones from the Silurian of SW Sardinia. *In* The James Hall Symposium (2nd Internat. Symposium on the Silurian System), Program and Abstracts: 52.

Kriz J., Degardin J.M., Ferretti A., Serpagli E., Hansch W., Paris F., Schonlaunb H.P. (1996). Silurian stratigraphy and paleogeography of the Western, Central and Southern Europe (North Gondwana and Perunica). *In* The James Hall Symposium (2nd Internat. Symposium on the Silurian System), Program and Abstracts: 68.

Ferretti A. & Serpagli E. (1996). Geological outline, community sequence and paleoecology of the Silurian of Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 102: 353-362.

Corradini C., Olivieri R. & Serpagli E. (1996). Possible relationship between anomalous conodonts and Silurian oceanic episodes. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1995-H.12: 737-746.

Serpagli E., Corradini C. & Olivieri R. (1997). Occurrence and range of the Silurian conodont *Coryssognathus dubius* (Rhodes 1953) in southern Sardinia. *Bollettino della Società Paleontologica Italiana*, 35(3) (1996): 239-243.

Hanson D., Berry B., Fortey R. & Serpagli E. (1997). Paleogeographic implications of new fossil finds in the Altun Mountains, Xinjiang Province, NW China. 1997 American Association Petroleum Geology, Annual Convention, Official program, 6: A47.

Serpagli E. (Ed.), 1998, Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue, 215 pp.

Leone F., Ferretti A., Hammann W., Loi A., Pillola G.L. & Serpagli E. (1998). Outline of the post-Sardic Ordovician sequence in South-western Sardinia. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 39-56.

Ferretti A., Corradini C. & Serpagli E. (1998). The Silurian and Devonian sequence in SW Sardinia. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 57-61.

Corradini C., Ferretti A. & Serpagli E. (1998). The Silurian and Devonian sequence in SE Sardinia. *In* Serpagli E. (Ed.), Sardinia Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 71-74.

Serpagli E. & Corradini C. (1998). New taxa of *Kockelella* (Conodonta) from Late Wenlock-Ludlow (Silurian) of Sardinia. *In* E. Serpagli (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 79-83.

Corradini C. & Serpagli E. (1998). A Late Llandovery-Pridoli (Silurian) conodont biozonation in Sardinia. *In* E. Serpagli (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 85-88.

Ferretti A., Serpagli E., Leone F. & Loi A. (1998). The late Ordovician section Cea Brabetza near San Basilio. *In* E. Serpagli (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 96-101.

Serpagli E., Corradini C. & Ferretti A. (1998). Conodonts from a Ludlow-Pridoli section near the Silius Village. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 104-111.

Corradini C., Ferretti A., Serpagli E. & Barca S. (1998). The Ludlow-Pridoli Section "Genna Ciuerciu" west of Silius. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 112-118.

Serpagli E., Ferretti A., Leone F., Loi A. & Pillola L. (1998). Conodonts of the Late Cambrian section Prabetza near Villamassargia. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 138-143.

Ferretti A., Corradini C. & Serpagli E. (1998). Wenlock-Ludlow conodonts from Perd'e Fogu (Fluminimaggiore). *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 156-167.

Corradini C., Ferretti A. & Serpagli E. (1998). An Early Devonian section near Fluminimaggiore (Galemmu). *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 168-174.

Ferretti A., Serpagli E., Hamman W. & Leone F. (1998). Conodonts and biofacies from the Late Ordovician of Cannamenda (Bacu Abis). *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 178-187.

Corradini C., Ferretti A. & Serpagli E. (1998). Wenlock and Pridoli conodonts from Argiola, East of Domusnovas. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 194-198.

Ferretti A., Serpagli E., Barca S. & Leone F. (1998). Late Ordovician conodonts from Umbrarutta between Donigala and Lago Mulargia. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 202-208.

Bagnoli G., Ferretti A., Serpagli E. & Vai G.B. (1998). Late Ordovician conodonts from the Valbertad Section (Carnic Alps). *In*: Perri M.C. & Spalletta C. (Eds.), Southern Alps Field trip Guidebook, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 138-149.

Barnes C.R., Ferretti A. & Serpagli E. (1998). Upper Ordovician conodont faunas of South Wales. *In* Bagnoli G. (Ed.), ECOS VII Abstracts, Bologna-Modena, 1998: 9-10.

Corradini C. & Serpagli E. (1998). Proposal of a conodont stratigraphy from late Llandovery to end Pridoli (Silurian) in Sardinia. *In* Bagnoli G. (Ed.), ECOS VII Abstracts, Bologna-Modena, 1998: 27-29.

Ferretti A. & Serpagli E. (1998). Stratigraphic and biogeographic significance of Late Ordovician conodonts from Sardinia (Italy). *In* Bagnoli G. (Ed.), ECOS VII Abstracts, Bologna-Modena, 1998: 35-36.

Serpagli E. & Corradini C. (1998). Late Wenlock-Ludlow (Silurian) *Kockelella* (Conodonta) from Sardinia. *In* Bagnoli G. (Ed.), ECOS VII Abstracts, Bologna-Modena, 1998: 101-102.

Serpagli E. & Ferretti A. (1998). First record of Upper Cambrian conodonts from Sardinia. *In* Bagnoli G. (Ed.), ECOS VII Abstracts, Bologna-Modena, 1998: 102-103.

Serpagli E. (1998). In Ricordo di E. Montanaro Gallitelli: un allievo racconta. *Atti e Memorie dell'Accademia Nazionale di Scienze Lettere e Arti di Modena*, s. 7, 14: 189-192.

Corradini C., Ferretti A. & Serpagli E. (1999). Updated conodont biostratigraphy of the Sardinian Ockerkalk (late Silurian). *In* Feist R., Talent J. & Orth B. (Eds), Abstract book-Errachidia meeting SDS-IGCP 421, April 23rd-May 1st 1999: 9-11.

Serpagli E. (ed.) (1999). Studies on Conodonts, Proceedings of the 7th European Conodont Symposium. *Bollettino della Società Paleontologica Italiana*, 37(2/3) (1998): 145-557.

Serpagli E. (1999). Address of the President of the Symposium, *In* Serpagli E. (Ed.), Studies on Conodonts, Proceedings of the 7th European Conodont Symposium. *Bollettino della Società Paleontologica Italiana*, 37 (2/3) (1998), V.

Ferretti A. & Serpagli E. (1999). Late Ordovician conodont faunas from southern Sardinia, Italy: biostratigraphic and paleogeographic implications. *Bollettino della Società Paleontologica Italiana*, 37(2/3)(1998),215-236.

Corradini C. & Serpagli E. (1999). A Silurian conodont zonation from late Llandovery to end Pridoli in Sardinia. *Bollettino della Società Paleontologica Italiana*, 38 (2-3): 255-273.

Serpagli E. & Corradini C. (1999). Taxonomy and evolution of *Kockelella* (Conodonta) from Silurian of Sardinia. *Bollettino della Società Paleontologica Italiana*, 38 (2-3): 275-298.

Serpagli E. & Ferretti A. (1999). L'Europa durante il Paleozoico. *In* Pinna G.(a cura di), Alle radici della storia naturale. Seicento milioni di anni attraverso i grandi giacimenti paleontologici d'Europa: 17-20. Jaca Book.

Corradini C., Ferretti A. & Serpagli E. (2000). Correlazioni biostratigrafiche negli "Ockerkalk" (Siluriano sup.) della Sardegna sud-orientale. *In* Cherchi A.& Corradini C. (Eds), Crisi biologiche, radiazioni adattative e dinamica delle piattaforme carbonatiche. *Accademia Nazionale di Scienze Lettere Arti di Modena, Collana di Studi*, 21: 87-92.

Ferretti A., Hamman W. & Serpagli E. (2000). La collocazione paleogeografica della Sardegna nel tardo Ordoviciano: nuovi dati. *In* Cherchi A.& Corradini C. (Eds), Crisi biologiche, radiazioni adattative e dinamica delle piattaforme carbonatiche. *Accademia Nazionale di Scienze Lettere Arti di Modena, Collana di Studi*, 21: 105-110.

Serpagli E. & Ferretti A. (2000). Europa im Paleozoikum. *In* Meischner D. (Ed.), Europeische Fossillagerstetten: 17-20. Springer Verlag.

Corradini C. & Serpagli E. (2000). A new (standard?) Silurian conodont zonation. *Silurian Times*, 8: 25-28.

Serpagli E. & Hammann W. (2000). *Cyclocrinites* Eichwald, 1840 (Dasycladales) from the Upper Ordovician Portixeddu Formation of SW-Sardinia and its bearing on palaeogeography and systematics. Palaeontology Down Under 2000. *Geological Society of Australia Abstracts*, 61: 94-95.

Serpagli E., Corradini C. & Ferretti A., 2001, Biostratigrafia del basamento ercinico. *In* Carmignani L., Conti P., Barca S., Cerbai N., Eltrudis A., Funedda A., Oggiano G. & Patta D., Note Illustrative della Carta Geologica d'Italia 1:50000, Foglio 549 (Muravera). Istituto Poligrafico e Zecca dello Stato, Roma.

Corradini C., Leone F., Loi A. & Serpagli E. (2001). Conodont Stratigraphy of a highly tectonised Siluro-devonian Section in the San Basilio area (SE Sardinia). *Bollettino della Società Paleontologica Italiana*, 40 (3): 315-323.

Leone F., Loi A., Ferretti A., Hamman W., Pillola G.L & Serpagli E. (2002). A general view on the post-Sardic Ordovician sequence from SW Sardinia. *Rendiconti della Società Paleontologica Italiana*, 1: 51-68.

Corradini C., Ferretti A. & Serpagli E. (2002). The Gerrei Tectonic Unit (SE Sardinia, Italy). *Rendiconti della Società Paleontologica Italiana*, 1: 69-76.

Leone F., Loi A., Ferretti A., Hammann W., Pillola G.L & Serpagli E. (2002). The Portixeddu Formation in the Punta Pedrona Section. *Rendiconti della Società Paleontologica Italiana*, 1: 231-334.

Corradini C., Ferretti A. & Serpagli E. (2002). The "Ockerkalk" limestone in the Genna Ciuerciu Section (SE Sardinia, Italy). *Rendiconti della Società Paleontologica Italiana*, 1: 255-260.

Storch P., Serpagli E. & Barca S. (2002). Silurian graptolites of the *spiralis* and *lapworthi* biozones (uppermost Telychian, Llandovery) in the Sulcis area, SW-Sardinia. *Bollettino della Società Paleontologica Italiana*, 41(2-3): 97-107.

Serpagli E. (2003). In ricordo di Wolfgang Hammann (1942-2002) - In memory of Wolfgang Hammann (1942-2002). *Bollettino della Società Paleontologica Italiana*, 42 (1-2), I-II.

Hamman W. & Serpagli E. (2003). The algal genera *Ischiadites* Murchison, 1839 and *Cyclocrinites* Eichwald, 1840 from the Late Ordovician Portixeddu Formation of SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 42 (1-2): 1-29.

Kriz J., Degardin J.M., Ferretti A., Hansch W., Gutiérrez Marco J.C., Paris F., Picarra D-Almeida, J.M., Robardet M., Schönlaub H.P. & Serpagli E. (2003). Silurian stratigraphy and paleogeography of

Gondwananan and Perunican Europe. *In* Landing E. & Johnson M.E. (Eds.), Silurian Lands and Seas: Paleogeography outside of Laurentia. *New York State Museum Bulletin*, 493: 105-178.

Corradini C. & Serpagli E., 2004, Conodont biostratigraphy of the Ockerkalk of South-East Sardinia, Italy (Late Silurian). GSA annual meeting, Boise, May 2004. *Geological Society of America Abstracts with Programs*, 36 (4): 74.

Piras S., Serpagli E. & Menghi L. (2004). Prima segnalazione del graptolite dendroide *Rhabdinopora flabelliformis norvegica* (Kjerulf, 1865) nella parte alta della Fm. di Cabitza (Tremadoc, Ordoviciano inf. del Fluminese, Sardegna SW). 4° Giornate di Paleontologia 2004 Bolzano 21/23 Maggio 2004, Abstract book: 46.

Corradini C., Ferretti A. & Serpagli E. (2004). The "Ockerkalk" limestone (late Silurian) of the Silius area: palaeobiological content and biostratigraphy. In Barca S., Carannante G., Cassinis G., Cherchi A., Corradini C., Cortesogno L., Del Rio M., Durand M., Ferretti A., Fontana D., Funedda A., Gaggero L., Garau A.M., Leone F., Macciotta G., Marchi M., Matteucci R., Murru M., Neri C., Loi A., Pillola G.L., Pittau P., Ronchi A., Salvadori I., Sarria E., Schroeder R., Serpagli E., Simone L. & Stefani C., Sardinian Paleozoic basement and its meso-cainozoic covers (Italy). 32 IGC - Field Trip Guide Book - P39: 18-20

Serpagli E. (2005). First record of the ichnofossil *Atollites* from Late Cretaceous of the Northern Apennines, Italy. *Acta Palaeontologica Polonica*, 50 (2): 403-408.

Alvaro J.J., Ferretti A., Gonzalez-Gomez C., Pierre C., Serpagli E., Subias I., Vecoli M. & Vizcaino D. (2005). An updated Furongian Stratigraphic framework for Southwestern Europe. *Acta Micropaleontologica Sinica*, 22: 3-5.

Bagnoli G., Corradini C., Ferretti A. & Serpagli E. (2006). La Formazione di Uqua nella Sezione Valbertad - The Uqua Fm in the Valbertad Section. *In* Corradini C., Muscio G. & Simonetto L. (eds.), Escursione in Friuli. Edizioni Università di Trieste: 111-113.

Ferretti A., Serpagli E. & Storch P. (2006). Problematic phosphatic plates from the Silurian-Early Devonian of Bohemia, Czech Republic. *Journal of Paleontology*, 80 (5): 1026-1031.

Serpagli E. & Serventi P. (2006). *Atollites*, un misterioso fiore di pietra di novanta milioni di anni. *Museo Civico di Vignola, Quaderni*, 7: 4-20.

Alvaro J.J., Ferretti A., Gonzalez-Gomez C., Serpagli E., Tortello F.M., Vecoli M. & Vizcaino D. (2007). A review of the Late Cambrian (Furongian) palaeogeography in the Western Mediterranean region, NW Gondwana. *Earth-Science Reviews*, 85: 47-81.

Serpagli E., Ferretti A., Vizcaïno D. & Álvaro J.J. (2007). A new Early Ordovician conodont genus from southern Montagne Noire, France. *Palaeontology*, 50 (6): 1447-1457.

Schallreuter R., Hinz-Schallreuter I., Serpagli E. & Ferretti A. (2007). Late Ordovician Ostracodes from Sardinia and Perigondwanan Ostracode Palaeobiogeography. *Zeitschrift für Geologische Wissenschaften*, 35: 253-331.

Pillola G.L., Piras S. & Serpagli E. (2008). Upper Tremadoc-Lower Arenig? Anisograptids-Dichograptid fauna from the Cabitza Formation (Lower Ordovician, SW Sardinia, Italy). *Revue de Micropaleontologie*, 51: 167-181.

Ferretti A. & Serpagli E. (2008). *Eurytholia* plates (Problematica) from the late Silurian of the Austrian Carnic Alps. *Revue de Micropaleontologie*, 51:183-187.

Serpagli E, Ferretti A., Nicoll R.S. & Serventi, P. (2008). The conodont genus *Teridontus* (Miller, 1980) from the Early Ordovician of Montagne Noire, France. *Journal of Paleontology*,82: 612-620.

Serpagli E., Serventi P. & Monegatti P. (2008). The ichnofossil genus *Paradictyodora* Olivero, Buatois & Scasso (2004) from the Pliocene of the Northern Apennines, Italy. *Rivista Italiana di Paleontologia e Stratigrafia*, 114 (1): 161-167.

Corradini C., Ferretti A, Corriga M.G. & Serpagli E. (2009). The reference section of the Sardinian Ockerkalk: the Silius Section. *Rendiconti della Società Paleontologica Italiana*, 3 (2): 209-216.

Corradini C., Ferretti A, Corriga M.G. & Serpagli E. (2009). Loboliths (crinoids) and conodont biostratigraphy of the Genna Ciuerciu Section (southeastern Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 217-224.

Ferretti A, Corradini C., Kriz. J., Piras S. & Serpagli E. (2009). The Perd'e Fogu outcrop: a classical exposure of "*Orthoceras* limestone" in the Fluminimaggiore area (SW Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 253-264.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 11-22

The Silurian of Sardinia (Italy): more than one and half century of researches

SEBASTIANO BARCA

S. Barca - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); barcas@unica.it

ABSTRACT - This paper is a synthetic historical review of researches on the Silurian of Sardinia, that, starting from the XVIII Century, were carried out by manly Italian scientists (palaeontologists, geologists, mining engineers) often with the valuable contribution by other European experts.

KEY WORDS - Historical studies, stratigraphy, palaeontology, Silurian, Sardinia.

INTRODUCTION

Silurian sediments have been recognized for the first time in Sardinia on a palaeontological basis by La Marmora (1857) - pioneer of geological studies on the island. Such rocks crop out mainly in southern Sardinia, both in the southwestern (Sulcis, Iglesiente, Fluminese, Guspinese, Arburese subregions) and in the southeastern part (Sarrabus and Gerrei subregions; Fig. 1). Silurian sediments are part of the Cambrian-Lower Carboniferous sequences developed in the "External Zone" and in the "External Nappes Zone" of the "Sardic Hercynian Chain", respectively (Barca, 1998; Carmignani et al, 2001b; and references therein). The metamorphic grade is always quite low in these zones, but tectonic deformations (folds, overthrusts, etc.) are responsible of considerable discontinuity of Silurian outcrops.

In the Inner Nappes Zone (North-central Sardinia: Barbagia, Ogliastra, Anglona, Logudoro, Baronie, Nurra subregions; Fig. 1) the Silurian outcrops are scarce and fossils are very rare due to increasing metamorphic grade and stronger Variscan tectonic deformations. In these areas, owing to the lack of palaeontological data, rocks are referred to Silurian (or to indifferentiated "Silurian-Devonian") on the basis of lithological analogies (black shales, lydites, metalimestones, marbles) with fossiliferous facies occurring in southern Sardinia.

For better understanding old papers, it should be pointed out that stratigraphical and structural features of the Variscan Basement of Sardinia were made clear only recently. Therefore, several outcrops of dark slates, metasandstones and quarzites, mainly in southeastern Sardinia, were referred to Silurian or indifferentiated Silurian-Devonian (i.e.: Servizio Geologico d'Italia, 1959, 1963, 1976). These rocks actually belong to various lower Palaeozoic periods. Furthermore, large Silurian olistoliths (namely graptolitic black shales and/or lydites) within the thick siliciclastic Lower Carboniferous succession of the so called "Sardic Hercynian Flysch" (Pala Manna Formation; Barca, 1991; Barca & Olivieri, 1991; Barca et al., 1998) were previously considered as true outcrops, both in the eastern part of Sulcis-Iglesiente (southwestern Sardinia) and in the Sarrabus-Gerrei (southeastern Sardinia).

Fig. 1 - Main sub-regions of Sardinia with location of historical Silurian fossiliferous localities.

This paper is a brief historical review of researches that, starting from the middle of the XVIII Century, brought to the present lithostratigraphical and biostratigraphical knowledge of the Silurian of Sardinia. Many papers arose from cooperation between palaeontologists and mining engineers (Taricco, Testa, Novarese, Sartori) and geologists, responsible for discovering new localities, mapping and even collecting fossils.

Scientists from several European countries (mainly Germany and Czech Republic) spent time and efforts on the Silurian of Sardinia, sometimes working alone, more often in collaboration with Italian geologists and palaeontologists.

Studies on the Silurian of Sardinia

According to what mentioned above, the large majority of the papers on the Silurian of Sardinia deals with the low metamorphic grade fossiliferous rocks of the southern part of the island.

The first palaeontological paper on the Silurian of Sardinia was published by Meneghini (1857), author of a chapter on “Paléontologie de l’Ile de Sardaigne” in the historical “Voyage en Sardaigne” by La Marmora (1857). There the author describes and beautifully figures several fossil groups of various Palaeozoic age. As regards the Silurian, Meneghini reports a dozen of new species of graptolites from samples collected by La Marmora in the famous Goni locality (Gerrei). The Meneghini`s collection was restudied sixty-five years later by Gortani (1923a), who examined also new material from the same locality and describing about thirty new graptolite species. Gortani (1923b, 1934) published two more monographs on graptolites from southeastern Sardinia, describing several species and recognizing for the first time the occurrence of Llandovery (with *Diplograptus palmeus, D. tamariscus, Climacograptus normalis, Rastrites*) and Wenlock (with *Monograptus sardous, M. vomerinus, M. falcatus, M. antennularius, Cyrtograptus rigidus*) sediments in Sardinia. The same author (Gortani, 1922, 1927, 1935) described the Silurian-Devonian sequences of Sardinia, comparing with the coeval succession of the Carnic Alps (northeastern Italy). An unconformity between Silurian and Upper Devonian of the Gerrei (southeastern Sardinia) was supposed by Gortani (1922) and later denied by the same author (Gortani, 1927).

Most of the Gortani’s original graptolite collection is now housed in the museum of the University of Pisa, together with the Meneghini’s collection. Other graptolites collected by Gortani are preserved in the university museums in Bologna, Parma, Pavia and Cagliari (Piras et al., 2008).

In the same period of Gortani’s researches, Taricco (1922a,b) listed some Lower Silurian graptolites from the Fluminimaggiore area (southwestern Sardinia), but unfortunately without any illustration. The same author (Taricco, 1911) had already reported the occurrence of graptolites near Gadoni village (Barbagia, central Sardinia), published a short note on the “Gotlandian” of Sardinia (Taricco, 1913) and discovered Silurian fossiliferous localities in the Sarrabus subregion (Taricco, 1915).

Important papers on graptolites from southeastern Sardinia are also due to Teichmüller (1931), Helmcke (1973), Helmcke & Koch (1974) and mainly Jaeger (1976, 1977). The latter author observed the strong affinities between the Silurian sequence of southeastern Sardinia and Thuringia and reported for the first time Early Devonian graptolites (*Monograptus uniformis* and *M. hercynicus* biozones) from the Baccu Scottis section. The knowledge on graptolites from southeastern Sardinia considerably increased owing to Jaeger (in Barca & Jaeger, 1990; Jaeger, 1991). Further occurrences of graptolitic black shales in that area were also reported by Barca (1981), Tistl (1981) and Schwab (1982).

In southwestern Sardinia, outcrops with Silurian graptolites are described by Amadei et al. (1957) and Barca & Marini (1983) at Genna Muxerru and Genna Gruxi, close to the Guspini village, by Barca & Salvadori (1974) and Barca et al. (1992a, b) in the Arburese subregion, and by Barca et al. (1986; 1998) in the Sulcis area. Finally Palmer & Gnoli (1985) reported an important find of *Saetograptus* cf. *fritschi* Perner close to the Fluminimaggiore village.

Recent papers dealing with these important Silurian fossils from Sardinia are due to Gnoli et al. (1990), Storch & Serpagli (1993), Rickards et al. (1995), Pittau & Del Rio (1998), Pittau et al. (2002), Storch et al. (2002) and Corradini (2007). Finally, Piras et al. (2008) described graptolites from the Gortani collection housed in the Palaeontological Museum “D. Lovisato” of Cagliari University, which includes seven Wenlockian taxa from Goni and one from the Llandovery of Fluminimaggiore. The current knowledge on Silurian graptolite fauna of southern Sardinia and its application in biostratigraphy is reviewed by Storch & Piras (2009, this volume).

Beside graptolites, Meneghini (1857) described and illustrated several taxa of nautiloid cephalopods from the Silurian "*Orthoceras* limestone" of southern Sardinia. Reports on these abundant fossils are also due to Taricco (1913), from central-eastern Sardinia, and Teichmüller (1931) and Ristedt (1968) from the South. A rare "*Orthoceras* breccia", reported by Venerandi (1965) from the Nurra sub-region, is probably Silurian in age and represents one of the few Palaeozoic fossils found in the northwestern part of the island.

A revision of the Meneghini collection was carried on by Gnoli & Serpagli (1977). The same authors (Serpagli & Gnoli, 1977) published also an important monograph on Silurian nautiloid cephalopods from southwestern Sardinia, describing and illustrating several species, a few of them new. Later on, Gnoli et al. (1979) emphasized palaeoecological significance of the middle-upper Silurian "Calcare ad *Orthoceras*" of southwestern Sardinia, and Gnoli (1990) evidenced the affinities between nautiloid communities of Sardinia and Bohemia. Other important papers on these fossils were published by Gnoli et al. (1988, 1990), Gnoli & Serpagli (1991) and Histon & Gnoli (1994) from southwestern Sardinia, and by Gnoli (1993) from southeastern Sardinia.

Occurrences of Silurian limestones with orthoceratids from southeastern Sardinia were reported by Barca (1981; Sarrabus) and Barca & Argiolas (1985; Gerrei), whereas Barca & Salvadori (1974) and Barca et al. (1992a, b) referred on outcrops in the Arburese area (southwestern Sardinia).

Among other fossil groups from the Silurian of Sardinia, several papers refer to the occurrence of crinoids. Meneghini (1887) described *Actinocrinus* from the Sarrabus. The occurrence of the pelagic *Scyphocrinites* in southeastern Sardinia is reported by Helmcke (1973), Jaeger (1976, 1977) and Corradini et al. (1998). Serpagli & Mastandrea (1980) and Gnoli et al. (1988) encountered scyphocrinids in the southwestern part of the island. The claimed occurrence of Silurian crinoids near the Domusnovas village (Scarzella, 1915) and Corr'e Boi (Testa, 1922b) should be disregarded, the first being probably Ordovician, and the latter Devonian in age. It should be noted that Testa (1915, 1918, 1922a, c) is the author also of other unconfirmed occurrences of crinoids and "Silurian fossils" in several localities of southeastern Sardinia, and in the Iglesiente (Testa & Sartori, 1915).

A dozen of species of Silurian bivalves, mainly *Cardiola*, were described from the "*Orthoceras* limestone" of southern Sardinia by Meneghini (1857, 1880), Barrande (1881, in Serpagli 1982), Taricco (1922a, b), Gortani (1922) and Teichmüller (1931). More recently Kriz & Serpagli (1993) described and illustrated several Bohemian-type bivalve-dominated communities from southwestern Sardinia.

Gastropods are quite rare in Sardinia and only small specimens have been described from Silurian black limestones by Meneghini (1857) and Gortani (1922).

Trilobites are very rare in the Silurian of Sardinia. Fondi (1985) and Carosi et al. (1987) claimed the occurrence of Silurian trilobites (Harpidae and Phacopidae) close to the Ballao village (southeastern Sardinia), but their specimens likely come from the Lower Devonian. More sure is the occurrence of *Ampyx* sp. aff. *roualti* Barrande near Fluminimaggiore (Palmer & Gnoli, 1985).

Reports on other macrofauna are quite rare from the Silurian of Sardinia: phyllocarids (Gnoli & Serpagli, 1984; Gnoli & Serventi, 2005), eurypterids (Gnoli, 1992a) and the problematic *Kolihaia sardiniensis* (Gnoli, 1992b) were described from the southwestern areas; the occurrence of brachiopods (*Merista passa* and three doubtful specimens) is reported by Teichmüller (1931) from the southeastern Sardinia.

Starting from the sixties of the XX Century, investigation on microfossils largely increased the stratigraphical knowledge of the Palaeozoic of Sardinia. Most of these researches were carried on by the Palaeozoic research group of Modena University, led by Enrico Serpagli, and were mainly based on conodont associations from Silurian and Devonian calcareous rocks from southern Sardinia (Corradini, 1998). Studies on conodonts are still in progress, but several scientific papers have been already published. Furthermore, in connection with the "*Seventh International Conodont Symposium Held in Europe (ECOS VII)*" (June 1998) a field trip was organized in Sardinia and the guide book (Serpagli, 1998) includes many recent data on the Palaeozoic, especially Silurian, of Sardinia.

Serpagli (1967) firstly reported the occurrence of Silurian conodonts in Sardinia, collected from the "Calcari ad *Orthoceras*" of Fluminimaggiore area; slightly later the same author (Serpagli, 1971) described and illustrated the complete association. Thanks to these data, Serpagli better defined the Silurian sequence of the Iglesiente, previously defined by Taricco (1922a) and Novarese & Taricco (1923). More precisely Serpagli was able to confirm a Devonian age for the upper part of the sequence described by Taricco (1922a) as:

- upper Gotlandian - nodular limestones, calcareous shales with *Tentaculites* (partly Devonian?), shaley limestones and black shales;
- middle Gotlandian - Ampelitic limestones with *Monograptus priodon*, *Cardiola interrupta*, (a.o.).
- lower Gotlandian - Black shales with *Rastrites peregrinus*, *Diplograptus palmens*, (a.o.).

For several years researches were mainly focused on the Fluminimaggiore area. Serpagli & Mastandrea (1980) described a conodont association across the Silurian-Devonian boundary from Fluminimaggiore, and Serpagli (1983) described the apparatus of *Icriodus woschmidti woschmidti*. Gnoli et al. (1988) studied the Mason Porcus section as a reference section for the uppermost Silurian-Lower Devonian in southwestern Sardinia, Ferretti (1989) described the microbiofacies and Olivieri & Serpagli (1990) illustrated the rich conodont fauna. Gnoli et al. (1990) established formal lithostratigraphic units in the Silurian and Lower Devonian of southwestern Sardinia, while Barca et al. (1992a, b) provided stratigraphical and structural data in the Arburese unit.

Several papers on Silurian conodonts from southern Sardinia provided important contributions on biostratigraphy, palaeoecology and stratigraphic correlations: for a complete list refer to the appendix to Corriga et al. (2009, this volume).

The stratigraphical sequence and conodont associations from the Ockerkalk limestone of southeastern Sardinia are described in detail by Barca et al. (1994, 1995) and Corradini et al. (2000, 2001, 2002a, b). Recently, Gouwy & Corradini (2006) applied the graphic correlation method on eight sections from the Ockerkalk, and stressed important implications for conodont biostratigraphy.

Several papers and reports have been dealing also with other microfossil group from the Silurian of Sardinia since the second half of the XIX Century. Bornemann (1860, in Meneghini) reports the occurrence of Palaeozoic ostracods from the "Silurian shales", listing three species of *Berychia*; however, these findings should be referred to Ordovician sediments (Schallreuter et al, 2007). Canavari (1899, 1900) published two important studies on Silurian ostracods from the "dark limestones with *Cardiola* and *Orthoceras*"; more recently Palmer & Gnoli (1985) described myodocopid ostracods from southwestern Sardinia, providing a careful taxonomic and biostratigraphical revision of this fauna.

Micropalaeontological researches carried on by scientists of the Istitute di Geology and Palaeontology (now Earth Science Department) of Cagliari University since the seventies of the last century mainly dealt with Silurian acritarchs and chitinozoans discovered in several areas, both in southwestern (Del Rio et al., 1980) and in southeastern Sardinia (Pittau & Del Rio, 1998, 2002; Pittau et al., 1998). Silurian and Devonian chitinozoans from southwestern Sardinia were described also by Dufka & Gnoli (1996).

Rare Foraminifera were reported from the upper Silurian-Lower Devonian of Fluminimaggiore (Gnoli & Serpagli, 1985), whereas probable agglutinated foraminifers are described from the Wenlock of Goni, together with radiolarians (Pittau et al., 2002). The occurrence of radiolarians in southeastern Sardinia was underlined also by Greiling (1977, in Barca & Jaeger, 1990). Finally, Pittau et al. (2003) refer to the occurrence of Silurian silicispongia.

Conclusions

Present knowledge on the Silurian of Sardinia is backed by more that one and half century of researches. All the four Silurian series (Llandovery, Wenlock, Ludlow and Pridoli) are palaeontologically documented and a good biostratigraphic resolution has been achieved, mainly on the basis of graptolites and conodonts.

The sedimentary sequence is continuous in Sardinia from the base through to the top of the Silurian System. A prominent unconformity between the uppermost Ordovician and the lower Silurian, marked by a hiatus where Llandovery and part of the Wenlock would have been missing, claimed by a few authors (Cocozza et al., 1974) can be definitely excluded. Analogously, a continuos sedimentation occurs at the Silurian-Devonian boundary.

According to the present stratigraphical scheme, the Silurian of southwestern Sardinia is represented by two lithostratigraphical units (Gnoli et al., 1990): the lower Silurian Genna Muxerru Formation ("Scisti a graptoliti" Auct.), followed by the Fluminimaggiore Formation ("Calcari ad *Orthoceras*" Auct.). Faunal content has strong affinities with coeval associations from Bohemia (Gnoli, 1990; Kriz & Serpagli, 1993).

In southeastern Sardinia the sequence is similar to those cropping out in Thuringia (Jaeger, 1976, 1977; Barca & Jaeger, 1990). Two lithostratigraphical units, still not formalized, are called: the "Lower Graptolitic Shales" (Barca & Jaeger, 1990) ("Scisti a graptoliti" Auct.), including Llandovery to lower Wenlock shales (Gortani, 1923 a, b; Helmcke,1973; Barca & Jaeger, 1990; Jaeger, 1991), and the "Ockerkalk limestone" of Ludlow-Pridoli age.

Recent stratigraphical, structural and petrographic investigations in connection with a new detailed mapping project of southern Sardinia (Carmignani et al., 2001a, b; Barca et al., 2005 and references therein) allow to deny the presence of volcanics interbedded to Silurian metasediments in southeastern Sardinia, claimed by several authors of the XIX Century (Cavinato, 1948; Calvino, 1961; Pomesano Cherchi, 1962; Cocozza et al., 1974; Di Simplicio et al., 1974; Cocozza & Minzoni, 1977; Beccaluva et al., 1981). These volcanics actually are Middle Ordovician (rhyolites, "porfiroidi", etc.; Barca & Di Gregorio, 1979; Barca & Maxia, 1982; Carmignani et al., 2001a, b) or Upper Ordovician (basic volcanics; Lehmann, 1975; Memmi et al., 1982; Naud, 1982; Barca & Argiolas, 1985; Leone et al., 1991; Di Pisa et al., 1992; Carmignani et al., 2001a, b; and references therein). Their wrong stratigraphical placement came from the still unclear tectonic interpretation of the region, where tectonic contacts were often considered as stratigraphical boundaries.

Silurian sediments had also a strong importance in the history of mining exploitation of Sardinia. This is true mainly in the southeastern part of the island, where mesothermal mineralizations (mainly sphalerite, galena, chalcopyrite, fluorite and baryte, native silver, etc.) occur within a cataclastic-mylonitic belt (Traverso, 1890; De Castro, 1890; Cavinato, 1939; Vardabasso, 1948; Zuffardi, 1967; Valera, 1974; Marcello et al., 1978, 1994, 2004; Salvadori et al., 1982; Bakos et al., 1991; Stara et al., 1993; Carmignani et al., 2001a; Tocco et al., 2009; and references therein). In the Sarrabus sub-region, that level was historically known as "Filone Argentifero" (= "Silver belt").

Always in southeastern Sardinia, another cataclastic-mylonitic belt with antimony mineralization within Silurian shales occurs in connection with the "Villasalto overthrust", an important tectonic structure between the Gerrei and Sarrabus tectonic units (Carmignani et al., 2001a, b).

Finally, beside papers reported in this summary on the Silurian of Sardinia, further information can be obtained from bibliographical papers by Cartisano et al. (1922), Taricco & Sotgia (1922), Maxia (1941, 1973), Comaschi & Caria (1949), Segre (1964), Nicosia (1968), and Serpagli & Gnoli (1984).

REFERENCES

Amadei G., Del Bono G.L. & Stampanoni G. (1957). Prime notizie sui rilevamenti dei quadranti II e III del F. 225 (Guspini) in Sardegna. *Bollettino del Servizio Geologico d'Italia*, 59: 989-1005.

Bakos F., Garbarino C., Mazzella A., Valera R. & Pani E. (1991). Mineral association in the Sarrabus, SE Sardinia, Italy, gold silver lode and its genetic relevance. *In* Ladeira E.A. (ed.) The Economics Geology, Geochemistry and Genesis of Gold Deposits. Proceeding of the Symposium Brazil Gold '91: 515-522.

Barca S. (1981). Contributo alla stratigrafia del Siluriano-Devoniano del Sarrabus (Sardegna sud-orientale). *Bollettino della Società Geologica Italiana*, 100: 85-98.

Barca S. (1991). Phénomènes de résedimentation et flysch hercynien à faciès Culm dans le "synclinal du Sarrabus" (SE de la Sardaigne, Italie). *Comptes Rendu de l'Academie des Sciences de Paris*, 313, s. II: 1051-1057.

Barca S. (1998). Structural and stratigraphical outlines of the Sardinian Massif. *In* Serpagli E. (ed.), Sardinia Field Trip Guidebook, ECOS VIII. *Giornale di Geologia*, 60, Spec. Issue: 1-23.

Barca S. & Argiolas M. (1985). Contributo allo studio stratigrafico-strutturale del Paleozoico della Sardegna sud-orientale: il settore ad ovest di Silius (Gerrei). *Bollettino della Società Geologica Italiana*, 104: 43-52.

Barca S., Cocozza T. & Leone F. (1986). Il Paleozoico dell'area di San Leone: nuovi dati stratigrafico-strutturali (Sulcis, Sardinia SW). *Bollettino della Società Geologica Italiana*, 105: 21-26.

Barca S., Corradini C., Ferretti A., Olivieri R. & Serpagli E. (1994). Conodont evidences from the "Ockerkalk" of Southeastern Sardinia (Silurian, Silius area). *In* Schönlaub H.P. & Kreutzer L.H. (eds.), IUGS Subcommission on Silurian Stratigraphy. Field Meeting Eastern+Southern Alps. *Berichte der Geologischen Bundesanstal*t, 30/1994, 30: 126.

Barca S., Corradini C., Ferretti A., Olivieri R. & Serpagli E. (1995). Conodont biostratigraphy of the "Ockerkalk" (Silurian) from southeastern Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 100 (4) (1994): 459-476.

Barca S. & Di Gregorio F. (1979). La successione ordoviciano-siluriana inferiore del Sarrabus (Sardegna sud-orientale). *Memorie della Società Geologica Italiana*, 20: 189-202.

Barca S., Farci G. & Forci A. (1998). I depositi sinorogenici ercinici del Sulcis (Sardegna sud-occidentale). *Bollettino della Società Geologica Italiana*, 117: 407-417.

Barca S., Ferretti A., Massa P. & Serpagli E. (1992a). The Hercynian Arburese Tectonic Unit of SW Sardinia. New stratigraphic and structural data. *Rivista Italiana di Paleontologia e Stratigrafia*, 98 (2): 119-136.

Barca S., Ferretti A., Massa P. & Serpagli E. (1992b). Minor tectonic units within the Hercynian Arburese Nappe in Southwestern Sardinia. New structural and stratigraphic evidence. *In* Carmignani L. & Sassi F.P. (eds.), Contribution to the Geology of Italy with special regard to the Paleozoic basement. A volume dedicated to Tommaso Cocozza. *IGCP Project No 276 Newsletter*, 5: 51-55.

Barca S. & Jaeger H. (1990). New geological and biostratigraphical data on the Silurian in SE Sardinia. Close affinity with Thuringia. *Bollettino della Società Geologica Italiana*, 108 (1989): 565-580.

Barca S. & Marini C. (1983). Le mineralizzazioni stratiformi a solfuri misti del settore paleozoico del Monte Linas (Sardegna sud-occidentale). Contesto geologico e caratteri geochimici. *Resoconti dell'Associazione Mineraria Sarda*, A.88, 1: 5-54.

Barca S. & Maxia M. (1982). Assetto stratigrafico e tettonico del Paleozoico del Sarrabus occidentale. In: Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C. & Ricci C.A. (eds.), Guida alla Geologia del Paleozoico sardo. *Società Geologica Italiana, Guide Geologiche Regionali*: 87-93.

Barca S., Melis E., Annino E. & Cincotti F. (2005). Note illustrative della Carta Geologica d'Italia 1.50000 "Foglio 557-Cagliari". *Servizio Geologico d'Italia*, 240 pp.

Barca S. & Olivieri R. (1991). Age and source of calcareous blocks resedimented into Hercynian Flysch type sediments of the Sarrabus area (Southeastern Sardinia). *Atti della Società dei Naturalisti e Matematici di Modena*, 122: 49-66.

Barca S. & Salvadori I. (1974). Nuovo contributo alla geologia del Paleozoico a nord di Monte Arcuentu (Sardegna sud-occidentale). *Bollettino della Società Sarda di Scienze Naturali*, 14: 77-88.

Barrande J. (1881). Systéme silurien du centre de la Bohéme. Classe des Mollusques, ordre des Acéphalés. 6. Prague, Paris. 342 pp.

Beccaluva L., Leone F., Maccioni L. & Macciotta G. (1981). Petrology and tectonic setting of the Paleozoic basic rocks from Iglesiente-Sulcis (Sardinia, Italy). *Neues Jahrbuch für Mineralogie Abhandlungen*, 140: 184-201.

Calvino F. (1961). Lineamenti strutturali del Sarrabus-Gerrei. *Bollettino del Servizio Geologico d'Italia*, 81 (1959): 489-556.

Canavari M. (1899). Ostracodi Siluriani in Sardegna. *Atti della Società Toscana di Scienze Naturali*, 11: 150-153.

Canavari M. (1900). La fauna dei calcari nerastri con *Cardiola* ed *Orthoceras* di Xea S. Antonio in Sardegna. Introduzione e parte I: Ostracoda. *Paleontographia Italica*, 5: 187-210.

Carmignani L., Conti P., Barca S., Cerbai N., Eltrudis A., Funedda A., Oggiano G. & Patta E.D. (2001a). Note Illustrative della Carta Geologica d'Italia 1: 50000 "Foglio 549-Muravera". *Servizio Geologico d'Italia*, 140 pp.

Carmignani L., Oggiano G., Barca S., Conti P., Salvadori I., Eltrudis A., Funedda A. & Pasci S. (2001b). Geologia della Sardegna. Note Illustrative della Carta Geologica della Sardegna a scala 1: 200000. *Memorie descrittive della Carta Geologica d'Italia, Servizio Geologico*, Istituto Poligrafico e Zecca dello Stato, 283 pp.

Carosi R., Elter F.R. & Fondi R. (1987). Fossiliferous metapelites with *Denckmannites* (Phacopida, Trilobita) in the Gerrei complex near Ballao (Cagliari, southeastern Sardinia). *In* Sassi F.P. & Bourrouilh R. (eds.), IGCP No. 5 Newsletter 7: 30-33.

Cartisano D., Palumbo E. & Sotgia T. (1922). Bibliografia geologica e mineraria della Sardegna (1896-1921). *Resoconti dell'Associazione Minerario Sarda*, 27 (2), 30 pp.

Cavinato A. (1939). Epoche metallogeniche in Sardegna. *Associazione Mineraria Sarda*, 44 (2): 42-50.

Cavinato A. (1948). Cicli magmatici in Sardegna. Atti del Congresso Mineralogico Italiano, Iglesias: 131-133.

Cocozza T., Jacobacci A., Nardi R. & Salvadori I. (1974). Schema stratigrafico-strutturale del Massiccio Sardo-Corso e minerogenesi della Sardegna. *Memorie della Società Geologica Italiana*, 13: 85-186.

Cocozza T. & Minzoni N. (1977). Osservazioni sul vulcanismo paleozoico sardo. *In* Vai G.B. (ed.), Gruppo di Lavoro sul Paleozoico, Suppl., 2-1977: 25-29.

Comaschi Caria I. (1949). I fossili della Sardegna. *Istituto per gli Studi Sardi, Università di Cagliari*, Tip. V. Musanti, 410 pp.

Corradini C. (1998). Thirty-five years of conodont studies in Sardinia. *In* Serpagli E. (ed.), Sardinia Field Trip Guidebook, ECOS VIII. *Giornale di Geologia*, 60, Spec. Issue: 75-78.

Corradini C. (2007). Scisti a Graptoliti. In: Carta Geologica d'Italia 1:50000. Catalogo delle Formazioni, fascic. VI – Unità tradizionali e/o storiche. *Quaderni*, s. 3, 7: 293-297.

Corradini C., Ferretti A. & Serpagli E. (1998). The Silurian and Devonian sequence in SE Sardinia. *In* Serpagli E. (ed.), Sardinia Field Trip Guidebook, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 71-74.

Corradini C., Ferretti A. & Serpagli E. (2000). Correlazioni biostratigrafiche negli "Ockerkalk" (Siluriano sup.) della Sardegna sud-orientale. *Accademia Nazionale di Scienze, Lettere ed Arti di Modena, Collana di Studi*, 21: 87-92.

Corradini C., Ferretti A. & Serpagli E. (2002a). The Gerrei Tectonic Unit (SE Sardinia, Italy). *Rendiconti della Società Paleontologica Italiana*, 1: 69-76.

Corradini C., Ferretti A. & Serpagli E. (2002b). The "Ockerkalk" limestone in the Genna Ciuerciu Section (SE Sardinia, Italy). *Rendiconti della Società Paleontologica Italiana*, 1: 255-260.

Corradini C., Ferretti A. & Serpagli E. (2004). The "Ockerkalk" limestone (late Silurian) of the Silius area: paleobiological content and biostratigraphy. *In* "Sardinian Paleozoic basement and its Meso-Cainozoic covers (Italy)". 32nd IGC-Field Trip Guide Book- P39: 18-20.

Corradini C., Leone F., Loi A. & Serpagli E. (2001). Conodont stratigraphy of a higly tectonised Siluro-Devonian Section in the San Basilio area (SE Sardinia). *Bollettino della Società Paleontologica Italiana*, 40: 315-323.

Corriga M.G., Corradini C. & Ferretti A. (2009). Silurian conodonts from Sardinia: an overview. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 95-107.

De Castro C. (1890). Descrizione geologico-mineraria della zona argentifera del Sarrabus. *Memorie Descrittive della Carta Geologica d'Italia, Servizio Geologico d'Italia,* 5, 68 pp.

Del Rio M., Leone F. & Pittau P. (1980). Acritarchi siluriani della successione paleozoica di Domusnovas (Sardegna sud-occidentale). *Memorie della Società Geologica Italiana*, 20 (1979): 289-299.

Di Pisa A., Gattiglio M. & Oggiano G. (1992). Pre-Hercynian magmatic activity in the Nappe Zone (internal and external) of Sardinia: evidence of two within-plate basaltic cycles. *In* Carmignani L. & Sassi F.P. (eds.), Contribution to the Geology of Italy with special regard to the Paleozoic basement. A volume dedicated to Tommaso Cocozza. *IGCP Project No. 276 Newsletter*, 5: 33-44.

Di Simplicio P., Ferrara G., Ghezzo C., Guasparri G., Pellizzer R., Ricci C.A., Rita F. & Sabatini G. (1974). Il metamorfismo e il magmatismo paleozoico della Sardegna. *Rendiconti Società Italiana di Mineralogia e Petrografia*, 30: 979-1068.

Dufka P. & Gnoli M. (1996). A report on Silurian and lowermost Devonian chitinozoans from South-western Sardinia. *Bollettino della Società Paleontologica Italiana*, 34 (3), (1995): 263-269.

Ferretti A. (1989). Microbiofacies and constituent analysis of Upper Silurian-Lowermost Devonian limestones from Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 28 (1): 87-100.

Fondi R. (1985). I Trilobiti siluriani di Ballao (Gerrei, Sardegna sud-orientale). *In* Cocozza T. & Ricci C.A.(Eds.), Evoluzione stratigrafica, tettonica, metamorfica e magmatica del Paleozoico italiano, Note Brevi e Riassunti, Siena 13-14 dicembre 1985: 43-44.

Gnoli M. (1990). New evidence for faunal links between Sardinia and Bohemia in Silurian time on the basis of Nautiloids. *Bollettino della Società Paleontologica Italiana*, 29 (3): 289-307.

Gnoli M. (1992a). Occurrence of Eurypterids (Artropoda) in the Silurian of Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 3 (1): 147-149.

Gnoli M. (1992b). The problematic organism *Kolihaia sardiniensis* n. sp. of the latest Wenlock-earliest Ludlow of SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 31 (3): 383-385.

Gnoli M. (1993). Occurrence of middle-late Silurian nautiloids from San Basilio area (Gerrei, SE Sardinia). *Bollettino del Museo Regionale di Scienze Naturali di Torino*, 10 (2): 265-269.

Gnoli M., Kriz M., Leone F., Olivieri R., Serpagli E. & Storch P. (1990). Lithostratigraphic units and biostratigraphy of the Silurian and Early Devonian of Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 11-23.

Gnoli M., Leone F., Olivieri R. & Serpagli E. (1988). The Mason Porcus section as reference section for Uppermost Silurian-Lower Devonian in SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 27 (3): 323-334.

Gnoli M., Parea G.C., Russo F. & Serpagli E. (1979). Paleoecological remarks on the “Orthoceras Limestone” of Southwestern Sardinia (Middle-Upper Silurian). *Memorie della Società Geologica Italiana*, 20: 405-423.

Gnoli M. & Serpagli E. (1977). Silurian cephalopods of Meneghini collection (1857) with the reproduction of the original plate. *Bollettino della Società Paleontologica Italiana*, 16 (2): 137-142.

Gnoli M. & Serpagli E. (1984). Evidence of Phyllocarid remains from Silurian-Devonian boundary beds in southwestern Sardinia. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1984-H5: 257-268.

Gnoli M. & Serpagli E. (1985). An unusually preserved foraminiferal association from the Upper Silurian-Lower Devonian beds in southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 23 (2) (1984): 211-220.

Gnoli M. & Serpagli E. (1991). Nautiloid assemblages from middle-late Silurian of Southwestern Sardinia: a proposal. *Bollettino della Società Paleontologica Italiana*, 30 (2): 187-194.

Gnoli M. & Serventi P. (2005). New Evidence of Silurian Phyllocarid remains from SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 44 (3): 255-262.

Gortani M. (1922). Osservazioni sul Paleozoico della Sardegna. *Bollettino della Società Geologica Italiana*, 41 (4): 362-371.

Gortani M. (1923a). Faune paleozoiche della Sardegna. Parte I. Le Graptoliti di Goni. *Paleontographia Italica*, 28: 51-67.

Gortani M. (1923b). Faune paleozoiche della Sardegna. Parte II. Graptoliti della Sardegna orientale. *Paleontolographia Italica*, 28: 85-112.

Gortani M. (1927). La serie paleozoica nelle Alpi Carniche e della Sardegna. *Compte-Rendu XIV Congrés Géologique International*, 1926: 3-7.

Gortani M. (1934). Successioni di faune a Graptoliti nei dintorni di Goni (Sardegna). *Rendiconti della Reale Accademia Nazionale dei Lincei, Classe di Scienze fisiche, matematiche e naturali*, 19 (6): 763-765.

Gortani M. (1935). L’esplorazione geologica della Sardegna. *Atti del XII Congresso Geografico Italiano*: 105-108.

Greiling R. (1977). Die Lagerstättenprovinz Sarrabus-Gerrei (SE-Sardinien/Italien) und ihr geologischer Rahmen. *Europäische Hochschulschriften: Reihe* 17, Erdwissenschaften, 3, 145 pp.

Gouwy S. & Corradini C. (2006). Graphic correlation of the Sardinian Ockerkalk (Upper Silurian): implications on the conodont biostratigraphy. *GFF*, 128: 103-108.

Helmcke D. (1973). Zur Stratigraphie des Silur und Unterdevon der lagerstättenprovinz Sarrabus-Gerrei. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1973-H.9: 529-544.

Helmcke D. & Koch G. (1974). Schichtgebundene NE-Metall-und F-Ba-Lagerstätten im Sarrabus-Gerrei-Gebiet SE-Sardinien III. Bericht: Zur Alters-stellung der Porphyroide in der Lagerstättenprovinz Sarrabus-Gerrei. *Zeitschrift der Deutschen geologischen Gesellschaft*, 125: 91-98.

Histon K. & Gnoli M. (1994). Bathymetry of the Silurian Nautiloid fauna from the "Orthoceratite Limestone", SW Sardinia. *In* Schönlaub H.P. & Kreutzer L.H. (Eds.), IUGS Subcommission on Silurian Stratigraphy. Field Meeting Eastern+Southern Alps. *Berichte der Geologischen Bundesanstal*t, 30/1994, 30: 131-132.

Jaeger H. (1976). Das Silur und Unterdevon vom thüringischen Typ in Sardinien und seine regionalgeologische Bedentung. *In* Watznauer A. (ed.), Franz-Kossmat-Symposium. *Nova Acta Leopoldina*, 45 (224): 263-299.

Jaeger H. (1977). The Silurian-Devonian boundary in Thuringia and Sardinia. In: Martinsson A. (ed.) - The Silurian-Devonian boundary International Union of Geologist Sciences (IUGS), s.A, 5: 117-125.

Jaeger H. (1991). Neue Standard-Graptolithenzonenfolge nach der "Grossen Krise" an der Wenlock/Ludlow-Grenze (Silur). *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen*, 182 (3): 305-354.

Kriz J. & Serpagli E. (1993). Upper Silurian and Lowermost Devonian Bivalvia of Bohemian type from Western Sardinia. *Bollettino della Società Paleontologica Italiana*, 32 (3): 289-347.

La Marmora A. (1857). Voyage en Sardaigne: Troisième partie. Description géologique et paléontologique. Bocca Impr. Royale, Torino, 2 vol.: 707-781.

Lehmann B. (1975). Stratabound polymetallic and F-Ba-deposits of the Sarrabus-Gerrei region, Se-Sardinia. IV report: Initial Variscan magmatism in SE-Sardinia. *Neue Jahrbuch für Geologie und Paläontologie Monatshefte*, 1973-H.9: 529-544.

Leone F., Hamman W., Laske R., Serpagli E. & Villas E. (1991). Lithostratigraphic units and biostratigraphy of the post-sardic Ordovician sequence in the south-west Sardinia. *Bollettino della Società Paleontologica Italiana*, 30 (2): 201-232.

Marcello A., Pretti S. & Salvadori I. (1978). Carta Metallogenica della Sardegna. Scala 1/250000. Servizio Geologico d'Italia - Ente Minerario Sardo, Roma.

Marcello A., Pretti S. & Salvadori I. (1994). Introduction to the minerogenesis and economic geology of Sardinia. *In* Carmignani L., Ghezzo C., Marcello A., Pertusati P.C., Pretti S., Ricci C.A. & Salvadori I. (eds), 16th General Meeting of the International Mineralogical Association, Pisa, Italy. Guide-book to the field excursion: Petrology, geology and ore deposits of the Paleozoic basement of Sardinia: 37-43.

Marcello A., Pretti S., Valera P., Boni M. & Fiori M. (2004). Metallogeny in Sardinia (Italy): from the Cambrian to the Tertiary. 32nd IGC-Field Trip Guide Book- P30: 40pp.

Maxia C. (1941). Bibliografia Mineraria della Sardegna. Istituto per gli Studi Sardi, Istituto di Geologia dell'Università di Cagliari, 248 pp.

Maxia C. (1973). Il Paleozoico inferiore della Sardegna. *In* Geologia dell'Italia (A. Desio). Volume celebrativo del 1° Centenario del Comitato Geologico dell'Italia, Torino, UTET, 1973, 10: 84-93.

Memmi I., Barca S., Carmignani L., Cocozza T., Franceschelli M., Gattiglio M., Ghezzo C., Minzoni N., Naud G., Pertusati P.C. & Ricci C.A. (1982). Il magmatismo pre-ercinico della Sardegna. *In* Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C. & Ricci C.A. (eds.), Guida alla Geologia del Paleozoico Sardo. *Società Geologica Italiana, Guide Geologiche Regionali*: 157-164.

Meneghini G. (1857). Paléontologie de l'ile de Sardaigne ou déscription des fossiles recueilli dans cette contrée par le général A. De La Marmora. *In* La Marmora A., de, Voyage en Sardaigne, 3, 584 pp., Bocca Imprimerie Royale, Torino.

Meneghini G. (1880). Nuovi fossili siluriani della Sardegna. *Memorie della Reale Accademia dei Lincei*, 3: 216-229.

Meneghini G. (1887). Actinocrinus del Sarrabus. *Proc. Verbali Atti Società Toscana di Scienze Naturali*, 5.

Naud G. (1982). Schema stratigrafico-strutturale del Paleozoico della zona di San Basilio (Sardegna sud-orientale). *In* Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C. & Ricci C.A. (eds.), Guida alla Geologia del Paleozoico sardo. *Società Geologica Italiana, Guide Geologiche Regionali*: 109-115.

Nicosia M.L. (1968). Bibliografia del Paleozoico italiano. Consiglio Nazionale delle Ricerche, Roma, 212 pp.

Novarese V. & Taricco M. (1923). Cenni sommari sul Paleozoico dell'Iglesiente. *Bollettino della Società Geologica Italiana*, 4: 316-325.

Olivieri R. & Serpagli E. (1990). Latest Silurian-Early Devonian conodonts from Mason Porcus Section near Fluminimaggiore, Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 59-76.

Palmer D. & Gnoli M. (1985). A preliminary report on new micropaleontological discoveries in the Silurian of Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 23 (2) (1984): 221-238.

Piras S., Simonetto L. & Corradini C. (2008). I Graptoliti siluriani della Collezione "M. Gortani" del Museo Paleontologico "D. Lovisato" dell'Università degli Studi di Cagliari. *Gortania*, 29 (2007): 9-28.

Pittau P., Cotza F. & Del Rio M. (2002). Gonispheres: probable agglutinated foraminifera lining and radiolaria capsular membranes. *In* Cherchi A., Corradini C. & Putzu M.T. (eds.), Sardinia Field Trip - Paleontology & Stratigraphy. *Rendiconti della Società Paleontologica Italiana,* 1: 159-168.

Pittau P., Cotza F. & Del Rio M. (2003). Early Silurian siliceous sponge spicule assemblages from the Sardinia Hercynian Chain (Italy). *Bollettino della Società Paleontologica Italiana,* 4 (3): 225-239.

Pittau P. & Del Rio M. (1998). The Silurian of SE Sardinia: the Llandovery at Riu Ollastu. *In* Pittau P. (ed.), CIMP Symposium and Workshop (Pisa and Sardinia, 1998), Palynological Research in the Sardinian Basement- Field Trip Guide-book, Sept. 16-19, 1998: 43-50.

Pittau P. & Del Rio M. (2002). Wenlock Chitinozoans of SE Sardinia (Italy). *Bollettino della Società Paleontologica Italiana,* 39: 257-291.

Pittau P., Del Rio M., Aresu V. & Deidda D. (1998). Wenlock Chitinozoa of the Goni Section. *In* Pittau P. (ed.), CIMP Symposium and Workshop (Pisa and Sardinia, 1998), Palynological Research in the Sardinian Basement- Field Trip Guide-book, Sept. 16-19, 1998: 69-80.

Pittau P., Del Rio M.& Barca S. (2002). The Wenlockian Graptolitic Shales at Goni, SE Sardinia. *Rendiconti della Società Paleontologica Italiana,* 1: 247-253.

Pomesano Cherchi A. (1962). Ricerche sul vulcanismo gotlandiano del Gerrei (Sardegna sud-orientale). Ricerca Scientifica, 32 (II, A): 279-285.

Rickards R.B., Holland C.H. & Serpagli E. (1995). Aspects of Silurian and Lower Devonian graptolite faunas and stratigraphy in southern Sardinia. *Bollettino della Società Paleontologica Italiana,* 31 (1): 67-80.

Ristedt H. (1968). Zur Revision der Orthoceratidae. *Akademie der wiessenschaften und Literatur zu Wiesbaden, Abhaudlungen der klasse mathematic und naturwiessenshaften,* 4: 213-297.

Salvadori I., Uras I. & Zuffardi P. (1982). I giacimenti minerari del Paleozoico Sardo. *In* Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C. & Ricci C.A. (eds.), Guida alla Geologia del Paleozoico Sardo. *Società Geologica Italiana, Guide Geologiche Regionali*: 55-63.

Scarzella A. (1915). Notizie del ritrovamento di Favosites, Murchisonia, Scyphocrinus presso Domusnovas. *Resoconti dell'Associazione Mineraria Sarda,* 2.

Schallreuter R., Hinz-Schallreuter I., Ferretti A. & Serpagli E. (2007). Late Ordovician Ostracodes from Sardinia and Perigondwanan Ostracode Palaeobiogeography. *Zeitschrift für Geologische Wissenschaften, Berlin,* 35: 253-331.

Schwab K.H. (1982). Geologie und Geochemie der ehemaligen Lagerstätten S'Arcu Mannu und Tacconetta im Bereich des Riu Ollastu, Sarrabus/SE-Sardinien. Diplomarbeit Freie Universität Berlin (Maschinenschrift).

Segre A.G. (1964). Bibliografia geologica d'Italia: Sardegna. *Consiglio Nazionale delle Ricerche* (C.N.R.), 15, 387 pp.

Serpagli E. (1967). Prima segnalazione di Conodonti nel Siluriano della Sardegna e relative osservazioni stratigrafiche. *Atti dell'Accademia Nazionale dei Lincei, Rend. Cl. Sc. Fis. Mat. E Nat.*, 42 (6): 856-858.

Serpagli E. (1971). Uppermost Wenlockian-Upper Ludlovian (Silurian) Conodonts from Western Sardinia. *Bollettino della Società Paleontologica Italiana,* 9 (1) (1970): 76-96.

Serpagli E. (1982). Le conoscenze paleontologiche del Paleozoico sardo. *In* Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C. & Ricci C.A. (eds.), "Guida alla Geologia del Paleozoico Sardo", *Società Geologica Italiana, Guide Geologiche Regionali*: 25-32.

Serpagli E. (1983). The conodont apparatus of *Icriodus woschmidti woschmidti* Ziegler. *Fossils and Strata,* 15: 155-161.

Serpagli E. (ed.) (1998). Sardinia Field Trip Guidebook, ECOS VII, *Giornale di Geologia*, 60, Spec. Issue, 212 pp.

Serpagli E. & Gnoli M. (1977). Upper Silurian Cephalopods from Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana,* 16 (2): 153-196.

Serpagli E. & Gnoli M. (1984). Palaeozoic Palaeontology in Sardinia: a review (1857-1983). *Bollettino del Museo Regionale di Scienze Naturali di Torino,* 2 (1): 163-180.

Serpagli E. & Mastandrea A. (1980). Conodont assemblages from the Silurian-Devonian boundary beds of Southwestern Sardinia (Italy). *Neues Jahrbuch für Geologie und Paläontologie Monatshefte,* 1980-H1: 37-42.

Servizio Geologico d'Italia (1959). Carta Geologica d'Italia, Foglio 226 "Mandas".

Servizio Geologico d'Italia (1963). Carta Geologica d'Italia, Foglio 227 "Muravera".

Servizio Geologico d'Italia (1976). Carta Geologica d'Italia, Foglio 218 "Isili".

Stara P., Rizzo R. & Brizzi G. (1993). Sarrabus, Miniere e Minerali. Stige Milano s.r.l. (ed.), 208 pp.

Storch P. & Piras S. (2009). Silurian graptolites of Sardinia: assemblages and biostratigraphy. *Rendiconti della Società Paleontologica Italiana,* 3 (1): 77-93.

Storch P. & Serpagli E. (1993). Lower Silurian Graptolites from Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana,* 32 (1): 3-57.

Storch P., Serpagli E. & Barca S. (2002). Silurian graptolites of the *spiralis* and *lapworthi* biozones (upper Telychian, Llandovery) in the Sulcis area, SW Sardinia. *Bollettino della Società Paleontologica Italiana,* 41 (2-3): 97-107.

Taricco M. (1911). Osservazioni geologico-minerarie sui dintorni di Gadoni e sul Gerrei. *Bollettino della Società Geologica Italiana,* 30.

Taricco M. (1913). Il Gotlandiano in Sardegna. *Rendiconti della Regia Accademia dei Lincei,* s. 5, 22 (2): 109-115.

Taricco M. (1915). Nota preliminare su località fossilifere del Sarrabus (Sardegna). *Bollettino del Comitato Geologico Italiano,* 45 (3-4): 351-353.

Taricco M. (1922a). Sul Paleozoico del Fluminese (Sardegna). *Bollettino del Regio Comitato Geologico Italiano,* 48 (1920-21) (6): 1-22.

Taricco M. (1922b). Sul Paleozoico del Fluminese. *Resoconti dell'Associazione Mineraria Sarda,* 8.

Taricco M. & Sotgia T. (1922). Bibliografia geologica, paleontologica, mineralogica e mineraria della Sardegna. *Bollettino della Società Geologica Italiana,* 41: 373-437.

Teichmüller R. (1931). Zur Geologie des Tyrrhenisgebietes. Teil 1: Alte und junge Krustenbewegungen im südlichen Sardinien. *Abhandlungen der Gesellschaft der Wissenschaft zu Göttingen, Klasse mathematische-physische*, 3: 857-950.

Testa L. (1915). Notizie del ritrovamento di crinoidi siluriani nel M.S. Vittoria (Esterzili). *Resoconti dell'Associazione Mineraria Sarda*, 8.

Testa L. (1918). Notizia del ritrovamento di crinoidi nel Gotlandiano di Donigala Siurgus. *Resoconti dell'Associazione Mineraria Sarda*, 8.

Testa L. (1922a). Nuovi fossili silurici nel Sarrabus. *Associazione Mineraria Sarda*, 27 (3), 12 pp.

Testa L. (1922b). Fossili siluriani nella concessione di Corr'e Boi (Villagrande). *Associazione Mineraria Sarda*, 27 (6), 15 pp.

Testa L. (1922c). Ritrovamento di fossili siluriani presso Mogorella. *Associazione Mineraria Sarda*, 27 (7), 11 pp.

Testa L. & Sartori F. (1915). Fossili siluriani presso la grotta di Domusnovas. *Resoconti dell'Associazione Mineraria Sarda*, 3.

Tistl M. (1981). Die Geologie im Bereich der ehemaligen Pb, Zn, Ag-Lagerstätte s'Arcilloni (Sarrabus/SE Sardinien). Diplomarbeit, Freie Universität Berlin (Maschinenschrift).

Tocco S., Marcello A., Mazzella A., Naitza S., Pretti S., Valera P. & Valera R. (2009). Il nuovo quadre geo-giacimentologico della Sardegna dalla Carta Metallogenica e delle Georisorse in scala 1:250.000. *Rendiconti dell'Associazione Mineraria Sarda*, 112 (in press).

Traverso S. (1890). Note sulla geologia e sui giacimenti argentiferi del Sarrabus. Casanova F. Ed., Torino, 57 pp.

Valera R. (1974). Genesi ed evoluzione delle mineralizzazioni del Sarrabus (Sardegna sud-orientale). *Rendiconti della Società Italiana di Mineralogia e Petrografia*, 30: 1081-1108.

Vardabasso S. (1948). Inquadratura geologica dei giacimenti Sardi. Congresso Minerario Italiano, Iglesias 1948: 47-51.

Venerandi I. (1965). Nuove osservazioni sul giacimento ferrifero della Nurra. *Rendiconti della Società Mineralogica Italiana*, 21:317-333.

Zuffardi P. (1967). Sedimentary ores of the middle Silurian in Sardinia. 15th International University Geological Congress, Leicester: 207-239.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 23-35

Outline of the Variscan basement of Sardinia

ANTONIO FUNEDDA, GIACOMO OGGIANO

A. Funedda - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); afunedda@unica.it

G. Oggiano - Dipartimento di Scienze Botaniche Ecologiche e Geologiche, Università di Sassari, Via Muroni 25, 07100 Sassari (Italy); giacoggi@uniss.it

ABSTRACT - In Sardinia a quasi-complete section of the southern branch of the Variscan orogenic belt crops out, characterized by non-metamorphosed to high-grade rocks, whose age ranges from Early Cambrian to Early Carboniferous, and that are involved in a complex polyphase deformation. The main result of the Variscan orogeny in Sardinia is a tectono-metamorphic partition with, from north to south: an Inner Zone, with medium to high grade metamorphism, thrusted over a Nappe Zone, with green schist metamorphism that overthrusted a Foreland Zone affected by very low grade regional metamorphism. The pre-Variscan succession is well exposed in the Foreland and Nappe zones where four main synthemes can be recognized: i) a Lower Cambrian to Lower Ordovician terrigenous and carbonatic succession deposited in the Gondwana passive margin, sealed by an angular unconformity related to the Sardic Phase, ii) a Middle-Upper Ordovician magmatic complex, both intrusive and effusive, probably related to an Andean-type plate convergence, iii) a terrigenous to carbonatic succession from Late Ordovician to Early Carboniferous, again related to a passive margin evolution; iv) finally a flyschoid Culm-like succession accredited to Early Carboniferous.

KEY WORDS - Variscan orogenic belt, tectonics, stratigraphy, Sardinia.

INTRODUCTION

In Sardinia a segment of the southern branch of the European Variscan orogen crops out, involving metamorphic rocks aging from Early Cambrian to Early Carboniferous, and a late orogenic magmatic complex emplaced during Late Carboniferous and Permian (Fig. 1).

Restoring the eastward drifting and counter-clockwise rotation of the Sardinia-Corsica block occurred in early Miocene time (Arthaud & Matte, 1966, 1977; Alvarez, 1972; Westphal et al., 1976; Matte, 2001; Gattacceca et al. 2007), both stratigraphical and tectonic features of the Sardinian metamorphic basement find their prolongation in the Variscan domains of the South European margin, although some problems arise about the pre-Variscan paleogeography (Edel et al., 1981; Robardet, 2003). According to most of the authors, the European Variscides, before being dismembered and/or incorporated in the Alpine orogens, belonged to an arched orogenic belt that run from the Iberian Peninsula to the French Massif Central (Ibero-Armorican Arc) (Matte, 1986; Vai & Cocozza, 1986) (Fig. 2). The Sardinian metamorphic basement is thus a part of the South European Variscides that resulted (Matte, 2001) from the diachronic collision between Laurentia-Baltica to the NW and Gondwana to the SE. Between these two continents the occurrence of small, intermediate continental plates, as Avalonia and the so called Armorica-Terrane-Assemblage (Franke, 2000) or Hun Superterrane (von Raumer et al., 2003) contributed in generating a complex orogenic belt. In fact they are generally assumed to have been detached from Gondwana during the Ordovician and docked to Laurentia and Baltica before the Carboniferous collision between Gondwana and Laurussia; hence within the orogenic belt different oceanic sutures separate the different terranes.

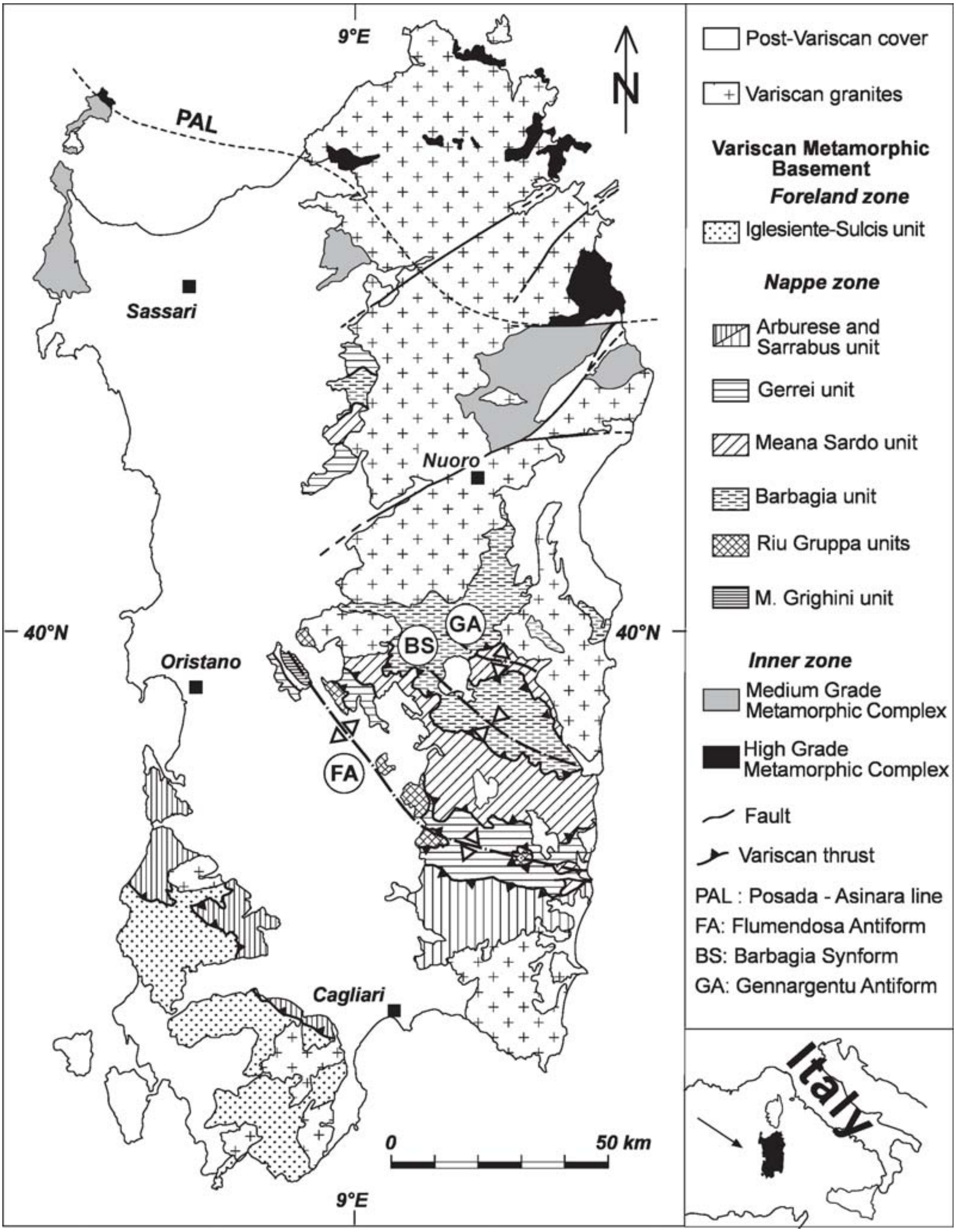


Fig. 1 - Geological sketch map of the Sardinian Variscides.

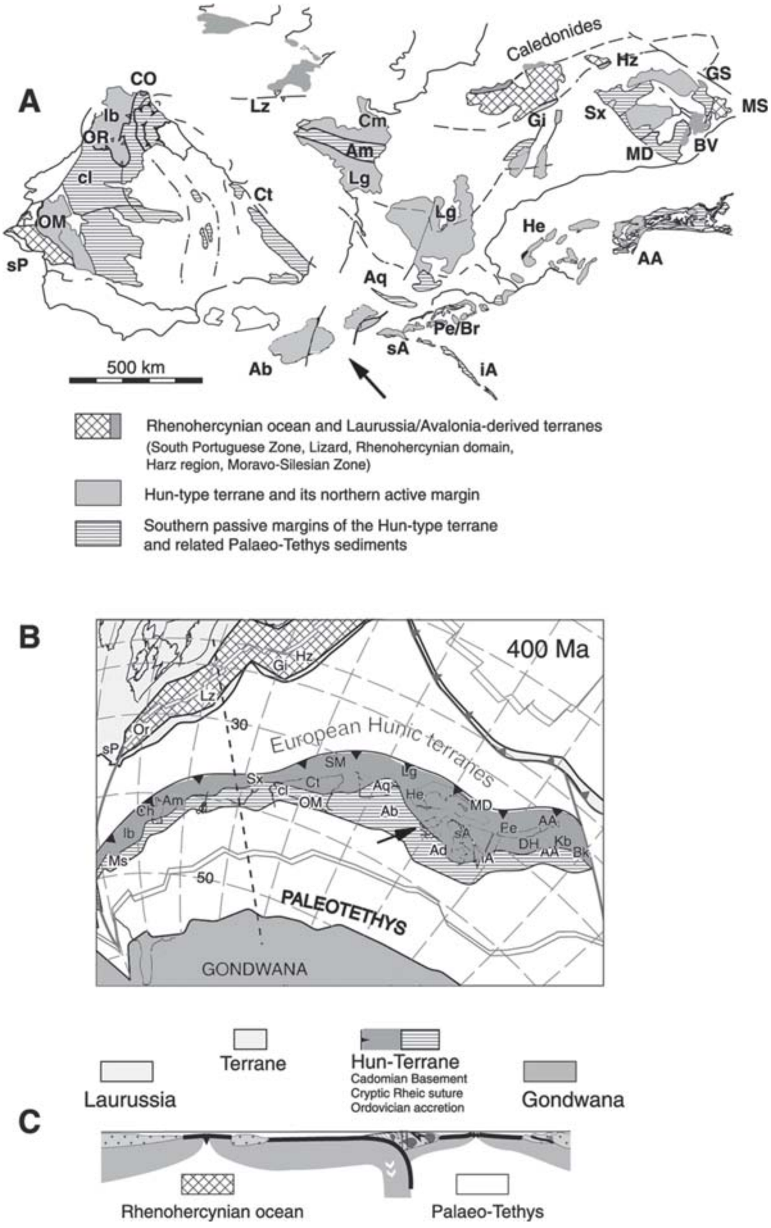


Fig. 2 - Schematic tectonic sketch map of the European Variscides. A) Reconstruction at Permian times (modified from Stampfli et al., 2001); B) Tectonic sketch reconstruction at Silurian times (modified from Stampfli & Borel 2002); C) Tentative schematic section at Silurian times. Abbreviations: AA, Austro-Alpine; Ab, Alboran plate; Ad, Adrias.str.; Am, Armorica; Aq, Aquitaine/French Pyrenees; Bk, Bolkardag; BV, Brunovistulian; Ch, Channel Islands; cI, central Iberia; Cm, Cadomia s.str.; CO, Cabo Ortegal; Ct, Cantabria–Asturia; Spanish Pyrenees; DH, Dinarides–Hellenides; GS, Gory Sowie; Gi, Giessen-nappe; He, Helvetic; Hz, Harz Mountains; iA, Intra-Alpine terrane; Ib, Iberia, NW-allochthon; Kb, Karaburun; Lg, Ligerian; Lz, Lizard; MD, Moldanubian; Ms, Meseta, Morocco; MS, Moravo-Silesian; OM, Ossa Morena; Or, Ordenes ophiolites; Pe, Penninic; Pe/Br Penninic/Brianconnais; sA, South Alpine; SM, Serbo-Mazedonian; sP, South Portugese; Sx, Saxothuringian. The black arrow indicates the position of Sardinia and Corsica.

As for the Sardinian segment of this chain, a simplified scheme can be described in terms of a collisional (D1) deformation, with Barrow type metamorphism increasing northwards during the Early Carboniferous, and in terms of an extensional deformation (D2), which affected the shortened orogenic wedge, leading to HT/LP metamorphism and emplacement of the Sardinia-Corsica Batholith during Late Carboniferous-Early Permian.

The main feature of the continental collision is a tectono-metamorphic zoning that, according to Carmignani et al. (1987), consists of (Fig., 3):

- a Foreland Zone in the SW (Iglesiente-Sulcis region), characterized by strong diagenesis to very-low-grade metamorphism;
- a tectonic Nappe Zone, within green schist facies metamorphic grade, in southeastern and central Sardinia overthrusted on the foreland;
- an Inner Zone, highly deformed with medium to high-grade metamorphism.

Three main tectonic phases with different tectonic transport direction (Carmignani et al., 1994) characterize the collisional deformation both in the Nappe Zone and in the Foreland Zone (Conti et al., 2001; Funedda, 2008):

i) the main syn-metamorphic phase is characterized by kilometric isoclinal folds and large thrusts with a "top-to-the-south" tectonic transport (D1 Phase of Carmignani & Pertusati, 1977; Gerrei and Meana Phase of Conti et al., 2001);
ii) non-cylindrical folds and wrench-thrusts characterize the second collisional phase. These regional structures commonly show a "top-to-the-west" tectonic transport (D2 Phase of Carosi & Oggiano, 2002; Sarrabus Phase of Conti et al., 2001). The structures owing to this phase are remarkably exposed close to the foreland, at Nurra in northwestern Sardinia, close to the PAL (Posada-Asinara line) and also in the Goceano region (Oggiano, 1994);
iii) finally, a third deformation phase gave rise to km-scale open upright folds with NNW-SSE oriented axis (Flumendosa Phase of Conti et al., 2001; D3 Phase of Oggiano & Di Pisa, 1988).

After collisional deformations and crustal thickening, negative tectonic inversion occurred involving extension at middle-upper crustal layers, plutonism, HT-LP metamorphism, exhumation of deep tectonic units and development of Late Carboniferous-Permian basins. Though the origin is controversial, most authors have considered this combination of processes to be related to the post-orogenic collapse (Dessau et al., 1982; Oggiano & Di Pisa, 1988; Conti et al., 1999; Oggiano & Casini, 2008).

AGE OF DEFORMATION

The age of deformation is related to the Variscan orogeny as supported by both stratigraphical and radiometric data:

a) in the Foreland and External Nappe zones the youngest formations affected by thrusting and folding and related regional metamorphism are Early Carboniferous in age (Maxia, 1983; Barca & Olivieri, 1991; Barca et al., 1992, 2003; Corradini et al., 2003;), whereas the oldest rocks not involved in both Variscan deformation and regional metamorphism are those infilling the Late Carboniferous - Early Permian basins (Cocozza, 1967; Del Rio, 1973; Fondi, 1979; Pittau et al., 2008).

b) In the Inner Nappe Zone (Nurra) Ar/Ar ages on syn-D1 amphibole yielded 340 Ma, and Rb/Sr blocking ages on white micas from D1-related fabrics in the medium-grade metamorphic complex (kyanite zone) yielded ages in the range of 350 Ma (Del Moro et al., 1991). Similar Ar/Ar ages were obtained on white micas from the same metamorphic complex (Ferrara et al., 1978; Di Vincenzo, 2004;).

c) The age of the late orogenic extensional deformation can be inferred by the blocking age of white micas in the areas affected by HT/LP (Asinara and Anglona) metamorphic evolution, where low angle normal shear and low angle normal fault led to core complexes-type structures. The mica age of this tectono-metamorphic event ranges between 320 and 300 Ma, showing a good fitting with the Ar/Ar age on amphibole from the same areas (Di Pisa & Oggiano, unpubl.). These data overlap that of the calk-alkaline plutonic association of the Sardinia-Corsica Batholith which emplaced between 311 and 274 Ma, mostly related to the post-collisional extensional events (Del Moro, et al. 1972, 1975; Cocherie, 1978; Ghezzo & Orsini, 1982; Oggiano, et al. 2005). The HT/LP metamorphic event also fits the U/Pb age of 321±0.8 Ma yielded by an anatectic, peraluminous, synkinematic granite, which emplaced within dextral shear zone (Oggiano et al., 2007).

TECTONO-STRATIGRAPHIC SETTING

FORELAND ZONE

A well constrained sedimentary succession crops out in the Foreland Zone, ranging from the Lower Cambrian to the Lower Carboniferous (Carmignani et al., 2001b, and references therein), affected by an anchizonal regional metamorphism (Fig. 4). This

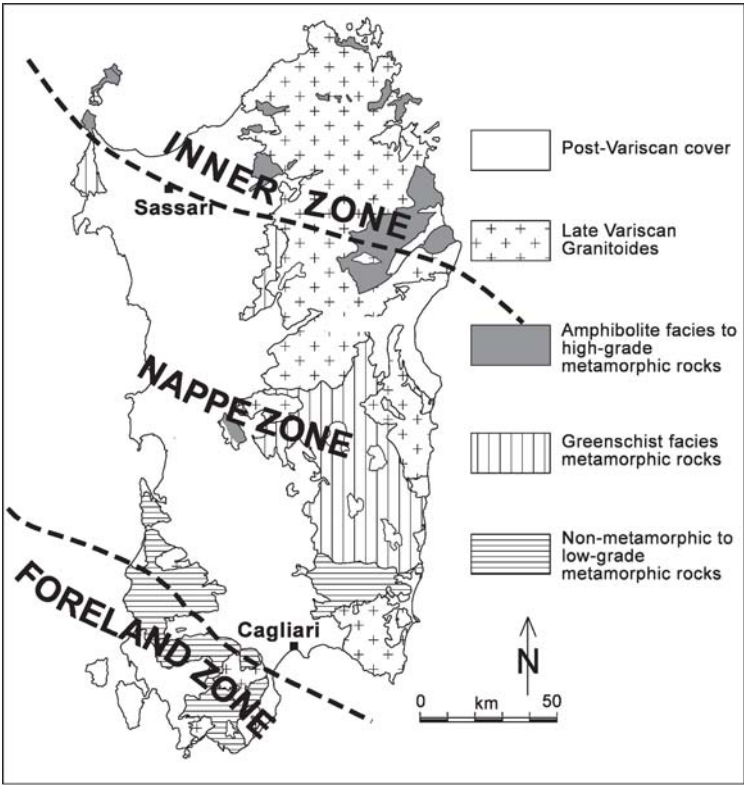


Fig. 3 - Tectonic and metamorphic partition of the Sardinian Variscides.

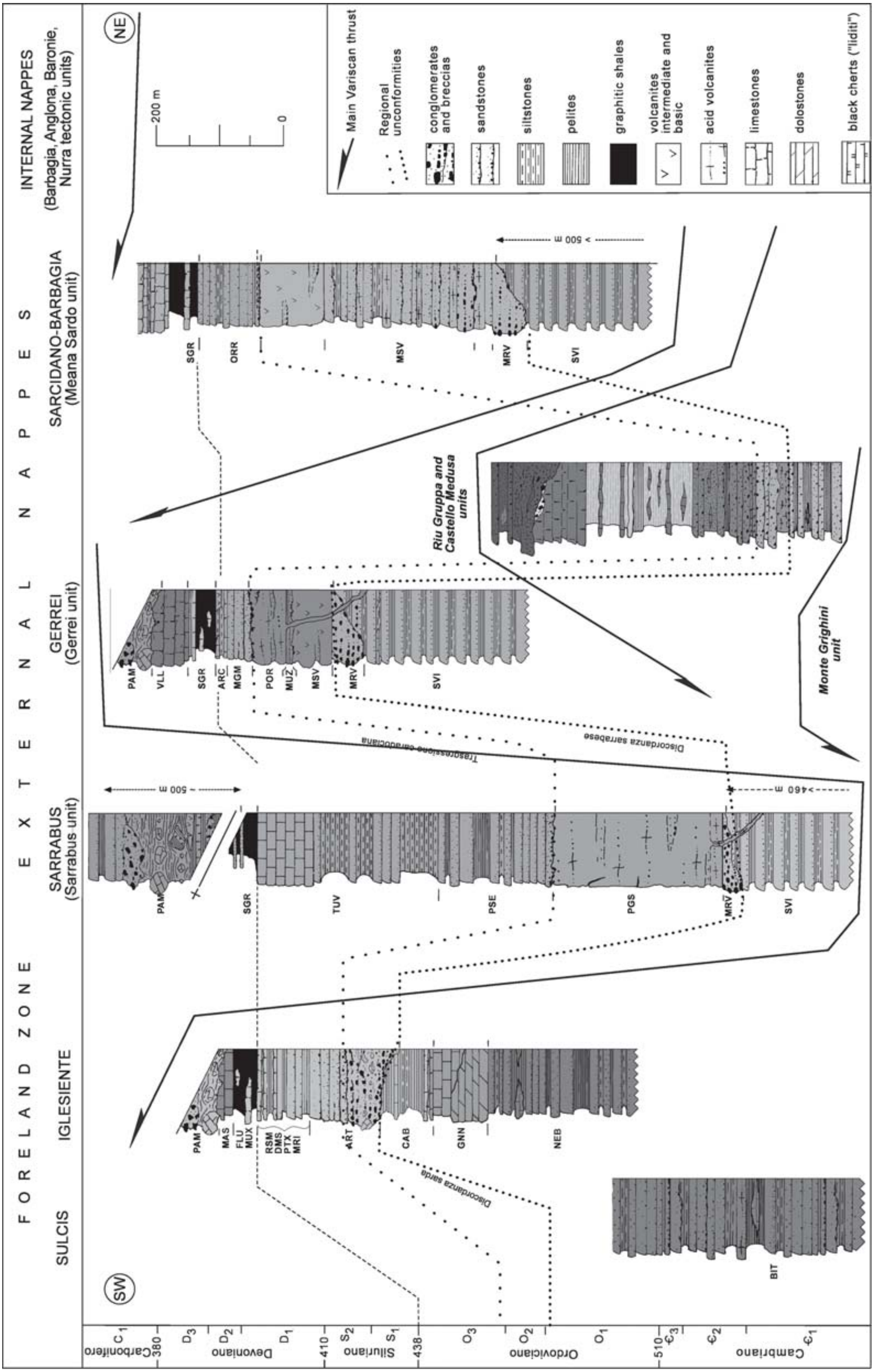
succession comprises two sequences separated by an important angular unconformity (Sardic Unconformity).

The first sequence starts with the Lower Cambrian Nebida Group (Cocozza, 1979; Pillola, 1991, 1995), made up by sandstones and pelites with carbonatic archeocyata-bearing mounds (Matoppa Fm.), oolitic limestones followed by sandstones and quarzites in alternation with limestones and dolostone (Punta Manna Fm.). In the Iglesiente region the apparent thickness reaches about 250 m. The Gonnesa Group (Lower Cambrian) follows the Punta Manna Fm. It consists of well stratified dolostone at the base (Santa Barbara Fm., previously knows as Dolomia rigata Mb.) and by grey massive, sometime dolomitic, limestone, (San Giovanni Fm., previously knows as Calcare Ceroide Mb.), with rare fossil content. Its total thickness is about 200 m (Rasetti, 1972; Cocozza, 1979; Bechstadt et al., 1994). The sequence is terminated by the Iglesias Group, the base of which is the nodular limestone of the Campo Pisano Fm. (previously known as Calcare nodulare), about 50 m thick, bearing trilobites, brachiopoda, echinodermata of Middle Cambrian. This formation grades into shale and siltsones of the Cabitza Fm., about 150 m thick, ranging in age from Middle Cambrian to Early Ordovician (Pillola et al., 2008). This sedimentary succession is truncated by the Sardic Unconformity: an angular unconformity which was related to an eo-Caledonian tectonic phase (Stille, 1935, 1939; Cocozza & Valera, 1966). Above the unconformity metaconglomerates, megabreccias ("Puddinga Ordoviciana" Auct.) and phyllites of the Monte Argentu Fm. rest (Laske et al., 1994, and references therein); their thickness ranges from few decameters to 200 m. Upwards the siliciclastic sediments of Late Ordovician age (Leone et al., 1991; Loi et al., 1992) crop out (from the base to the top: Monte Orri, Portixeddu, Domusnovas and Rio San Marco formations) followed by black shales and limestones of Silurian-Early Devonian age (Gnoli et al., 1990) (Genna Muxerru, Fluminimaggiore and Mason Porcus formations).

Unlike the Nappe Zone, in the Foreland Zone no volcanic succession has been recognized during the Middle Ordovician emergence phase. Volcanics occur, but as reworked pebbles in the basal member of the Rio San Marco Fm. On the top of Middle Devonian a syn-orogenic Lower Carboniferous rests (Barca et al., 1998), interpreted as Culm-like flysch.

The succession of the Foreland Zone of southwestern Sardinia exhibits no significant Variscan metamorphic imprint: both the pre-Sardic and post-Sardic sequences are non-metamorphic or anchimetamorphic at Iglesiente (Franceschelli et al., 1992). Whether metamorphism and significant deformation were associated with the Sardic phase is still matter of debate; some authors reject the concept of a Sardic "folding" phase (Minucci, 1935; Graulich, 1953; Del Bono, 1965; Brouwer, 1987) and attribute the structuring of the External Zone exclusively to the Variscan tectonism (Lüneburg & Lebit, 1998; Lüneburg et al., 1999).

Fig. 4 - Litho-stratigraphical synthetic columns of the tectonic units in the external nappes and Foreland zone. Abbreviations: ARC: "Argilloscisti di Rio Canoni"; ART: M. Argentu Formation (Puddinga Auct.); BIT: Bithia Formation; CAB: Cabitza Formation; MRV: "Metaconglomerato di Muravera"; DOM: Domusnovas Formation; FLU: Fluminimaggiore Formation; GNN: Gonnesa Formation; MGM: "Metarcose di Genna Mesa"; MUX: Genna Muxerru Formation; MUZ: "metarenarie e quarziti di Su Muzzioni"; NEB: Nebida Formation; ORR: Orroeledu Formation; MAS: Mason Porcus Formation; MRI: Monte Orri Formation; PAM: Pala Manna Formation; MSV: Monte Santa Vittoria Formation; PGS: "Porfidi grigi del Sarrabus"; POR: "Porfiroidi"; PSE: Punta Serpeddì Formation; PTX: Portixeddu Formation; RSM: Rio san Marco Formation; SGR: "Scisti a Graptoliti" + "Ockerkalk"; SVI: "Arenarie di San Vito"; TUV: Tuviois Formation; VLL: "Calcari di Villasalto".


FORELAND ZONE
EXTERNAL NAPPES
INTERNAL NAPPES (Barbagia, Anglona, Baronie, Nurra tectonic units)
SW
NE
SULCIS
IGLESIENTE
SARRABUS (Sarrabus unit)
GERREI (Gerrei unit)
SARCIDANO-BARBAGIA (Meana Sardo unit)
Riu Gruppa and Castello Medusa units
Monte Grighini unit
200 m
0
~500 m
> 500 m
>460 m
Discordanza sarda
Discordanza sarrabese
Trasgressione caradociana
BIT
PAM
MAS
FLU
MUX
RSM
DMS
PTX
MRI
ART
CAB
GNN
NEB
SGR
TUV
PSE
PGS
MRV
SVI
VLL
ARC
MGM
POR
MUZ
MSV
ORR
Main Variscan thrust
Regional unconformities
conglomerates and breccias
sandstones
siltstones
pelites
graphitic shales
volcanites intermediate and basic
acid volcanites
limestones
dolostones
black cherts ("liditi")
C1
380
D3
D2
D1
410
S2
S1
438
O3
O2
O1
510
€3
€2
€1
Carbonifero
Devoniano
Siluriano
Ordoviciano
Cambriano

The similarity of the Palaeozoic of the External Zone of Sardinia (Iglesiente) with the Montagne Noire succession (Arthaud, 1970) makes it possible to attribute these formations to the Gondwana margin, that acted as foreland during Early Carboniferous collision.

NAPPE ZONE

The Nappe Zone is divided in two parts: the external nappes, close to the foreland, characterized by a well defined litho-stratigraphic succession, and the inner nappes, closer to the Inner Zone, where clastic monotonous metasediments prevail, with interlayered rare metabasites.

Although the External Nappe Zone extent ranges from the northwestern side (Nurra) through the central part (Goceano) to the southeastern side of the island (Sarrabus-Gerrei), only the latter is generally described, due to its better exposition and low metamorphic grade that allows biostratigraphical investigations.

The best exposed section of the nappe stack outcrops in the southeastern part of the island, where the deepest tectonic unit is the Castello Medusa-Riu Gruppa unit is overridden by the Gerrei unit.

Northward the Meana Sardo unit in turn overrides the Gerrei unit. The Barbagia unit, of still poorly constrained age, occupies the top of the stack. Southward the Sarrabus unit lies above both the Gerrei and Meana Sardo units, hence it is also the shallowest tectonic unit in the Nappe Zone. Other units of the nappe stack crop in central-northern Sardinia, where the Ozieri unit is overridden by the Fiorentini unit (Oggiano, 1994), and in the Nurra region of nortwestern Sardinia (Li Trumbetti and Canaglia units; Oggiano & Mameli, 2006) (Fig. 4).

The lithostratigraphical succession that characterizes the different tectonic units is similar among the external nappes, but differences arise in that of the inner nappes.
The succession of the external nappe shows the following stratigraphical features:

1) A siliciclastic succession at the base (Arenarie di San Vito Fm., also reported as Arenarie di Solanas Fm.) (Calvino, 1959) dated from Middle Cambrian to Early Ordovician (Naud & Pittau Demelia, 1987; Di Milia & Tongiorgi, 1993). The top of the San Vito sandstone is unknown due to an erosive truncation (Sarrabese Unconformity; Calvino, 1959) that corresponds to the Sardic Unconformity.

2) On the unconformity surface a thin non-marine metaconglomerate (Metaconglomerati di Muravera; Carmignani et al., 2001a) and huge amounts of volcanic rocks rest: Monte Santa Vittoria Fm. (Carmignani et al., 2001a), Porfiroidi Fm., Porfidi grigi del Sarrabus Fm. (Calvino, 1956). They form a calc-alkaline suite, made up of andesitic to dacitic and rhyolitic rocks, about Middle Ordovician in age (Buzzi et al., 2007). The varied Ordovician volcanogenic formations are the most complete and best preserved within the South European Variscides. Their origin is related to an Ordovician arc that developed on the north-Gondwana margin as a consequence of the subduction of oceanic crust under continental crust (Andean type convergence) (Di Pisa et al., 1992, Stampfli & Borel, 2002). The age of the volcanic activity is well constrained by both stratigraphy and palaeontology; it post-dates the Sarrabese (i.e. Sardic) Unconformity and pre-dates the Katian transgression.

3) Shoreface to shelf sandstone and mudstone (Loi et al., 1992), deposited during the Katian and Hirnantian throughout the palaeogeographic domain of the Nappe Zone, as testified by the terrigeneous formations of the Upper Ordovician (Orroeledu Fm., Rio Canoni Shales, Punta Serpeddì Fm. and Tuviois Fm.) (Bosellini & Ogniben, 1968; Naud, 1979; Barca & Maxia, 1982; Loi, 1993; Loi & Dabard, 1997). These sediments contain interbedded metabasites and basic to intermediate meta-epiclastites. Locally, a submarine emplacement is indicated by pillow basalt embedded within fossiliferous Late Ordovician

metagreywacke in the external nappes (Lehmann, 1975; Di Pisa et al., 1992). Then, in the different units of the Nappe Zone, lies a Silurian succession typically represented by black graphitic shales and metasiltstones (Scisti a graptoliti; see Corradini & Ferretti, 2009, this volume), which have been well studied since the second half of XIX century because of their rich graptolite faunas (see Barca and Storch & Piras, 2009, this volume). The Silurian shale is everywhere overlain by a continuous Tentaculites-bearing marlstones (Scisti a Tentaculiti, Auct., see Corradini & Ferretti, 2009, this volume) and *Clymenia*-bearing shelf limestone that encompass the entire Devonian and base of the Carboniferous (Calcari di Villasalto, Carmignani et al., 2001a; Calcari a Clymenia, Olivieri, 1969; Corradini et al., 2003).

4) On the top of the Lower Carboniferous limestones, and sometimes directly on the Silurian black shales, a clastic succession rests, with an erosive unconformity (Pala Manna Fm., Barca et al., 2003). It consists mostly of sandstones and conglomerates, with olistoliths coming from the lowest formations, mainly marbles, completely involved in the Variscan structures, interpreted by the authors as a Culm-like deposits (Maxia, 1983; Barca, 1991; Barca & Olivieri, 1991).

INNER ZONE

This part of the chain is characterized by medium to high grade metamorphic rocks consisting in:

a) a polymetamorphic high-grade complex made up of anatexites and metatexites hosting orthogneiss and minor metabasite with relic granulite associations, which generally re-equilibrated under LP/HT conditions. This latter complex crops in the northernmost part of the island and extends to Corsica (Ghezzo et al., 1979; Di Pisa et al., 1993). The early granulite event is preserved within layered mafic–ultramafic bodies, including metagabbroes, cropping out at Golfo Aranci (Ghezzo et al., 1979; Giacomini et al., 2006). An eclogite body with a granulitic overprint is exposed at Punta de li Tulchi (Miller et al., 1976; Franceschelli et al., 1998, 2005; Cortesogno et al., 2004) within a complex of orthogneiss and metapelite affected by widespread anatectic mobilization under amphibolite-facies conditions in the stability field of sillimanite and, locally, cordierite. U/Pb zircon ages of this eclogite, give 450 Ma for the protolith, whilst ages close to 400 Ma are interpreted as dating the crystallization of a second zircon population during eclogite metamorphism (Cortesogno et al., 2004). Leptynite-amphibolite complexes are also found on Asinara Island (Castorina et al., 1996) and near Olbia, the former exhibiting an alkaline and the latter (Franceschelli et al., 2005) a continental tholeiitic affinity.

b) a medium grade, chiefly metapelitic complex, consisting of micaschists and paragneisses bearing Ky+/- Stau +/- garnet and including quartzites and N-MORB metabasalts boudins retaining eclogitic assemblage (Cappelli et al., 1992).

The contact between these two complexes is well exposed along the Posada Valley (Elter, 1987) as well as in southern Gallura and Asinara island (Del Moro et al., 1991; Oggiano & Di Pisa, 1992; Carmignani & Oggiano, 1997), consisting of a mylonitic shear zone with evident dextral strike–slip component.

Within the collisional frame the high grade migmatitic complex has been considered made up of chiefly crustal slices comparable to the inner crystalline nappes of the French Massif Central and the high strained complex B has been regarded as the Sardinia segment of the South Variscan Suture Zone (Carmignani et al., 1994) which re-equilibrated under intermediate P amphibolitic conditions.

After the construction of the orogenic buildup a late post collisional tectonics linked to the gravitational an thermal collapse of the chain took place in concomitance with the emplacement of the Sardina Batholith.

The high grade complex is juxtaposed with the medium grade metamorphic complex by mean of thrust or wrench-thrust shear zone (Posada-Asinara Line) in proximity of which more or less retrogressed eclogite boudins scatter. For this reason the PAL was compared to the South Variscan Suture Zone by Cappelli et al. (1992).

Acknowledgements

Funding for this work was provided by MIUR-PRIN 2007 (*Analysis of stratigraphic, palaentological and structural features of the Hercynian basement and the Tertiary cover in Sardinia and Calabria, as a contribution to the geodynamic reconstruction of the central-western Mediterranean basin*).

References

Alvarez W. (1972). Rotation of the Corsica-Sardinia microplate. *Nature Physics Science*, 235: 103-105.

Arthaud F. (1970). Etude tectonique et microtectonique comparée de deux domaines Hercyniens: Les nappes de la Montagne Noire (France) et l'anticlinorium de l'Iglesiente (Sardaigne). *Publications de l'Université des Sciences et Techniques du Languedoc - Série Géologie Structurale*: 1: 1-175.

Arthaud F. & Matte P. (1966). Contribution à l'étude de tectoniques superposées dans la chaine hercynienne: étude microtectonique des séries metamorphiques du Massif des Maures (Var.). *Comptes Rendus de l'Académie des Sciences de Paris*, 262: 436-439.

Arthaud F. & Matte P. (1977). Late Paleozoic strike-slip faulting in southern Europe and northern Africa: Result of a right-lateral shear zone between the Appalachians and the Urals. *Geological Society of America Bulletin*, 88: 1305-1320.

Barca S. (1991). Phénomènes de resédimentation et flysch hercynien à faciès Culm dans le "synclinal du Sarabus" (SE de la Sardaigne, Italie). *Comptes Rendus de l'Académie des Sciences de Paris*, 313 (2): 1051-1057.

Barca S. (2009). The Silurian of Sardinia: one and hal century of researches. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 11-22.

Barca S., Carmignani L., Eltrudis A., Gattiglio M. & Pala L. (1992). Relationship between foredeep deposits and Hercynian nappe building in southeastern Sardinia (Italy). *In* Carmignani L. & Sassi F.P. (eds.), Contributions to the Geology of Italy with Special Regard to the Paleozoic Basements: *IGCP No. 276, Newsletter*, 5: 33-44.

Barca S., Farci G. & Forci A. (1998). I depositi sinorogenici ercinici del Sulcis (Sardegna sud-occidentale). *Bollettino della Società Geologica Italiana*, 97 (2): 407-419.

Barca S., Forci A. & Funedda A. (2003). Nuovi dati stratigrafico-strutturali sul flysch ercinico dell'Unità del Gerrei (Sardegna SE). *In* Pascucci V. (ed.): GeoSed 2003. Alghero 28-30 settembre 2003: 291-298.

Barca S. & Maxia M. (1982). Assetto stratigrafico e tettonico del Paleozoico del Sarrabus occidentale. *In* Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C. & Ricci C.A. (eds.), Guida alla Geologia del Paleozoico sardo. Società Geologica Italiana. Guide Geologiche Regionali: 87-93.

Barca S. & Olivieri R. (1991). Age and source of calcareous blocks resedimented into Hercynian Flysch type sediments of the Sarrabus area (Southeastern Sardinia). *Atti della Società dei Naturalisti e Matematici di Modena*, 122: 46-66.

Bechstadt T., Boni M. & Frohler M. (1994). Facies development in early and middle Cambrian time. *In* Bechstadt T. & Boni M. (eds.), Sedimentological, stratigraphical and ore deposits field guide of the autochtonous cambro-ordovician of southwestern Sardinia: *Memorie descrittive della Carta Geologica d'Italia, Servizio Geologico Nazionale*, 48: 47-106.

Bosellini A. & Ogniben G. (1968). Ricoprimenti ercinici nella Sardegna centrale. *Annali dell'Università di Ferrara*, 1: 1-15.

Brouwer H. (1987). The Sardic tectonic phase in SW Sardinia: a concept rejected. *In* Sassi F.P. & Bourrouilh R. *IGCP Project No. 5*, 7: 134-138.

Buzzi L., Gaggero L., Funedda A., Oggiano G. & Tiepolo M. (2007). Zircon geochronology and Sm-Nd isotopic study of the Ordovician magmatic event in the southern Variscides (Sardinia). *Geologie de la France*, 2 (Meeting on Mechanics of Variscan Orogeny: a modern view on orogenic research): 73.

Calvino F. (1956). I porfidi grigi del Sarrabus. *Bollettino del Servizio Geologico d'Italia*, 78 (1/2): 265-275.

Calvino F. (1959). Lineamenti strutturali del Sarrabus-Gerrei (Sardegna sud-orientale). *Bollettino del Servizio Geologico d'Italia*, 81 (4-5): 489-556.

Cappelli B., Carmignani L., Castorina F., Di Pisa A., Oggiano G. & Petrini R. (1992). A Hercynian suture zone in Sardinia: geological and geochemical evidence. *Geodinamica Acta*, 5 (1-2): 101-118.

Carmignani L., Carosi R., Di Pisa A., Gattiglio M., Musumeci G., Oggiano G. & Pertusati P.C. (1994). The Hercynian chain in Sardinia (Italy). *Geodinamica Acta*, 7: 31-47.

Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C. & Ricci C.A. (1987). Structural Model of the Hercynian Basement of Sardinia. 1:500.000. CNR, Progetto Finalizzato Geodinamica. Stabilimento L. Salomone, Roma.

Carmignani L., Conti P., Barca S., Cerbai N., Eltrudis A., Funedda A., Oggiano G., Patta E.D., Ulzega A., Orrù P. & Pintus C. (2001a). Note illustrative del Foglio 549 - Muravera. *Memorie descrittive della Carta geologica d'Italia 1:50.000*: 140 pp.

Carmignani L. & Oggiano G. (1997). Terranes in the Variscan segment of Sardinia: a tentative approach. *Annales geologiques des pays helleniques*, 37: 199-209.

Carmignani L., Oggiano G., Barca S., Conti P., Salvadori I., Eltrudis A., Funedda A. & Pasci S. (2001b). Geologia della Sardegna. Note illustrative della Carta Geologica in scala 1:200.000. *Memorie Descrittive della Carta Geologica d'Italia*, 40: 283 pp. Servizio Geologico d'Italia, Roma.

Carmignani L. & Pertusati P.C. (1977). Analisi strutturale di un segmento della catena ercinica: il Gerrei (Sardegna sud-orientale). *Bollettino della Società Geologica Italiana*, 96: 339-364.

Carosi R. & Oggiano G. (2002). Transpressional deformation in NW Sardinia (Italy): insights on the tectonic evolution of the Variscan belt. *Comptes Rendus de l'Académie des Sciences de Paris*, 334: 287-294.

Castorina F., Cesaraccio G., Di Pisa A. & Oggiano G. (1996). The amphibolitic stratified complex of Punta Scorno (Asinara Island, Sardinia, Italy): petrogenesis and tectonic interpretation. *Plinius, supplement to the European Journal of Mineralogy*, 16: 74-76.

Cocherie A. (1978). Géochimique des terres rares dans les granodiorites. Thèse 3.me cycle, Univ. Rennes: 207 pp, unpublished.

Cocozza T. (1967). Il Permo-Carbonifero del Bacino di San Giorgio (Iglesiente, Sardegna Sud Occidentale). *Memorie della Società Geologica Italiana*, 6: 607-642.

Cocozza T. (1979). The Cambrian of Sardinia. *Memorie della Società Geologica Italiana*, 20: 163-187.

Cocozza T. & Valera R. (1966). Nuove osservazioni sulla "discordanza cambro-ordoviciana" nella zona di Nebida (Sardegna sud-occidentale). *Resoconti dell'Associazione Mineraria Sarda*, 71: 58-71.

Conti P., Carmignani L., Cerbai N., Eltrudis A., Funedda A. & Oggiano G. (1999). From thickening to extension in the Variscan belt - kinematic evidence from Sardinia (Italy). *Terra Nova*, 11 (2/3): 93-99.

Conti P., Carmignani L. & Funedda A. (2001). Changing of nappe transport direction during the Variscan collisional evolution of central-southern Sardinia (Italy). *Tectonophysics*, 332 (1-2): 255-273.

Corradini C., Barca S. & Spalletta C. (2003). Late Devonian-Early Carboniferous conodonts from the "Clymeniae Limestones" of SE Sardinia (Italy). *Courier Forschungs-Institut Senckenberg*, 245: 227-253.

Corradini C. & Ferretti A. (2009). The Silurian of the External Nappes (southeastern Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (1): 43-49.

Cortesogno L., Gaggero L., Oggiano G. & Paquette J.L. (2004). Different tectono-thermal evolutionary paths in eclogitic rocks from the axial zone of the Variscan Chain in Sardinia (Italy) compared with the Ligurian Alps. *Ofioliti*, 29: 125-144.

Del Bono G.L. (1965). Relazione generale su una nuova possibile interpretazione della serie cambrico-ordoviciana dell'Iglesiente. *Resoconti dell'Associazione Mineraria Sarda*, 70 (8): 5-80.

Del Moro A., Di Pisa A., Oggiano G. & Villa I.M. (1991). Isotopic ages of two contrasting tectonomorphic episodes in the Variscan chain in N Sardinia. *In* Lazzarotto A., Morten L., Ricci C.A., Sassi F.P. & Vai G.B. (eds.), Geologia del basamento italiano. Siena: 33-35.

Del Moro A., Di Simplicio C. & Rita F. (1972). Lineamenti geopetrologici del cristallino sardo. Età radiometrica delle plutoniti del settore Ogliastra-Gallura. *Mineralogica et Petrographica Acta*, 18: 245-254.

Del Moro A., Di Simplicio P., Ghezzo C., Guasparri G., Rita F. & Sabatini G. (1975). Radiometric data and intrusive sequence in the Sardinian Batholith. *Neues Jahrbuch für Mineralogie Abhandlungen*, 126 (1): 28-44.

Del Rio M. (1973). Palinologia di un livello «Permo-Carbonifero» del bacino di San Giorgio (Iglesiente, Sardegna sud-occidentale). *Bollettino della Società Geologica Italiana*, 92: 485-494.

Dessau G., Duchi G., Moretti A. & Oggiano G. (1982). Geologia della zona del Valico di Correboi (Sardegna centro-orientale). Rilevamento, tettonica e giacimenti minerari. *Bollettino della Società Geologica Italiana*, 101: 497-522.

Di Milia A. & Tongiorgi M. (1993). Tremadocian acritarch assemblages from the Solanas Sandstone Formation (nappe zone of central Sardinia). *Memorie della Società Geologica Italiana*, 49: 193-204.

Di Pisa A., Gattiglio M. & Oggiano G. (1992). Pre-Hercynian magmatic activity in the nappe zone (internal and external) of Sardinia: evidence of two within plate basaltic cycles. *In* Carmignani L. & Sassi F.P. (eds.), Contributions to the Geology of Italy with Special Regard to the Paleozoic Basements, *IGCP No. 276, Newsletter*: 107-116.

Di Pisa A., Oggiano G. & Talarico F. (1993). Post collisional tectono-metamorphic evolution in the axial zone of the Hercynian Belt in Sardinia: An example from the Asinara Island. *International Meeting, 4-6 March, Montpellier, "Late orogenic extension in mountain belts"*, Doc. BRGM Fr (219): 216-217.

Di Vincenzo G. (2004). 40Ar /39Ar dating of samples from Paleozoic gold prospects in southern Sardinia. Unpublished Final report to SGM company.

Edel J.B., Montigny R. & Thuizat R. (1981). Late Paleozoic rotations of Corsica and Sardinia: new evidence from Paleomagnetic and K-Ar studies. *Tectonophysics*, 79: 201-233.

Elter F.M. (1987). La fascia blastomilonitica della valle del Posada (Sardegna Nordorientale). Tesi di Dottorato: 122 pp,.

Ferrara G., Ricci C.A. & Rita F. (1978). Isotopic ages and tectono-metamorphic history of the metamorphic basement of north-eastern Sardinia. *Contributions to Mineralogy and Petrology*, 68: 99-106.

Fondi R. (1979). Orme di Microsauri nel Carbonifero superiore della Sardegna. *Memorie della Società Geologica Italiana*, 20: 347-356.

Franceschelli M., Eltrudis A., Memmi I., Palmieri R. & C.G.M.P. (1998). Multi-stage metamorphic re-equilibration in eclogitic rocks of Hercynian basement of NE Sardinia (Italy). *Mineralogy and Petrology*, 2: 167-193.

Franceschelli M., Gattiglio M., Pannuti F. & Fadda S. (1992). Illite crystallinity in pelitic rocks from external nappe zone of the Hercynian chain of Sardinia (Italy). *In* Carmignani L. & Sassi F.P. (eds.), Contributions to the Geology of Italy with special reard to the Paleozoic Basements: *IGCP Project No. 276, Newsletter*: 127-135.

Franceschelli M., Puxeddu M., Cruciani G. & Carcangiu G. (2005). Layered amphibolite sequence in NE Sardinia, Italy: remnant of a pre-Variscan mafic silicic layered intrusion? *Contributions to Mineralogy and Petrology*, 149: 164-180.

Franke W. (2000). The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. *Geological Society, London, Special Publications*, 179: 35-61.

Funedda A. (2008). Foreland- and hinterland-verging structures in fold-and-thrust belt: an example from the Variscan foreland of Sardinia. *International Journal of Earth Science*, 10.1007/s00531-008-0327-y.

Gattacceca J., Deino A., Rizzo R., Jones D.S., Henry B., Beaudoin B. & Vadeboin F. (2007). Miocene rotation of Sardinia: New paleomagnetic and geochronological constraints and geodynamic implications. *Earth and Planetary Science Letters*, 258 (3-4): 359-377.

Ghezzo C., Memmi I. & Ricci C.A. (1979). Un evento granulitico nella Sardegna nord-orientale. *Memorie della Società Geologica Italiana*, 20: 23-38.

Ghezzo C. & Orsini J.B. (1982). Lineamenti strutturali e composizionali del batolite ercinico Sardo-Corso in Sardegna. *In* Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C. & Ricci C.A. (eds.), Guida alla Geologia del Paleozoico sardo. Società Geologica Italiana. Guide Geologiche Regionali: 165-182.

Giacomini F., Bomparola R.M., Grezzo C. & Gulbransen H. (2006). The geodynamic evolution of the Southern European Variscides: constraints from the U/Pb geochronology and geochemistry of the lower Palaeozoic magmatic-sedimentary sequences of Sardinia (Italy). *Contributions to Mineralogy and Petrology*, 152: 19-42.

Gnoli M., Kriz J., Leone F., Olivieri F., Serpagli E. & Storch P. (1990). Lithostratigraphic units and biostratigraphy of the Silurian and Early Devonian of Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 23 (2): 221-238.

Graulich J.M. (1953). Osservazioni sulla scistosità nei terreni paleozoici dell'Iglesiente (Sardegna). Significato dell'Anagenite. *Bollettino della Società Geologica Italiana*, 72: 3-7.

Laske R., Bechstadt T. & Boni M. (1994). The post-Sardic Ordovician series. *In* Bechstadt T. & Boni M. (eds.), Sedimentological, stratigraphical and ore deposits field guide of the autochtonous cambro-ordovician of southwestern Sardinia. *Memorie descrittive della Carta Geologica d'Italia*, 48: 115-146.

Lehmann B. (1975). Stratabound polymetallic and F-Ba-deposits of the Sarrabus-Gerrei region, SE-Sardinia. IV Report: Initial Variscan magmatism in SE- Sardinia. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1975 (10): 460-470.

Leone F., Hamman W., Laske R., Serpagli E. & Villas E. (1991). Lithostratigraphic units and biostratigraphy of the post-sardic Ordovician sequence in south-west Sardinia. *Bollettino della Società Paleontologica Italiana*, 30 (2): 201-235.

Loi A. (1993). Studio sedimentologico-petrografico e considerazioni paleogeografiche dell'Ordoviciano superiore della Sardegna meridionale. unpublished Ph.D thesis, Dipartimento di Scienze della Terra, Università di Cagliari: 204 pp,.

Loi A., Barca S., Chauvel J.J., Dabard M.P. & Leone F. (1992). Analyse de la sédimentation post-phase sarde: le dépots initiaux à placers du SE de la Sardaigne. *Comptes Rendus de l'Académie des Sciences de Paris*, 315: 1357-1364.

Loi A. & Dabard M.P. (1997). Zircon typology and geochemistry in the palaeogeographic reconstruction of the Late Ordovician of Sardinia (Italy). *Sedimentary Geology*, 112: 263-279.

Lüneburg C. & Lebit H. (1998). The development of a single cleavage in an area of repeated folding. *Journal of Structural Geology*, 20 (11): 1531-1548.

Lüneburg C., Lampert S., Lebit H., Hirt A., Casey M. & Lowrie W. (1999). Magnetic anisotropy, rock fabrics and finite strain in deformed sediments of SW Sardinia (Italy). *Tectonophysics*, 307: 51-74.

Matte P. (1986). Tectonics and plate tectonics model for the Variscan belt of Europe. *Tectonophysics*, 126: 329-374.

Matte P. (2001). The Variscan collage and orogeny (480-290 Ma) and the tectonic definition of the Armorica microplate: a review. *Terra Nova*, 13 (2): 122-128.

Maxia M. (1983). Segnalazioni di potenti successioni carbonifere marine nella Sardegna meridionale. *Rendiconti della Società Geologica Italiana*, 6: 21-24.

Miller L., Sassi F.P. & Armari G. (1976). On the occurrence of altered eclogite rocks in north-eastern Sardinia and their implications. *Neues Jahrbuch für Mineralogie, Abhandlungen*, 11: 683-689.

Minucci E. (1935). Le condizioni del Paleozoico nel Sulcis orientale (Sardegna). *Bollettino della Società Geologica Italiana*, 54: 75-87.

Naud G. (1979). Les shales de Rio Canoni, formation-repère fossilifère dans l'Ordovicien supérieur de Sardaigne orientale. Conséquences stratigraphiques et structurales. *Bulletin de la Société Géologique de France*, 21 (2): 155-159.

Naud G. & Pittau Demelia P. (1987). Première decouverte d'acritarches du Cambrien moyen à superieur basal et du Tremadoc-Arenigien dans la basse vallee du Flumendosa: mise en evidence d'un nouveau temoin de la Phase Sarde en Sardaigne orientale. *I.G.C.P. No. 5 Newsletter*, 7: 85-86.

Oggiano G. (1994). Lineamenti stratigrafico-strutturali del basamento del Goceano (Sardegna centro-settentrionale). *Bollettino della Società Geologica Italiana*, 113: 105-115.

Oggiano G. & Casini L. (2008). Late orogenic collapse and thermal doming in the northern Gondwana margin incorporated in the Variscan Chain: A case study from the Ozieri Metamorphic Complex, northern Sardinia, Italy. *Gondwana research*, 13: 196-406.

Oggiano G., Casini L., Rossi P. & Mameli P. (2007). Long lived strike-slip tectonics in the Southern Variscan Belt: evidences from two synkinematic intrusions of North Sardinia (Italy). *Geologie de la France.*, 2 (Mechanics of Variscan Orogeny: a modern view in orogenic research): 141.

Oggiano G., Cherchi G.P., Aversano A. & A. D.P. (2005). Note illustrative F°428 Arzachena, settore terrestre. *Memorie Descrittive della Carta Geologica d'Italia*: 144 pp. IPSZ, Rome.

Oggiano G. & Di Pisa A. (1988). I graniti peralluminiferi sin-tettonici nell'area di Aggius-Trinità D'Agultu e loro rapporti con le metamorfiti di alto grado della Bassa Gallura (Sardegna Settentrionale). *Bollettino della Società Geologica Italiana*, 107: 471-480.

Oggiano G. & Di Pisa A. (1992). Geologia della catena ercinica in Sardegna-Zona assiale. *In* Carmignani L., Pertusati P.C., Barca S., Carosi R., Di Pisa A., Gattiglio M., Musumeci G. & Oggiano G. (eds.), Struttura della Catena Ercinica in Sardegna. Guida all'Escursione. Gruppo Informale di Geologia Strutturale: 147-167.

Oggiano G. & Mameli P. (2006). Diamictite and oolitic ironstones, a sedimentary association at Ordovician-Silurian transition in the north Gondwana margin: New evidence from the inner nappe of Sardinia Variscides (Italy). *Gondwana research*, 9: 500-511.

Olivieri R. (1969). Conodonti e zonatura del Devoniano superiore e riconoscimento di Carbonifero inferiore nei calcari di Corona Mizziu (Gerrei-Sardegna). *Bollettino della Società Paleontologica Italiana*, 8 (2): 63-152.

Pillola G.L. (1991). Trilobites du Cambrien inférieur du SW de la Sardaigne, Italie. *Palaeontographia Italica*, 78: 1-173.

Pillola G.L., Leone F. & Loi A. (1995). The Lower Cambrian Nebida Group of Sardinia. *In* Cherchi A. (ed.), 6th Paleobenthos International Symposium, Guide-Book. Cagliari, October 25-31, 1995: *Rendiconti del Seminario della Facoltà di Scienze dell'Università di Cagliari*, 65 suppl.: 27-62.

Pillola G.L., Piras S. & Serpagli E. (2008). Upper-Tremadoc-Lower Arenig? Anisograptid-Dichograptid fauna from the Cabitza Formation (Lower Ordovician, SW Sardinia, Italy). *Revue de Micropaleontologie.*, 51: 167-181.

Pittau P., Del Rio M. & Funedda A. (2008). Relationships between plant communities characterization and Basin formation in the Carboniferous-Permian of Sardinia. *Bollettino della Società Geologica Italiana*, 127 (3).

Rasetti F. (1972). Cambrian Trilobite faunas of Sardinia. *Memorie dell'Accademia Nazionale dei Lincei*, 11: 1-100.

Robardet M. (2003). The Armorica 'microplate': fact or fiction? Critical review of the concept and contradictory palaeobiogeographical data. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 195: 125-148.

Stampfli G.M. & Borel G. (2002). A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters*, 196: 17- 33.

Stampfli G.M., von Raumer J., Borel G. & Bussy F. (2001). The Variscan and pre-Variscan evolution. *In* Stampfli G.M. (ed.), Geology of the Western Swiss Alps. A Guide-book. *Mémoires de Géologie*, 36: 28-41.

Stille H. (1935). Der derzeitige tektoniske Erdzustand. - Sitz. *Preussisches Akademie des Wissenshaften Berlin - Phys-Math Klasse*: 179-219.

Stille H. (1939). Bemerkungen betreffend die "sardische Faltung" und den Ausdruck "ophiolitisch". *Zeitschrift der Deutschen Geologischen Gesellschaft*, 91: 771-773.

Storch P. & Piras S. (2009). Silurian graptolites of Sardinia: assemblages and biostratigraphy. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 77-93.

Vai G.B. & Cocozza T. (1986). Tentative schematic zonation of the Hercynian chain in Italy. *Bulletin de la Société Géologique de France*, 8: 95-114.

von Raumer J.F., Stampfli G.M. & Bussy F. (2003). Gondwana-derived microcontinents - the constituents of the Variscan and Alpine collisional orogens. *Tectonophysics*, 365 (1-4): 7-22.

Westphal M., Orsini J.B. & Vellutini P. (1976). Le micro-continent corso-sarde, sa position initiale: données paléomagnétiques et raccords géologiques. *Tectonophysics*, 30: 141-157.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 37-41

Silurian and its surroundings in the inner nappes of Sardinian Variscides: lithostratigraphical evidence from metamorphosed deposits

GIACOMO OGGIANO, PAOLA MAMELI

G. Oggiano - Dipartimento di Scienze Botaniche Ecologiche e Geologiche, Università di Sassari, Via Muroni 25, 07100 Sassari (Italy); giacoggi@uniss.it
P. Mameli - Dipartimento di Scienze Botaniche Ecologiche e Geologiche, Università di Sassari, Via Muroni 25, 07100 Sassari (Italy); mamelip@uniss.it

ABSTRACT - In the tectonic units of the Inner Nappe Zone of the Sardinian Variscides, due to metamorphism and deformation, the Silurian System and its lower and upper boundaries are badly defined. Apart the occurrence of black, graphite bearing phyllites and schists, no sedimentary and fossil record survived. Only in Nurra (northwestern Sardinia) a unique finding of *Orthoceras*-made black coquina allows attributing, even broadly, the thick, monotonous black phyllites outcrops to the Silurian System. Here, in addition, the metasediments lying at the Ordovician-Silurian transition exhibit high variability both in composition and texture: they include glaciomarine diamictite, oolitic ironstones, phosphorites, sub-aerial conglomerate and epiclastite. This succession is also characterized by the occurrence of alkaline metabasites. Different Variscan blocks, from Maures to eastern Alps, share similar litho-stratigraphic features possibly testifying glacial environment, emergence and rifting at northern Gondwana between Late Ordovician and early Silurian.

KEY WORDS - Ordovician/Silurian Boundary, Inner Nappe Zone, Silurian, Sardinia

The Silurian exhibits only weak variability among the different tectonic units of the Sardinian Variscides. Differences concern the abundance of calcareous beds as well as – although limited to the very base of this System – the occurrence of alkaline volcanics. The latter can be considered the prosecution of Late Ordovician volcanic activity as confirmed by a recent U/Pb datation (440 ± 1.7 My; Buzzi et al., 2007) on coarse alkaline epiclastic rocks in the external (Gerrei Unit) nappes.

As for the Silurian of the Inner Nappe Zone, some differences rise between the units of eastern Sardinia, from Gennargentu Mountain up to the Posada valley, and the units of northwestern Sardinia. In the former units the only evidence of Silurian deposit is restricted to the occurrence of black phyllites. Approaching to the Posada-Asinara Line, metalimestones tend to disappear and only rare, thin beds of marble occur within dark micaschists, which but supposedly can be referred to a protolith of Silurian age. Moreover, no alkaline metavolcanics are associated to the black metapelites and surrounding schists in this area. Over all, the increased metamorphic grade between green schist and amphibolite facies, along with strong deformation, prevent any stratigraphical distinction on the transition between Ordovician and Silurian systems. On the other hand this boundary, otherwise worthy of detailed investigation, is badly exposed even in the external nappes, as Upper Ordovician deposits and Silurian metargillites are generally juxtaposed along tectonic contacts.

Despite green-schist facies metamorphism and high strain, which affect most of the rocks, litho-stratigraphical correlations are still possible in some tectonic units of the Inner Nappe Zone. In fact, some metasediments retain primary meso- and micro-textures, which along with chemical bulk composition and mineralogy, represent distinctive features useful both as stratigraphical markers and palaeoenvironmental proxies. This is the case of the metasediments, which characterize the uppermost Ordovician and the lower Silurian in the Nurra region (northwestern Sardinia) (Fig. 1). Here black phyllites are exposed on the overturned limb of a SW verging anticline, which in turn is refolded in a wide E-W trending synform (Carmignani et al., 1979). Despite metamorphism erased any trace of

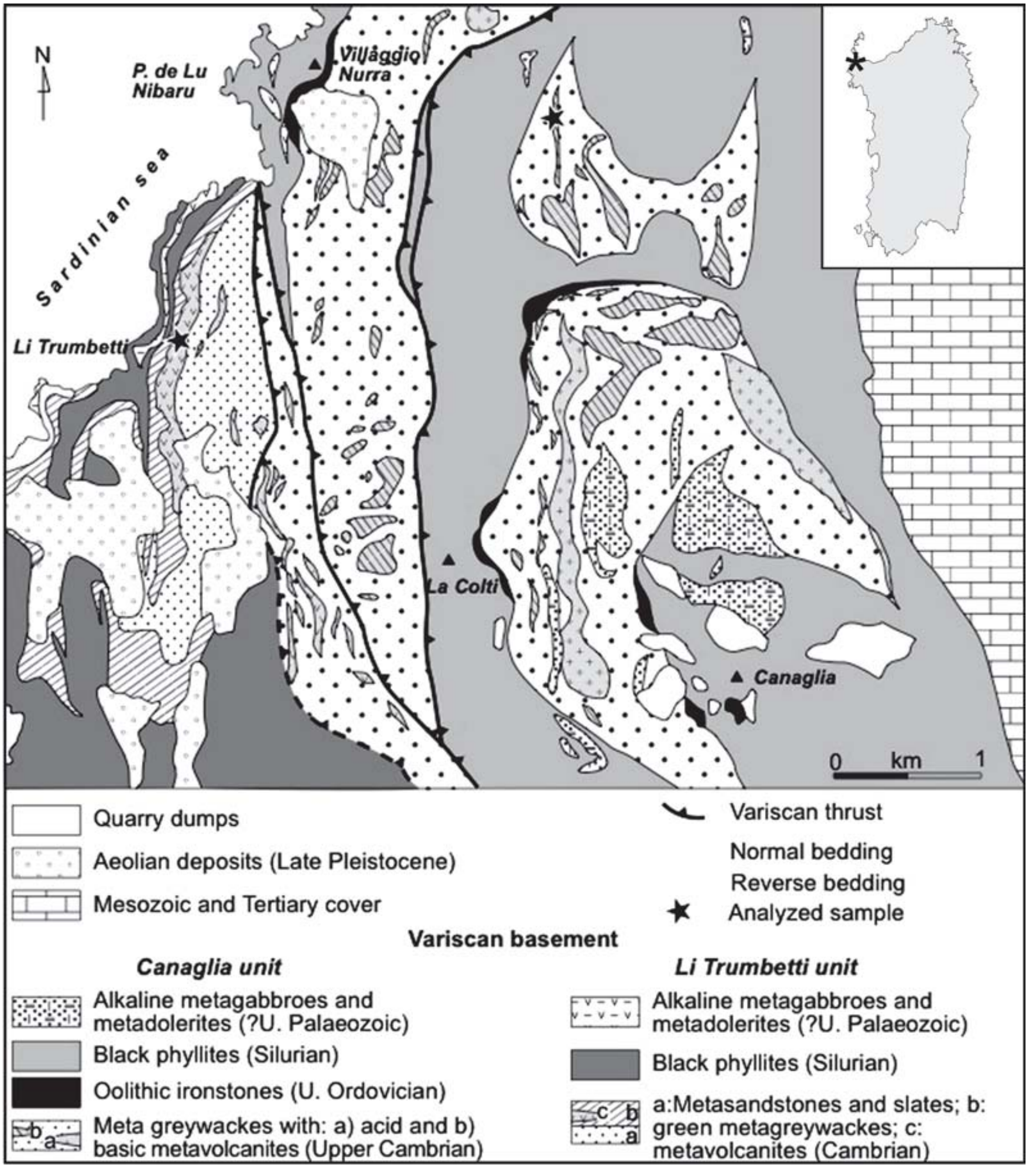


Fig. 1 - Geological sketch map of central Nurra.

graptolites, a broadly Silurian age of these metargillites is confirmed by the finding of rare *Orthoceras*-bearing black limestone (Venerandi, 1965) - which differs from the typical Ockerkalk limestone anyway - at La Colti mine.

In Nurra, black limestones associated with black metapelite are restricted to rare metric lenses. Devonian shelf limestones, widespread elsewhere in the external nappes, are missing in Nurra. On the other hand, the thickness of the black metargillites is higher than in the external nappes as it exceeds 200 meters.

Glaciomarine deposits, oolitic ironstone, phosphorus-rich and iron-rich (chamosite) mudstones characterize the Ordovician-Silurian boundary; moreover conglomerates reworking oolitic ironstones and sub aerial volcanoclastites give evidence for an emergence episode.

High facies variability between units and even, over short distance, within the same unit, is another clue that an emergence occurred at the end of the Ordovician, followed by transgression in the Silurian. How wide the gap linked to the continental period was is hard to establish lacking any biostratigraphical data. In the same way there is no evidence to establish whether the sea withdraw was driven only by glacioeustasy or if tectonics played also a role.

Similar associations, at different metamorphic grade, are decipherable from Maures Massif (Collobrieres, Le Murettes units), to the Carnic Alps (Rauchkofel) (Ferretti, 2005).

An overview of the Ordovician-Silurian boundary in Nurra can refer to three areas that probably correspond to different tectonic units (Fig. 2).

These units are all affected by green schist facies metamorphic overprint and by pervasive axial planar cleavage linked to the F1 olding phase of Carmignani et al. (1979). Locally, close to shears zone, a second pervasive cleavage could appear, but weak or no cleavage characterize the wide F3 upright, open folds with E-W trending axes and eastward axial immersion.

The structural arrangement issued from the Variscan collision, along with the eastward Cainozoic tilting of this basement block, brought Silurian and Upper Ordovician rocks to the surface in the central part of the coastal Nurra, just in the core of a regional F3 post-nappe synform.

Three tectonic units separated by tectonic contact have been distinguished (Oggiano & Mameli, 2006). Within each of these, beyond the Variscan deformation which generally makes the polarity reversed, it is possible to reconstruct with good approximation the stratigraphy at the Upper Ordovician-Silurian boundary (Fig. 2).

In the Canaglia Unit, at La Colti mine and in the excavations near Villaggio Nurra where oolitic ironstone was mined, the following succession can be reconstructed:

- Silurian black phyllite with pyrite crystals in the basal beds;
- 5-10 m thick black metargillite with thin, light-coloured, varve-like laminations;
- 1 m thick metamorphosed mudstone, chamositic in composition, in which thin clast-bearing layers alternate with a layer rich of clayey ooids;
- a discontinuous horizon of matrix-supported conglomerate with rounded, millimetric to metric, clasts mostly made of magnetite (hard ironstone). This rock is detectable only in an old adit, so that to assess its thickness is not easy, in any case it should not exceed a couple of meters;
- a few meters of a metamorphic diamictite consisting of chamosite matrix supporting chamosite ooids, nodules and clasts of phosporites;
- at least 50 meters of greenish metagraywacke hosting alkaline metabasite.

Metadolerite sills and metagabbroic bodies are scattered within this succession.

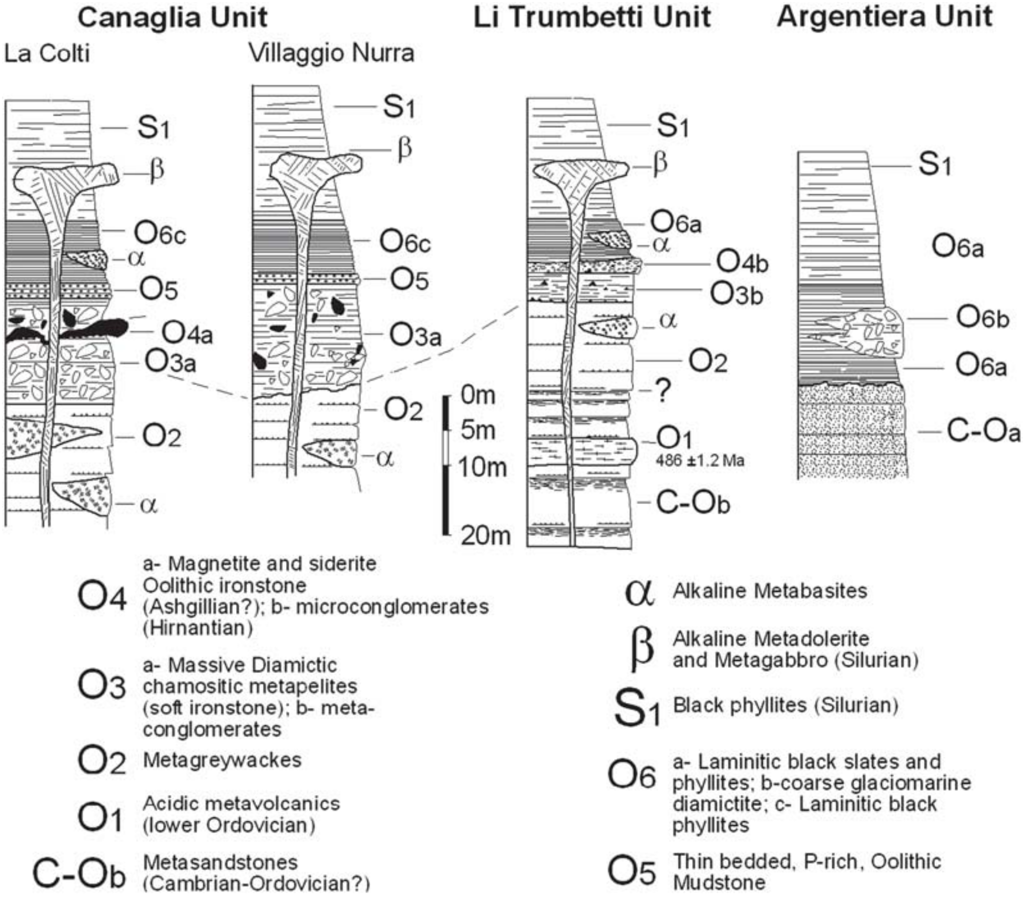


Fig. 2 - Litho-stratigraphical logs of the tectonic Units cropping out in Nurra (northwestern Sardinia), across the Ordovician-Silurian boundary

In the Li Trumbetti Unit a similar succession crops out but oolithic ironstones are absent and the older rocks are metasandstones and slates hosting metarhyolite bodies that yielded an age of 486 ± 1.2 My (U/Pb age on zircon; Buzzi et al., 2007), these metasediments are capped by:

- 30 meters of metagreywacke with metabasite bodies, coarse epiclastite and rare metalimestone or marble lenses;
- 1-2 meters of a fine, quartzitic, metamicroconglomerate with pyrite;
- a few meters of black metargillite with thin, light-coloured, varve-like laminations;
- At least 150 meters of black phyllites hosting rare level of black cherts (lydites). At places some metric lenses of black limestone were observed.

A different stratigraphical succession characterizes the Argentiera Unit (Fig 2). In fact here the metavolcanic products, the oolitic ironstone and the chamosite-bearing mudstone, which characterize the supposed Upper Ordovician in the previous units, are missing and the black metargillite with thin, light-coloured, varve-like laminations rests on pinkish quartzite with sericite and ankerite. Worthy of note is the discontinuous occurrence of angular, possibly rafted debris, embedded within the dark laminites. Despite deformation and metamorphism the characteristic of glaciomarine diamicton is still preserved. Oggiano & Mameli (2006) referred this metadiamictite to the Hirnantian glaciation.

In conclusion a number of noticeable features characterize the Silurian and, in particular, the Ordovician-Silurian transition in the inner nappe of Nurra:

i) The huge thickness of black phyllites in comparison with other sectors of the Sardinia and Corsica Variscides and the lack of meaningful amount of carbonate rocks, including the Devonian limestones;
ii) The occurrence of within-plate alkaline volcanism (Di Pisa et al., 1992);
iii) The occurrence of chamosite oolitic ironstone and phosphorus-rich sediments;
iv) The occurrence of an emergence just before the Silurian transgression;
v) Glaciomarine deposits and chlorite/chamosite-rich nearshore diamictic mudstones.

These stratigraphical features reflect a scenario characterized by the onset of rifting in the North Gondwana margin (alkaline metabasalt). The rifting stage embraced the time span during which Hirnantian glaciation occurred. This glacial event, along with a possible break up in the rift centre, enhanced the sea retreat from the shelf leading to an unconformity driven by break-up and eustatic minimum with stratigraphical gap embracing part of Hirnantian and part of Llandovery.

During the following early Silurian transgression this realm has got located in the outer shelf-upper slope settings on the Gondwanan passive margin pertaining to the broadened rift that allowed the drifting of the peri-Gondwanan terranes. This location could explain the lack of both Silurian and Devonian shelf limestones. Moreover the occurrence of glacial deposits in Armorica (Robardet & Doré, 1988; Picarra et al., 2002) in this time span, suggests that the “Armorican Terranes Assemblage” (Franke, 2000) or Hun Superterrane (von Raumer, 2003) - if ever detached from the Northern Gondwana margin - were still close to it in the early Silurian.

REFERENCES

BUZZI L., GAGGERO L., FUNEDDA A., OGGIANO G. & TIEPOLO M. (2007). Zircon geochronology and Sm-Nd isotopic study of the Ordovician magmatic event in the in the southern Variscides (Sardinia). *Geologie de la France*, 2 (Meeting on Mechanics of Variscan Orogeny:a modern view on orogenic research): 73.

CARMIGNANI L., FRANCESCHELLI M., PERTUSATI P.C., RICCI C.A. (1979). Evoluzione tettonico-metamorfica del basamento della Nurra (Sardegna NW). *Memorie della Società Geologica Italiana*, 20: 57-84.

DI PISA A., GATTIGLIO M., OGGIANO G. (1992). Pre-Hercynian magmatic activity in the Nappe Zone (internal and external) of Sardinia: evidence of two Within Plate basaltic cycles. *In* Carmignani L. & Sassi F.P. (Eds.), Contribution to the Geology of Italy with special regard to the Paleozoic basement. A volume dedicated to Tommaso Cocozza. *IGCP Project 276, Newsletter*, 5: 33-44.

FERRETTI A. (2005). Ooidal ironstones and laminated ferruginous deposits from the Silurian of the Carnic Alps, Austria. *Bollettino della Società Paleontologica Italiana*, 44 (3): 263-278.

FRANKE W. (2000). The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. *In* Franke W., Haak V., Oncken O. & Tanner D. (Eds.), Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geological Society of London, Special Publications, 179, London: 35-61.

OGGIANO G. & MAMELI P. (2006). Diamictite and oolitic ironstones, a sedimentary association at Ordovician-Silurian transition in the north Gondwana margin: New evidence from the inner nappe of Sardinia Variscides (Italy). *Gondwana Research*, 9 (4): 500-511.

PICARRA J.M., ROBARDET M., BOURAHROUH A., PARIS A., PEREIRA Z., LE MENN J., GOUVERNNEC R., OLIVEIRA T. & LARDEAUX H. (2002). Le Passage Ordovicien-Silurien et la partie inferieure du Silurien (Sud est du Massif Armoricaine, France). *Compte Rendu Geoscience*, 334: 1177-1183.

ROBARDET M. & DORE F. (1988). The late Ordovician diamictic formations from southwestern Europe: North-Gondwana glaciomarine deposits. *Palaeogeography Palaeoclimatology Palaeoecology*, 66: 19-31.

VENERANDI I. (1965). Nuove osservazioni sul giacimento ferrifero della Nurra. *Rendiconti della Società Mineralogica Italiana*, 21: 317-333.

VON RAUMER J.F., STAMPFLI G.M. & BUSSY F. (2003). Gondwana-derived microcontinents - the constituents of the Variscan and Alpine collisional orogens. *Tectonophysics*, 365: 7-22.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 43-49

The Silurian of the External Nappes (southeastern Sardinia)

CARLO CORRADINI, ANNALISA FERRETTI

C. Corradini - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); corradin@unica.it
A. Ferretti - Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia, largo S. Eufemia 19, I-41100 Modena (Italy);.ferretti@unimore.it

ABSTRACT - The most complete and best known Silurian succession of southeastern Sardinia is exposed in the Gerrei tectonic Unit. The Silurian sequence starts with Rhuddanian-lowermost Gorstian black graptolitic shales (Lower Graptolitic Shales), followed by a lower Gorstian-end Pridoli nodular calcareous unit (Ockerkalk). Graptolitic shales (Upper Graptolitic Shales) document the Lower Devonian. An integrated scheme of graptolite and conodont biozonation, compiled from Sardic data, is provided.

KEY WORDS - Silurian, southeastern Sardinia, biostratigraphy, Gerrei tectonic Unit, Lower Graptolitic Shales, Ockerkalk.

INTRODUCTION

Silurian rocks are quite widespread in southeastern Sardinia, where they crop out widely in the Gerrei tectonic Unit and more rarely in the other tectonic units of the area (Sarrabus and Meana Sardo tectonic units). In the first approximation, the sequence is constituted by black graptolitic shales in the lower part, followed by nodular limestones of late Silurian age.

THE GERREI TECTONIC UNIT

The Gerrei tectonic Unit spans from middle Cambrian to Lower Carboniferous and includes the most complete middle Palaeozoic sequence of Sardinia (Fig. 1), which was only weakly affected by metamorphic effects. Most of its components are not yet officially defined and informal names are still in use in literature.

The Gerrei tectonic Unit starts with more than 500 m of terrigenous sediments (San Vito Sandstones) deposited in different environments, varying from inter-tidal to a wide fan-delta system swept by turbidity currents. Monotonous alternances of grey micaceous sandstones, quartzites, siltites and pelites grade to levels of violet, greenish or blackish pelites and thick layers of coarse light-grey quartzites and conglomerates. The age of the San Vito Sandstones spans from the middle Cambrian to the Early Ordovician (Naud & Pittau Demelia, 1987).

The sequence continues, after an important disconformity (Sarrabese Phase) with up to 500 m of volcanics, volcaniclastics and epiclastics, representing the "Ordovician Volcanic Complex". The origin of these volcanic products is a magmatic arc related to subduction of oceanic crust under the North Gondwanan continental margin (Carmignani et al., 1992). The subduction ceased in the Late Ordovician before reaching the continental collision. The consequent gravitative collapse of the magmatic arc produced extensional stresses associated with basaltic intercalations in terrigenous continental to littoral sediments. Quartzites, sandstones and rarely conglomerates, greyish siltites and argillites with variable

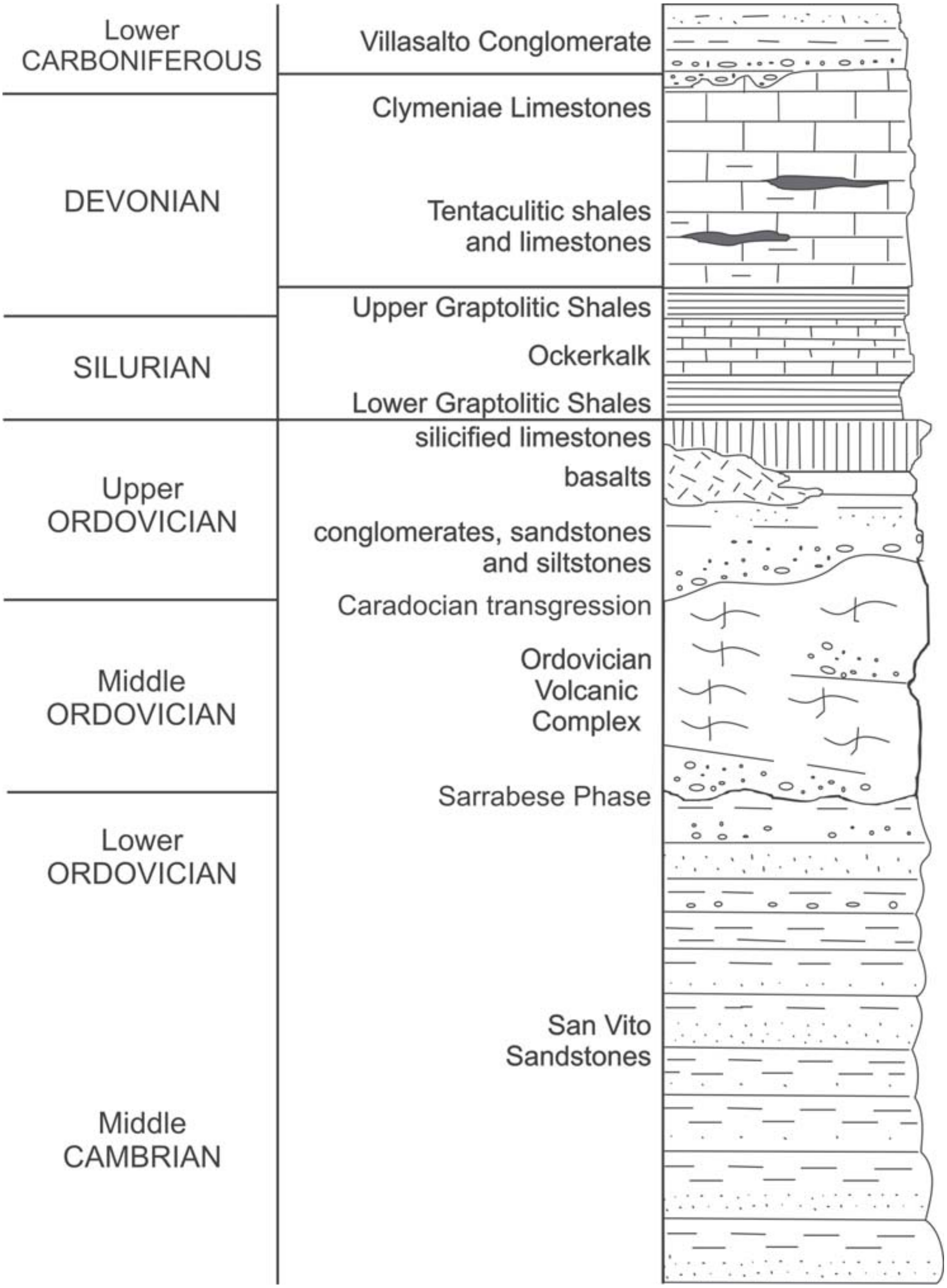


Fig. 1 - Stratigraphical column not to scale of the Gerrei tectonic Unit (modified after Corradini et al., 2002).

carbonatic content were deposited (“Caradocian transgression”). The topmost calcareous beds, locally silicifed, are constituted by echinoderm-or bryozoan packstones intercalated in fossiliferous mudstones. These limestones have been dated on the basis of conodonts as Late Ordovician (*Amorphognathus ordovicicus* Zone; Ferretti *et al*., 1998a, b; Ferretti & Serpagli, 1999).

The Silurian and Lower Devonian are represented by the classical Thuringian facies triad (Jaeger, 1976): “Lower Graptolitic Shales”, “Ockerkalk” and “Upper Graptolitic Shales” respectively.

The Lower Graptolitic Shales (30-40 m) are silica-argillaceous and siltitic shales rich in carbon and pyrite (“alum slates”; Jaeger, 1977). Lydites (cherts) are interbedded in the

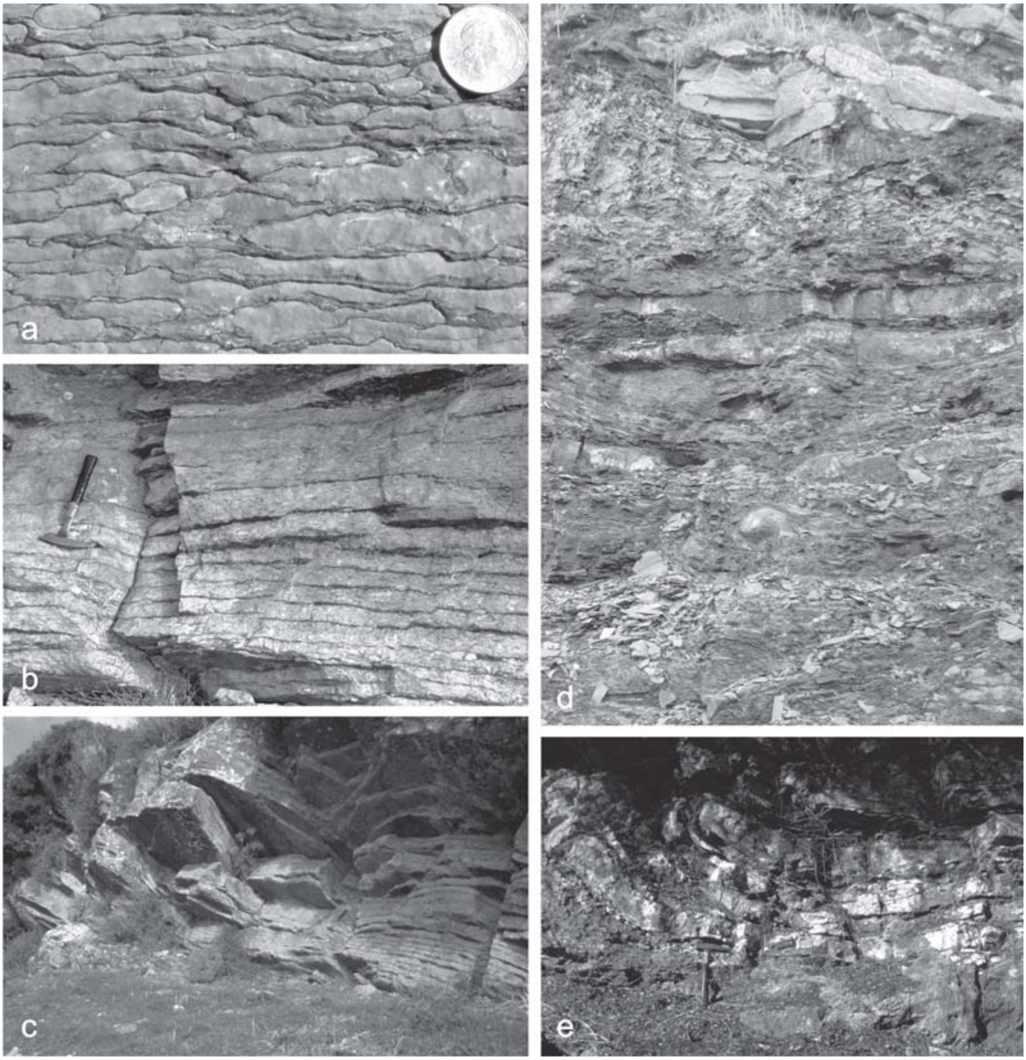


Fig. 2 - a) Typical flaser structure of the Ockerkalk limestone in the Silius section; b) Ockerkalk limestone near Silius; c) View of the Silius Cimitero section; d) The Lower Graptolitic Shales-Ockerkalk transition at Lantini Tunnel section; e) The Lower Graptolitic Shales-Ockerkalk boundary at the base of the Riu Murru de Callus section.

lower part as well as phosphorites occur in the middle-upper part of the unit. The age of the unit spans from Llandovery to earliest Ludlow, and a detailed biostratigraphy has been provided thanks to the abundant graptolite fauna (Meneghini, 1857; Gortani 1923a, b; Jaeger, 1977; Barca & Jaeger, 1990; Storch & Piras, 2009; Storch et al., 2009). The fossil association includes also chitinozoans, microplankton and sponge spiculae (Pittau & Del Rio, 2000; Pittau et al., 2002, 2006).

The Lower Graptolitic Shales grade to the overlying Ockerkalk within a few meters of interbedding shales and nodular limestones (Fig. 2d-e).

The Ockerkalk is an argillaceous limestone with a blue-grey colour, weathering into ochre (wherefrom the name), and a typical irregular flaser texture. It is about 25 m thick. The only macrofossils visible in the outcrops are crinoidal stems, rare cephalopods and loboliths. The lobolith level with bulbous holdfasts of giant pelagic scyphocrinoids, well-known from the Silurian-Devonian boundary beds of northern Gondwana, is found in the upper part of the Ockerkalk, at the base of the *detortus* conodont Zone. On a microscopic scale, ostracods, thin-shelled bivalves, brachiopods, gastropods, trilobite fragments, crinoids, small cephalopods and sponge spicules scattered in the matrix and only locally concentrated in millimetric shell-lags of disarticulated debris were also reported (Barca et al., 1995; Ferretti & Serpagli, 1996, Ferretti et al., 2009). Phyllocarids (mainly mandibles) were recovered from the conodont heavy-fraction. Trace fossils and very small solitary corals were reported by Jaeger (1977). The precise age location of the unit has been possible on the basis of a rich conodont fauna of Ludlow-Pridoli age (Fig. 3) spanning from the *hamata* to the *detortus* zones (Barca et al., 1995; Corradini & Olivieri, 1997; Corradini et al., 1998, 2000; Serpagli et al., 1998). The biostratigraphy of the unit has been recently updated by means of graphic correlations by Gouwy & Corradini (2006).

The boundary with the Upper Graptolitic Shales is never exposed, due to the strong tectonics; however biostratigraphical data from the two units allow to stress that the formation boundary is more or less coincident with the Silurian-Devonian boundary.

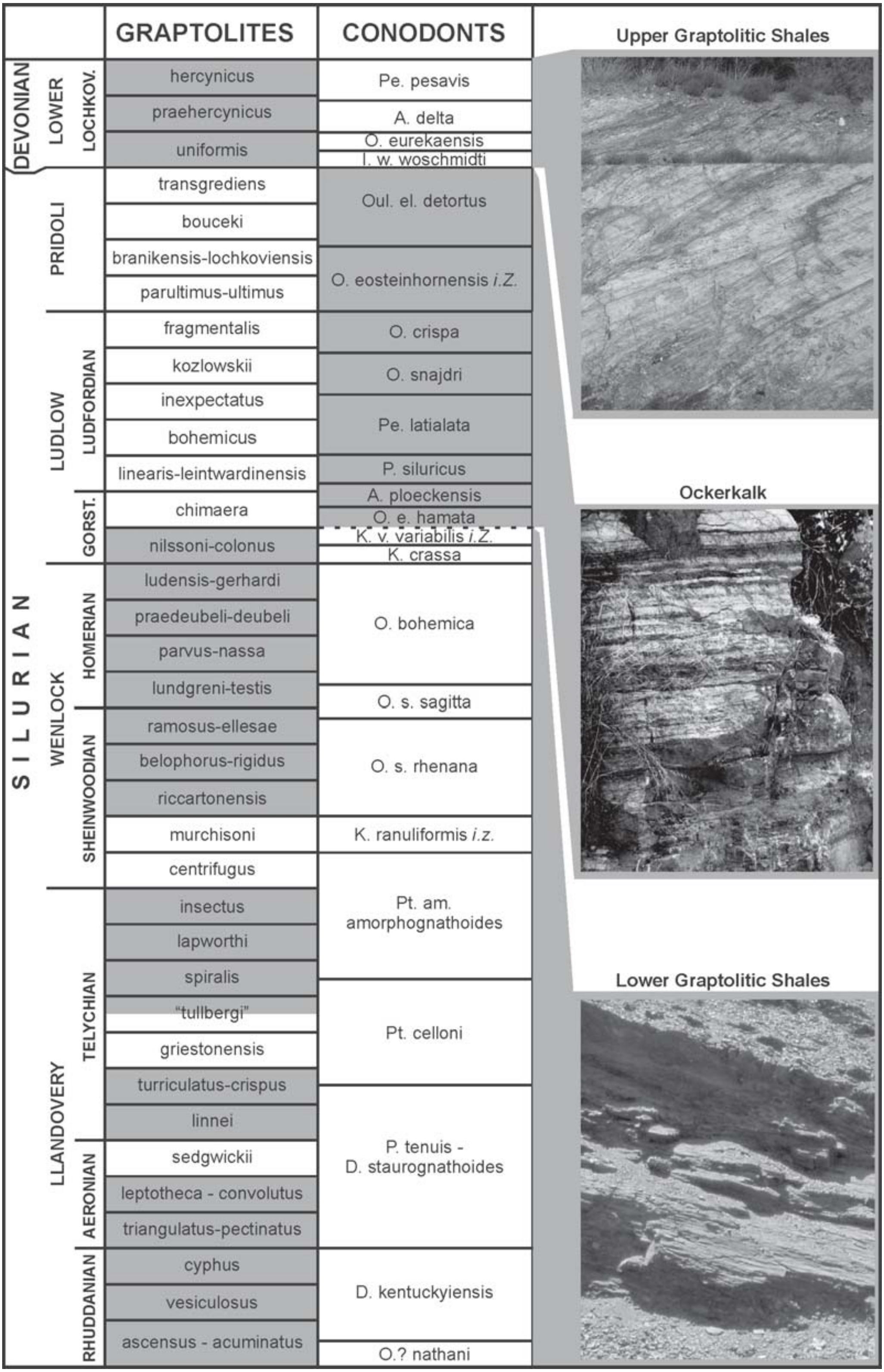
The Upper Graptolitic Shales (about 30 m) are exclusively composed by alum slates (Barca & Jaeger, 1990). Pelagic graptolites are the only abundant fossils found throughout the unit (Jaeger, 1976, 1977; Piras et al., 2009). Crinoidal stems, calyces and possible loboliths occur at the base of the unit. Rare *Ceratiocaris* (Jaeger, 1977) and bivalves (Barca & Jaeger, 1990) have been so far recorded. The lowermost Devonian graptolite biozones *uniformis*, *praehercynicus* and *hercynicus* were documented.

A few meters of poorly fossiliferous, thin nodular grey limestone may locally cover the shales, which otherwise grade to an alternation of dark and black phyllites and nodular limestones (Tentaculitic shales and limestones). On the basis of tentaculites (Alberti, 1963; Gessa, 1993) and rare conodonts (Bagnoli, 1980; Corradini et al., 2001; Gouwy & Corradini, 2007) the age of this strongly tectonised complex may be referred to the Early-Middle Devonian.

The succession continues with a thick sequence of massive limestone (Clymeniae Limestones) of Late Devonian-earliest Carboniferous age (Corradini et al., 2003; Corradini, 2007). Several dozen meters of sandstones and conglomerates (Conglomerato di Villasalto,

---

Fig. 3 - Stratigraphical distribution of the Silurian-lowermost Devonian units in southeastern Sardinia. Documented biozones are shaded (data from Sarrabus and Gerrei tectonic units are merged). Lower Graptolitic Shales, Sedda de S'Ortu, *turriculatus* Zone; Ockerkalk, Ponte Monte Lora, Pridoli; Upper Graptolitic Shales, Sa Ruinosa, *uniformis* Zone (modified after Corradini et al., 2002).



			GRAPTOLITES	CONODONTS
DEVONIAN	LOWER	LOCHKOV.	hercynicus	Pe. pesavis
			praehercynicus	A. delta
			uniformis	O. eurekaensis I. w. woschmidti
SILURIAN	PRIDOLI		transgrediens	Oul. el. detortus
			bouceki	
			branikensis-lochkoviensis	O. eosteinhornensis *i.Z.*
			parultimus-ultimus	
	LUDLOW	LUDFORDIAN	fragmentalis	O. crispa
			kozlowskii	O. snajdri
			inexpectatus	Pe. latialata
			bohemicus	
			linearis-leintwardinensis	P. siluricus
		GORST.	chimaera	A. ploeckensis O. e. hamata
			nilssoni-colonus	K. v. variabilis *i.Z.* K. crassa
	WENLOCK	HOMERIAN	ludensis-gerhardi	O. bohemica
			praedeubeli-deubeli	
			parvus-nassa	
			lundgreni-testis	O. s. sagitta
		SHEINWOODIAN	ramosus-ellesae	O. s. rhenana
			belophorus-rigidus	
			riccartonensis	
			murchisoni	K. ranuliformis *i.z.*
			centrifugus	Pt. am. amorphognathoides
	LLANDOVERY	TELYCHIAN	insectus	
			lapworthi	
			spiralis	
			"tullbergi"	Pt. celloni
			griestonensis	
			turriculatus-crispus	
			linnei	P. tenuis - D. staurognathoides
		AERONIAN	sedgwickii	
			leptotheca - convolutus	
			triangulatus-pectinatus	
		RHUDDANIAN	cyphus	D. kentuckyiensis
			vesiculosus	
			ascensus - acuminatus	O.? nathani

Auct.) are present above the Clymeniae Limestones. They represent the transition to the terrigenous sedimentation which terminates the pelagic succession of the Palaeozoic in southeastern Sardinia. Redeposited clasts and blocks of various Silurian and Devonian ages are recorded within this unit.

The Silurian in the Sarrabus and Meana Sardo tectonic units

The sequence described above for the Gerrei tectonic Unit is well comparable to those of the other units of the External Nappes. However, the following differences for the Silurian should be highlighted:

- The *Meana Sardo tectonic Unit* is the more internal of the External Nappes, and therefore the metamorphic degree is slightly higher. Black shales and nodular limestones, equivalent to the Lower Graptolitic Shales and to the Ockerkalk, are relatively abundant in some areas. However, fossils are quite rare, apart some crinoidal stems visible in some levels of the limestones. Unfortunately, up to now all attempts for a clear biostratigraphical definition of the unit were unsuccessful.

- In the *Sarrabus tectonic Unit* the sequence ends with the Lower Graptolitic Shales, which are here quite widespread. Lydites are more abundant than in the Gerrei. Graptolites fauna is quite rich and several biozones from Rhuddanian to Gorstian are documented in the Rio Ollastu area (Jaeger, 1977; Barca & Jaeger, 1990; Storch & Piras, 2009; Storch et al., 2009).

Acknowledgements

A. Funedda (Cagliari) provided useful comments on an early version of this manuscript. Funding for this work was provided by MIUR-PRIN 2007 (*Analysis of stratigraphic, palaentological and structural features of the Hercynian basement and the Tertiary cover in Sardinia and Calabria, as a contribution to the geodynamic reconstruction of the central-western Mediterranean basin*).

References

Alberti G. (1963). Sul Devoniano inferiore e medio nella Sardegna meridionale. *Rendiconti della Classe Scienze fisiche matematiche e naturali della Accademia Nazionale dei Lincei*, s. 8, 24 (5): 553-559.

Bagnoli G. (1980). Conodonti del Devoniano Inferiore di Monte Corongui Melas (Gerrei, Sardegna). *Memorie della Società Geologica Italiana*, 20: 315-321.

Barca S., Corradini C., Ferretti A., Olivieri R. & Serpagli E. (1995). Conodont biostratigraphy of the "Ockerkalk" (Silurian) from Southeastern Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 100 (1994): 459-476.

Barca S. & Jaeger H. (1990). New geological and biostratigraphical data on the Silurian in SE Sardinia. Close affinity with Thuringia. *Bollettino della Società Geologica Italiana*, 108 (1989): 565-580.

Carmignani L., Barca S., Carosi R., Di Pisa A., Gattiglio M., Oggiano G. & Pertusati P.C. (1992). Schema del basamento sardo. *In* Carmignani L., Pertusati P.C., Barca S., Carosi R., Di Pisa A., Gattiglio M., Musumeci G. & Oggiano G. (Eds), Struttura della Catena Ercinica in Sardegna - Guida all'escursione: 11-38.

Corradini C. (2007). Calcari a Clymenie. *In* Carta Geologica d'Italia 1:50000 – Catalogo delle Formazioni; fascicolo VI – Unità tradizionali e/o storiche. *Quaderni*, s. III, 7: 298-301.

Corradini C., Barca S. & Spalletta C. (2003). Late Devonian-Early Carboniferous conodonts from the "Clymeniae limestones" of SE Sardinia (Italy). *Courier Forschungs-Institut Senckenberg*, 245: 227-253.

Corradini C., Ferretti A. & Serpagli E. (2000). Correlazioni biostratigrafiche negli "Ockerkalk" (Siluriano sup.) della Sardegna sud-orientale. *In* Cherchi A. & Corradini C. (Eds), Crisi biologiche, radiazioni adattative e dinamica delle piattaforme carbonatiche. *Accademia Nazionale di Scienze Lettere Arti di Modena*, Collana di Studi 21: 87-92.

Corradini C., Ferretti A. & Serpagli E. (2002). The Gerrei Tectonic Unit (SE Sardinia, Italy). *Rendiconti della Società Paleontologica Italiana,* 1: 69-76.

Corradini C., Ferretti A., Serpagli E. & Barca S. (1998). The Ludlow-Pridoli Section "Genna Ciuerciu" west of Silius. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 112-118.

Corradini C., Leone F., Loi A. & Serpagli E. (2001). Conodont stratigraphy of a highly tectonised Silurian-Devonian Section in the San Basilio area (SE Sardinia, Italy). *Bollettino della Società Paleontologica Italiana*, 40 (3): 315-323.

Corradini C. & Olivieri R. (1997). Conodont biostratigraphy of some supplementary sections in the Sardinian "Ockerkalk" (Upper Silurian). *Bollettino del Museo regionale di Scienze Naturali di Torino*, 15: 89-100.

Ferretti A. & Serpagli E. (1996). Geological outline, community sequence and paleoecology of the Silurian of Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 102: 353-362.

Ferretti A. & Serpagli E. (1999). Late Ordovician conodont faunas from southern Sardinia, Italy: biostratigraphic and palaeogeographic implications. *Bollettino della Società Paleontologica Italiana*, 37 (2-3): 215-236.

Ferretti A., Serpagli E. & Leone F. (1998a). Late Ordovician conodonts from Umbrarutta between Donigala and Lago Mulargia. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 202-208.

Ferretti A., Serpagli E., Leone F. & Loi A. (1998b). The Late Ordovician section Cea Brabetza near San Basilio. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 96-101.

Ferretti A., Storch S. & Corradini C. (2009). The Silurian of Sardinia: facies development and palaeoecology. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 57-65.

Gessa S. (1993). Nouvelles données sur les Tentaculites du Dévonien inférieur de la Sardaigne méridionale (Italie). *Compte Rendu de l'Academie des Sciences de Paris*, 317 (II): 235-241.

Gortani M. (1923a). Faune Paleozoiche della Sardegna - parte I le graptoliti di Goni. *Paleontographia Italica*, 28: 1-69.

Gortani M. (1923b). Faune Paleozoiche della Sardegna - parte II Graptoliti della Sardegna Orientale. *Paleontographia Italica,* 28: 85-112.

Gouwy S. & Corradini C. (2006). Graphic correlation of the Sardinian Ockerkalk (Late Silurian): implications on the conodont biostratigraphy. *GFF*, 128: 103-108.

Gouwy S. & Corradini C. (2007). Preliminary data on the Lower-Middle Devonian conodont biostratigraphy of South-East Sardinia (Italy). *In* Over J.D. & Morrow J. (Eds.), Subcommission on Devonian Stratigraphy and IGCP 499 Devonian Sea Land Interactions, Eureka, Nevada, 9-17 September 2007, Program and Abstract: 39.

Jaeger H. (1976). Das Silur und Unterdevon vom thuringischen Typ in Sardinien und seine regionalgeologische Bedeutung. *Nova Acta Leopoldina*, 45 (224): 263-299.

Jaeger H. (1977). The Silurian-Devonian boundary in Thuringia and Sardinia. *In* Martinsson, A. (Ed.): The Silurian-Devonian boundary. IUGS, s. A, 5: 117-125.

Meneghini G. (1857). Palèontologie de l'Ile de Sardaigne. *In* La Marmora A., Voyage en Sardaigne: 53-144.

Naud G. & Pittau Demelia P. (1987). Première decuverte d'acritarches du Cambrien moyen à superieure basal et du Tremadoc-Arenigien dans la basse vallée du Flumendosa: mise en evidence d'un nouveau temoin de la Phase Sarde en Sardaigne orientale. I.G.C.P. n.5 Newsletter, 7: 85-86.

Piras S. & Paschina F. (2009). The Lower Devonian Upper Graptolitic Shales in the Sa Ruinosa Section (SE Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 191-194.

Piras S., Storch P., Pittau P. & Del Rio M. (2009). The Lower Graptolitic Shales at Rio Minderri and Rio Brabaisu-Rio Ollastu confluence (Rio Ollastu area (Sarrabus, SE Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 181-186.

Pittau P., Cotza F., Cristini S., Del Rio M. & Loi M. (2006). Paleontologic and biogeochemical characterization of the *Cyrtograptus lungreni* event in the black shales of eastern Mid-Sardinia, Italy. *Lethaia*, 39: 111-127.

Pittau P., Cotza F. & Del Rio M (2002). Goni's spheres: probable agglutinated Silurian foraminifera linings and radiolaria capsular membranes (South-east Sardinia). *Rendiconti della Società Paleontologica Italiana*, 1: 159-168.

Pittau P. & Del Rio M. (2000). Wenlock chitinozoans of SE Sardinia (Italy). *Bollettino della Società Paleontologica Italiana*, 39: 293-309.

Serpagli E., Corradini C. & Ferretti A. (1998). Conodonts from a Ludlow-Pridoli section near the Silius Village. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 104-111.

Storch P. & Piras S. (2009). Silurian graptolites of Sardinia: assemblages and biostratigraphy. *Rendiconti della Società Paleontologica Italiana,* 3 (1): 77-93.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 51-56

The Silurian of the Foreland Zone (southwestern Sardinia)

CARLO CORRADINI, MARIA G. CORRIGA, ANNALISA FERRETTI, FRANCESCO LEONE

C. Corradini - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); corradin@unica.it
M.G. Corriga - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); maria.corriga@unica.it
A. Ferretti - Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia, largo S. Eufemia 19, I-41100 Modena (Italy); ferretti@unimore.it
F. Leone - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); leonef@unica.it

ABSTRACT - The Silurian exposed in southwestern Sardinia is well-known for its precious faunal content. Lower part of the sequence consists of black graptolitic shales (Genna Muxerru Formation) comprising much of the Llandovery. It is suceeded by a calcareous unit (Fluminimaggiore Formation), locally rich in cephalopods, covering the rest of the Silurian. Even the Lower Devonian is represented by limestones. A precise and detailed biostratigraphical assignment of the units has been achieved by graptolites and conodonts.

KEY WORDS - Silurian, southwestern Sardinia, biostratigraphy, Genna Muxerru Fm., Fluminimaggiore Fm., graptolitic limestone.

INTRODUCTION

Silurian rocks of southwestern Sardinia are, from a palaeontological point of view, among the best known sediments of the whole Palaeozoic succession of the island. Several authors, starting from Meneghini (1857), illustrated different aspects of that rich fauna which includes graptolites, cephalopods, bivalves, and conodonts, beside several other less abundant fossil groups.

Despite the richness and the good preservation of the fossil material, outcrops are in general quite disappointing, since only a few meters of rocks, normally strongly tectonized, or a group of scattered blocks are exposed here and there, without any undisturbed section. Two formations (Fig. 1) were formally described by Gnoli et al. (1990) in the Silurian of southwestern Sardinia: the Genna Muxerru Formation (Llandovery) and the Fluminimaggiore Formation (uppermost Llandovery-lowermost Lochkovian).

THE GENNA MUXERRU FORMATION

The Genna Muxerru Fm. consists of about 20-25 metres of graptolitic silica-argillaceous and siltitic shales, interbedded by subordinate lydites in the lower part (Gnoli et al., 1990). Local greywacke bodies crop out at the type locality Genna Muxerru (Storch & Serpagli, 1993). Faulting, cleavage and small scale folding characterized the whole unit.

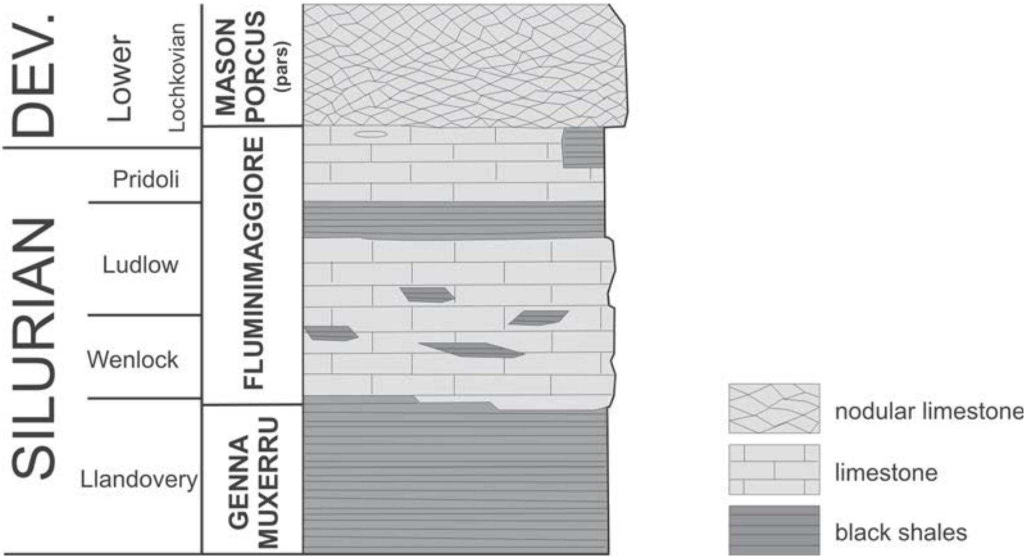


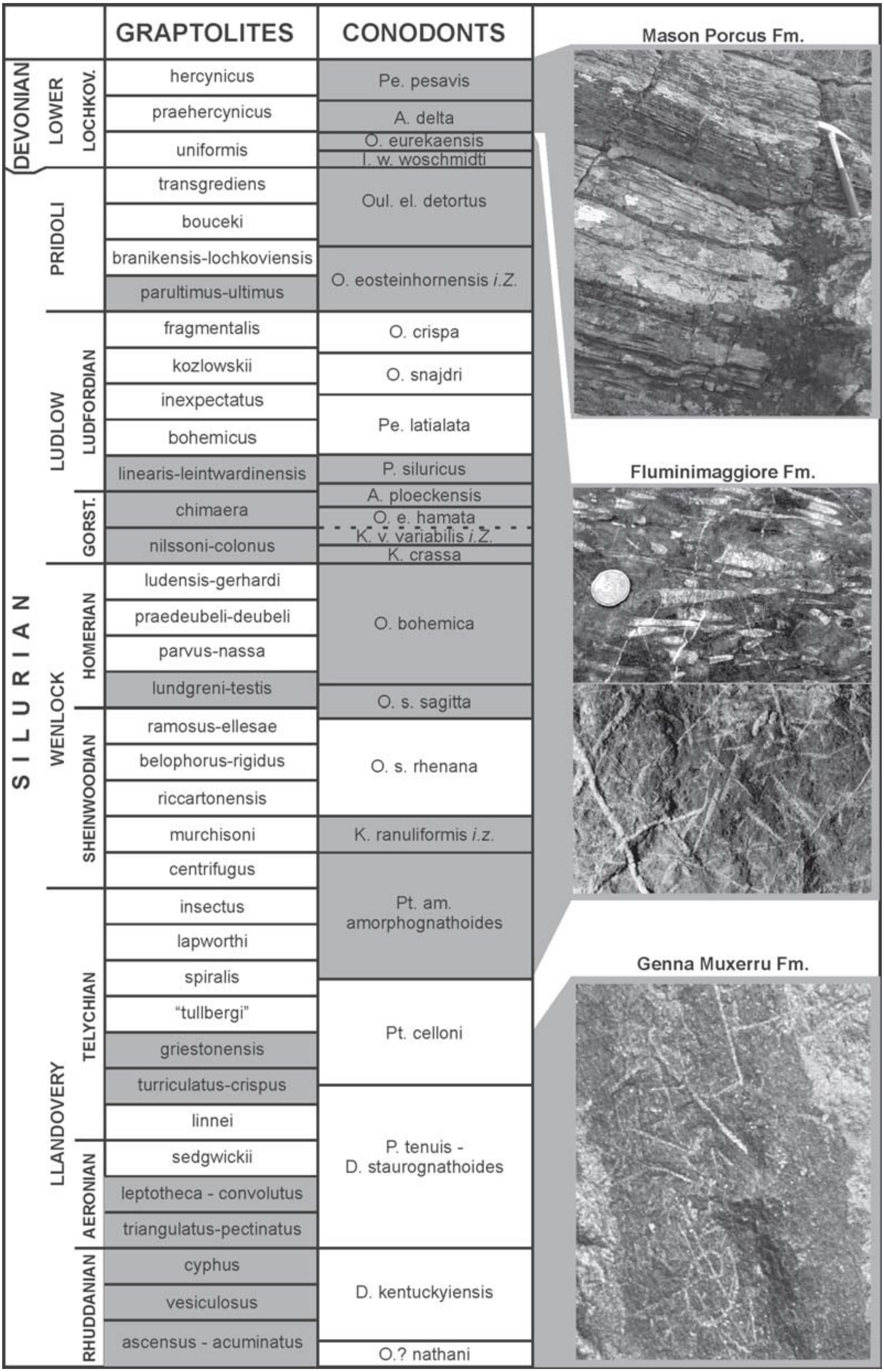
Fig. 1 - Stratigraphical scheme of the Silurian and lowermost Devonian of southwestern Sardinia (modified after Gnoli et al., 1990).

The lower boundary of the formation is never clearly exposed but no evidence of discontinuity in sedimentation between Ordovician and Siluro-Devonian sequences is present. Furthermore, the latest Hirnantian age of the Rio San Marco Fm. (Leone et al., 1991; Storch & Leone, 2003) is in accordance with the occurrence of *A. ascensus* and *P. acuminatus* in the lowermost beds of the Genna Muxerru Fm. (Storch & Piras, 2009).

Graptolites are the only fossils documented from the unit: more than fifty taxa have been described by Storch & Serpagli (1993) and Rickards et al. (1995), documenting several Llandovery biozones, from early Rhuddanian *ascensus-acuminatus* Zone, through to middle Telychian *griestonensis* Zone (Fig. 2).

The Genna Muxerru Fm. seems to grade into the overlying Fluminimaggiore Fm., but the boundary is never exposed (Gnoli et al., 1990). In the Perda S'Altari area, south of Arbus, an unusual situation occurs: a gradual transition between the Genna Muxerru and the Mason Porcus formations has been recently described and illustrated, without apparently any evidence of the Fluminimaggiore Fm. in the area (Corriga & Corradini, 2008). In this case, the thickness of the Genna Muxerru Fm. needs to be increased as the unit could span the whole Silurian (Corriga & Corradini, 2008).

Fig. 2 - Stratigraphical distribution of the Silurian-lowermost Devonian units in southwestern Sardinia. Documented biozones are shaded. Mason Porcus Fm.: view of the Perda S'Altari section; Fluminimaggiore Fm.: *Orthoceras* limestone, Sant'Antonio Donigala [top] and graptolitic limestone, Fluminimaggiore area [below]; Genna Muxerru Fm.: slab from the type locality.



			GRAPTOLITES	CONODONTS
DEVONIAN	LOWER	LOCHKOV.	hercynicus	Pe. pesavis
			praehercynicus	A. delta
			uniformis	O. eurekaensis I. w. woschmidti
SILURIAN	PRIDOLI		transgrediens	Oul. el. detortus
			bouceki	
			branikensis-lochkoviensis	O. eosteinhornensis *i.Z.*
			parultimus-ultimus	
	LUDLOW	LUDFORDIAN	fragmentalis	O. crispa
			kozlowskii	O. snajdri
			inexpectatus	Pe. latialata
			bohemicus	
			linearis-leintwardinensis	P. siluricus
		GORST.	chimaera	A. ploeckensis O. e. hamata
			nilssoni-colonus	K. v. variabilis *i.Z.* K. crassa
	WENLOCK	HOMERIAN	ludensis-gerhardi	O. bohemica
			praedeubeli-deubeli	
			parvus-nassa	
			lundgreni-testis	O. s. sagitta
		SHEINWOODIAN	ramosus-ellesae	O. s. rhenana
			belophorus-rigidus	
			riccartonensis	
			murchisoni	K. ranuliformis *i.z.*
			centrifugus	Pt. am. amorphognathoides
	LLANDOVERY	TELYCHIAN	insectus	
			lapworthi	
			spiralis	Pt. celloni
			“tullbergi”	
			griestonensis	
			turriculatus-crispus	
			linnei	P. tenuis - D. staurognathoides
		AERONIAN	sedgwickii	
			leptotheca - convolutus	
			triangulatus-pectinatus	
		RHUDDANIAN	cyphus	D. kentuckyiensis
			vesiculosus	
			ascensus - acuminatus	O.? nathani

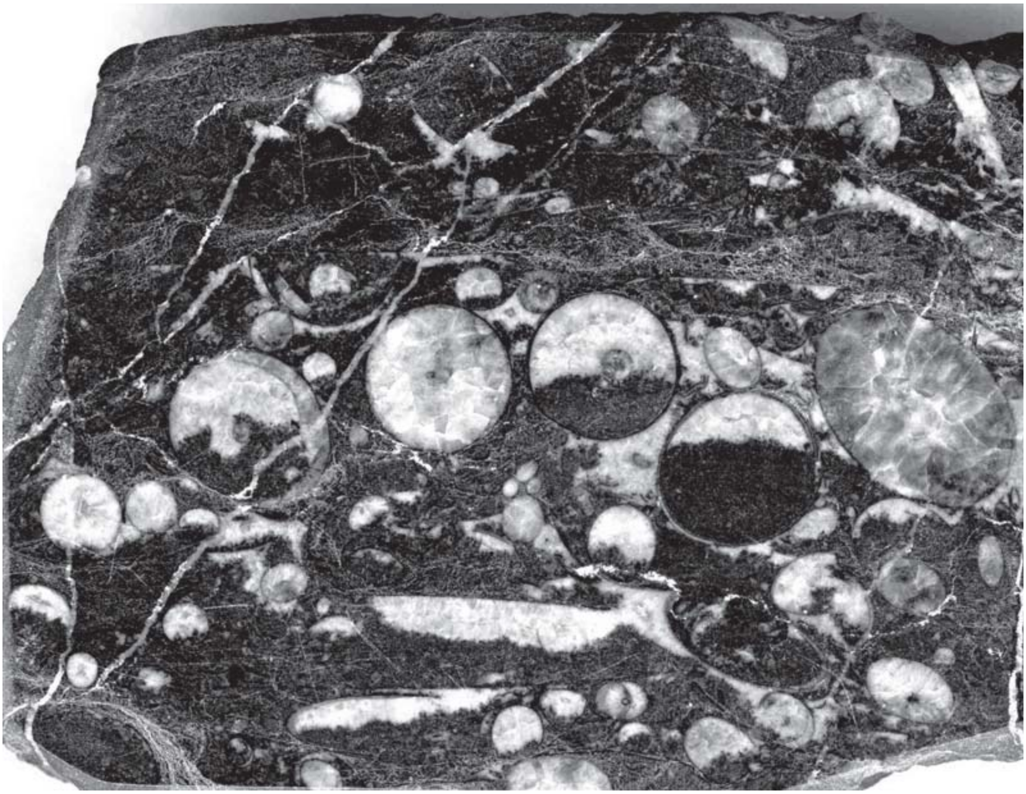


Fig. 3 - Polished slab of the *Orthoceras* limestone of the Fluminimaggiore Fm. (Sant'Antonio Donigala area).

THE FLUMINIMAGGIORE FORMATION

The Fluminimaggiore Fm. roughly corresponds to the "calcari a *Orthoceras*, *Cardiola*, *Monograptus*, etc." of the early authors. It is mainly constituted by black limestone lenses and layers alternating with dark non-calcareous pelites and shales. Carbonate deposition is characterized by dominant fossiliferous wackestones-packstones, that grade to fossiliferous mudstones. Microbiofacies were described by Ferretti (1989) and Ferretti et al. (2009). Plastic deformation and cleavage strongly altered the shales, while limestone blocks preserve fossils mostly in full three dimensions (Gnoli et al., 1980). The black colour and the peculiar bituminous smell reveal a high content of organic matter. The thickness of the Fluminimaggiore Fm. should be 40-50 m, but it can be only indirectly estimated, since no sections expose completely the unit due to the strong tectonic deformation. A septariae-bearing horizon occurs in the middle part of the formation, whereas an encrinitic packstone with crinoidal bioclasts is present at the top (Gnoli et al., 1990).

The fauna is dominated by cephalopods (Serpagli & Gnoli, 1977; Gnoli & Serventi, 2009) and bivalves (Kriz & Serpagli, 1993; Kriz, 2009), associated with pelagic ostracodes, graptolites, conodonts, chitinozoans. Gastropods, eurypterid fragments and the problematic *Kolihaia* are rare. Phyllocarids and pelagic crinoids are occasionally present in the upper part of the unit. Bivalves are the only significant indicators of an epibenthic fauna, while almost no trilobites and brachiopods have been reported, revealing the presence of oxygen-depleted environmental conditions unfavourable to these organisms.

Graptolites are frequently found packed together in peculiar pseudo-lenticular limestone bodies or thin calcareous layers preserving three-dimensional specimens. Five graptolite biozones and co-occurring conodonts document the lower Homerian to lower Pridoli (Ferretti & Serpagli, 1996), allowing a precise tying between the two biozonation schemes (Corradini & Serpagli, 1999).

A precise biostratigraphical assignment of the Fluminimaggiore Fm. was established on the basis of conodonts, that have documented twelve conodont Zones from the *amorphognathoides* Zone (top Llandovery-early Wenlock) to the *woschmidti* Zone (Lochkovian) either from the *Orthoceras* or the graptolitic limestones (Fig. 2). However, some intervals have not been found yet: they are probably represented by shales strongly deformed and displaced by tectonics (Gnoli et al., 1990). The Silurian/Devonian boundary occurs in the uppermost part of the Fluminimaggiore Fm., just below the lobolith horizon with the giant pelagic crinoid *Scyphocrinites* (Gnoli et al., 1988), well known along the northern Gondwana margin across the Silurian/Devonian boundary.

The Fluminimaggiore Fm. is overlaid by the Mason Porcus Formation (Lochkovian-Emsian), which mainly consists of nodular and massive limestones alternating with compact dark siltstones and shales. Stromatactis bearing carbonate mounds, forming lenticular bodies of massive limestone have been documented in the Mt. Padenteddu area (Gnoli et al., 1981). The unit is dominated by dacryoconarida, cephalopods, conodonts, and ostracodes in association with minor crinoids, trilobites, phyllocarids, corals and sponge spiculae (Gnoli et al., 1990). In the mud mound facies, tabulate and colonial corals are also present, together with abundant stromatactis structures (Gnoli et al., 1981). Conodonts have documented seven Lower Devonian biozones, from the *delta* Zone to the *serotinus* Zone (Olivieri & Serpagli, 1990; Ferretti et al., 1998).

Acknowledgements

Funding for this work was provided by MIUR-PRIN2007 (*Analysis of stratigraphic, palaeontological and structural features of the Hercynian basement and the Tertiary cover in Sardinia and Calabria, as a contribution to the geodynamic reconstruction of the central-western Mediterranean basin*).

References

Corradini C. & Serpagli E. (1999). A Silurian conodont zonation from late Llandovery to end Pridoli in Sardinia: *Bollettino della Società Paleontologica Italiana*, 38 (2-3): 255-273.

Corriga M.G. & Corradini C. (2008). Nuovi dati sulla sequenza Siluriano-Devoniana della Sardegna sud-occidentale. *Rendiconti online della Società Geologica Italiana*, 3: 262-263.

Ferretti A. (1989). Microbiofacies and constituent analysis of Upper Silurian-Lowermost Devonian limestones from Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana,* 28 (1): 87-100.

Ferretti A., Corradini C. & Serpagli E. (1998). The Silurian and Devonian sequence in SW Sardinia. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 57-61.

Ferretti A. & Serpagli E. (1996). Geological outline, community sequence and paleoecology of the Silurian of Sardinia: *Rivista Italiana di Paleontologia e Stratigrafia,* 102: 353-362.

Ferretti A., Storch S. & Corradini C. (2009). The Silurian of Sardinia: facies development and palaeoecology. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 57-65.

Gnoli M., Jaanusson V., Leone F. & Serpagli E. (1981). A Lower Devonian stromatactis-bearing carbonate mud-mound from Southern Sardinia. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1981-H6: 339-345.

Gnoli M., Kriz J., Leone F., Olivieri R., Serpagli E. & Storch P. (1990). Lithostratigraphic units and biostratigraphy of the Silurian and early Devonian of Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 11-23.

Gnoli M., Leone F., Olivieri R. & Serpagli E. (1988). The Mason Porcus Section as reference section for Uppermost Silurian-Lowermost Devonian in SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 27 (3): 323-334.

Gnoli M., Parea G.C., Russo F. & Serpagli E. (1980). Paleoecological remarks on the "*Orthoceras* limestone" of Southwestern Sardinia (middle-upper Silurian). *Memorie della Società Geologica Italiana*, 20 (1979): 405-423.

Gnoli M. & Serventi P. (2009). Silurian Cephalopods from Sardinia: the state of the art. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 109-118.

Kriz J. (2009). The upper Silurian Bivalvia dominated palaeocommunities succession of southwestern Sardinia – correlation with Perunica and the peri-Gondwanan regions of Europe. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 119-130.

Kriz J. & Serpagli E. (1993). Upper Silurian and Lowermost Devonian Bivalvia of Bohemian type from Western Sardinia. *Bollettino della Società Paleontologica Italiana*, 32 (3): 289-347.

Leone F., Hammann W., Laske R., Serpagli E. & Villas E. (1991). Lithostratigraphic units and biostratigraphy of the post-Sardic Ordovician sequence in south-west Sardinia. *Bollettino della Società Paleontologica Italiana*, 30 (2): 201-235.

Meneghini G. (1857). Paléontologie de l'Ile de Sardaigne. *In* Lamarmora A., Voyage en Sardaigne, 3: 1-584; Imprimerie Royal, Torino.

Olivieri R. & Serpagli E. (1990). Latest Silurian-early Devonian conodonts from Mason Porcus Section near Fluminimaggiore, Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 59-76.

Rickards R.B., Holland C.H. & Serpagli E. (1995). Aspects of Silurian and Lower Devonian graptolite faunas and stratigraphy in southern Sardinia. *Bollettino della Società Paleontologica Italiana*, 34 (1): 67-80.

Serpagli E. & Gnoli M. (1977). Upper Silurian cephalopods from southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 16 (2): 153-195.

Storch P. & Leone F. (2003). Occurrence of late Ordovician (Hirnantian) graptolite *Normalograptus ojsuensis* (Koren & Mikhaylova, 1980) in south-western Sardinia, Italy. *Bollettino della Società Paleontologica Italiana*, 42 (1-2): 31-38.

Storch P. & Piras S. (2009). Silurian graptolites of Sardinia: assemblages and biostratigraphy. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 77-93.

Storch P. & Serpagli E. (1993). Lower Silurian Graptolites from Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 32 (1): 3-57.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 57-65

The Silurian of Sardinia: facies development and palaeoecology

ANNALISA FERRETTI, PETR STORCH, CARLO CORRADINI

A. Ferretti - Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia, largo S. Eufemia 19, I-41100 Modena (Italy); ferretti@unimore.it
P. Storch - Institute of Geology Academy of Sciences of the Czech Republic, Rozvojova 269, 165 02 Praha 6 (Czech Republic); storch@gli.cas.cz
C. Corradini - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); corradin@unica.it

ABSTRACT - Main features of the Silurian sequences exposed in Sardinia (Italy) are here described. Oldest sediments are represented by black shales, rich in graptolites, grading into a calcareous facies throughout the middle Silurian; however, the sequences exposed in the southeast and in the southwest are different, even if some similitude is evident. The spectacular variety of invertebrate fossils is briefly outlined and their environmental settings are discussed in the attempt of giving a contribution to the global picture of Silurian events.

KEY WORDS - Silurian, Sardinia, Palaeoenvironment, Facies distribution.

INTRODUCTION

Silurian rocks of Sardinia contain abundant, diverse and well preserved marine faunas whose study has been continuous for about 150 years, starting from Meneghini pioneer paper of 1857 where the oldest Italian nautiloids, bivalves and graptolites were illustrated. However, descriptions of these faunas are spread across a large number of disparate monographs and shorter papers. The strong tectonic activity which repeatedly affected the region resulted in the absence of continuous sections spanning across the full system. The outcrops, although extensive, are mostly constituted of displaced blocks of tectonized - faulted, folded and cleaved rocks. This drawback often discouraged attempts to get a comprehensive vision of the Silurian scenario of Sardinia. The best known Silurian fossils from the region are the cephalopods and the graptolites, which represent the most significant pelagic elements of the fauna, and have the latter been used, to a greater or lesser extent, for biostratigraphical correlation. Later on, new information were added either on the benthic (e.g. Kriz & Serpagli, 1993) or pelagic (e.g. Palmer & Gnoli, 1985; Storch & Serpagli, 1993) fauna and a more precise stratigraphical assignment was finally achieved by means of conodonts (e.g. Serpagli, 1998).

SILURIAN LIFE AND DEPOSITIONAL SETTINGS IN THE SARDINIAN SEA

As described previously, fossiliferous Silurian rocks crop out almost exclusively in southern Sardinia, in two different areas of the island: in the southwestern sector with the Iglesiente and Sulcis sub-regions, and in the southeastern sector that involves the Gerrei and Sarrabus sub-regions. Silurian successions of the two parts of the island remind to coeval successions exposed in Bohemia and Thuringia respectively. However, their mutual relation is still unraveled.

BLACK-SHALE ENTRANCE

The Silurian Period spans about 27 million years (Ogg et al., 2008). The terminal Ordovician faunal extinction, triggered by a major glaciation on the southern supercontinent of Gondwana, produced a radical change-over of the marine biota. After the marked provincialism of the pre-glacial Late Ordovician, rather uniform facies of pelagic and hemipelagic black shales characterize post-glacial Silurian succession of northwestern Gondwana and close-by areas. Rapid late Hirnantian (terminal Ordovician) deglaciation of the Gondwana supercontinent lead to a dramatic rise of sea-level that, together with ocean stratification, triggered a wide-spread early Silurian post-glacial marine anoxia. Graptolite-rich black shales predominated in the Llandovery and Wenlock of the peri-Gondwanan Europe (Storch, 1998) with most spectacular sections exposed in Spain, Portugal, Sardinia, the Carnic Alps, Thuringia and Bohemia (Storch, 1998). Their rich and closely similar faunal content, in graptolite terms, has enabled a precise biostratigraphical correlation within the area. Rapid evolution of moderately to highly diversified graptolite faunas was punctuated by several extinction events assigned by Melchin et al. (1998) and Loydell (1998) to persisting glacioeustatic sea-level fluctuations. Graptolite faunas extended over wide shelves and basins along the northwestern margin of Gondwana, with local differences explained largely by different depositional depths and local environmental conditions expressed in three depth-/nutrient related graptolite sub-faunas recognized by Storch (1998): 1) a low diversity, oxygen tolerant sub-fauna in shallow-shelf environments; 2) a moderate diversity sub-fauna, associated with non-graptolite macrofossils (e.g., eurypterids, ceratiocarids, nautiloids, bivalves, brachiopods and crinoids) suggesting anoxic conditions at the sediment/water interface; 3) a sub-fauna of typical hemipelagic anoxic black shales, with particularly rich graptolite assemblages. The last named graptolite sub-

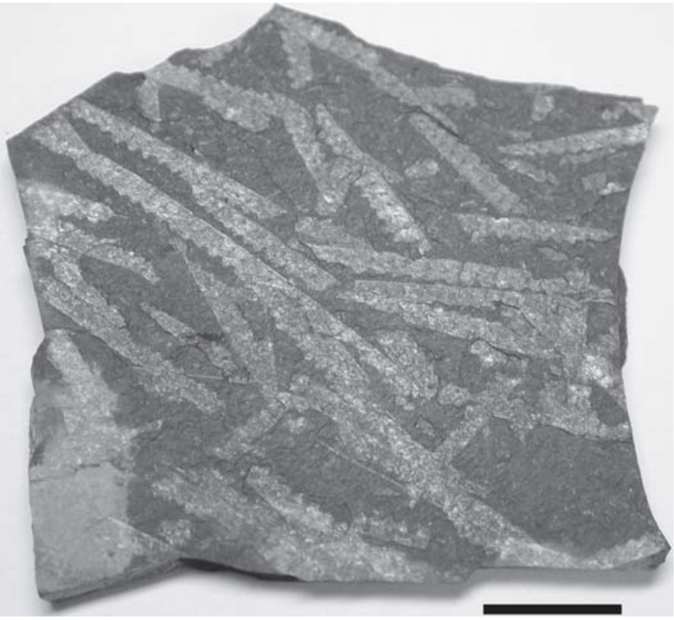


Fig. 1 - Lower Graptolitic Shales, Goni Section, level with *M. praedeubeli* (Wenlock, identified by H. Jaeger, 1987, pers. com.). Scale bar = 1 cm (refigured after Corradini *et al.*, 2002).

fauna has a wide distribution in the peri-Gondwanan Europe, reflecting presumably deep shelf to upper slope facies, or even a deeper, sediment starved depositional environment for the alum shales and silicites which occur in Thuringia and southeastern Sardinia (Storch, 1998).

Also in the territory of Sardinia, the lower Silurian is characterized with rather uniform graptolitic silica-argillaceous and siltitic black shales (Fig. 1). In southeastern Sardinia, graptolitic black shales (alum shales) are subordinate to lydites (black silicites) in the lower part of the succession. Phosphorites are present, but only in southeastern Sardinia, in the middle-upper part of the shales in form of nodules, lenses or proper layers (Barca & Jaeger, 1990).

In southwestern Sardinia, 20-25 m thick graptolitic shales assigned to the Genna Muxerru Formation have documented a Llandovery age (Storch & Serpagli, 1993; Storch et al., 2002). In southeastern Sardinia, the deposition of the 40 m thick Lower Graptolitic Shales spans over a longer time period, persisting in this area also through Wenlock to earliest Ludlow times. In both sectors of the island, graptolitic shales appear to have started just at the very beginning of the Silurian, as the *ascensus-acuminatus* graptolite Biozone is documented (Storch & Piras, 2009). Random orientation of the graptolite rhabdosomes was more commonly observed on bedding planes than alignment by currents. Apart from graptolites, radiolarians (Barca & Jaeger, 1990), chitinozoans (Pittau et al., 1998; Pittau & Del Rio, 2000) and muellerisphaerid spherulae (Pittau et al., 1998) have been reported from the graptolitic shales.

Limestone propagation

The shaley deposition was replaced diachronously by a calcareous sedimentation which started sporadically already in late Llandovery (Barca et al., 1992) and more definitely in late Wenlock times with lenticular limestone beds intercalated to shales in southwestern Sardinia. In the southeastern Sardinian sub-regions, the limestone deposits commenced in Ludlow times.

The calcareous unit of southwestern Sardinia belongs to the Fluminimaggiore Formation, a unit 45-50 m thick spanning from late Llandovery to earliest Lochkovian. Black calcareous lens-shaped beds alternate with dark non calcareous pelites and shales. These well known limestones, often referred to as “calcari a *Orthoceras*, *Cardiola*, *Monograptus*, ecc.”, are similar to other cephalopod-dominated limestones (Fig. 2) developed in other sectors of the northern Gondwana setting, having certainly in the Prague Basin the most typical exposures. Cephalopods are the most striking elements of the fauna, but at naked eyes also bivalves, pelagic ostracodes and graptolites may be easily recognized. Conodonts, forams, chitinozoans and muellerisphaerids are also present. Gastropods, brachiopods, trilobites and eurypterid fragments are, on the contrary, extremely rare. Phyllocarids and pelagic crinoids may be found towards the top of the formation.

The nautiloid fauna recovered in southwestern Sardinia is most closely related to that occurring in coeval levels of Bohemia. Gnoli et al. (1980), on the basis of measurements made on large cephalopod slabs and blocks and of laboratory experiments, reported a definite double alignment of orthoconic shells, similar to the crest and trough of ripple marks and to the distinctive bimodal orientation model of wave accumulation. A constant cephalopod orientation was reported from isolated spots in a late Wenlock-Ludlow locality of southwestern Sardinia by Ferretti et al. (1998). Displaced blocks, with random oriented orthocones, are also present (Ferretti et al., 1995).

Largely epibyssate bivalves of the *Cardiola* Community Group (Kriz, 1999) represent the only significant indicators of a benthic epifauna, as almost no trilobites and brachiopods

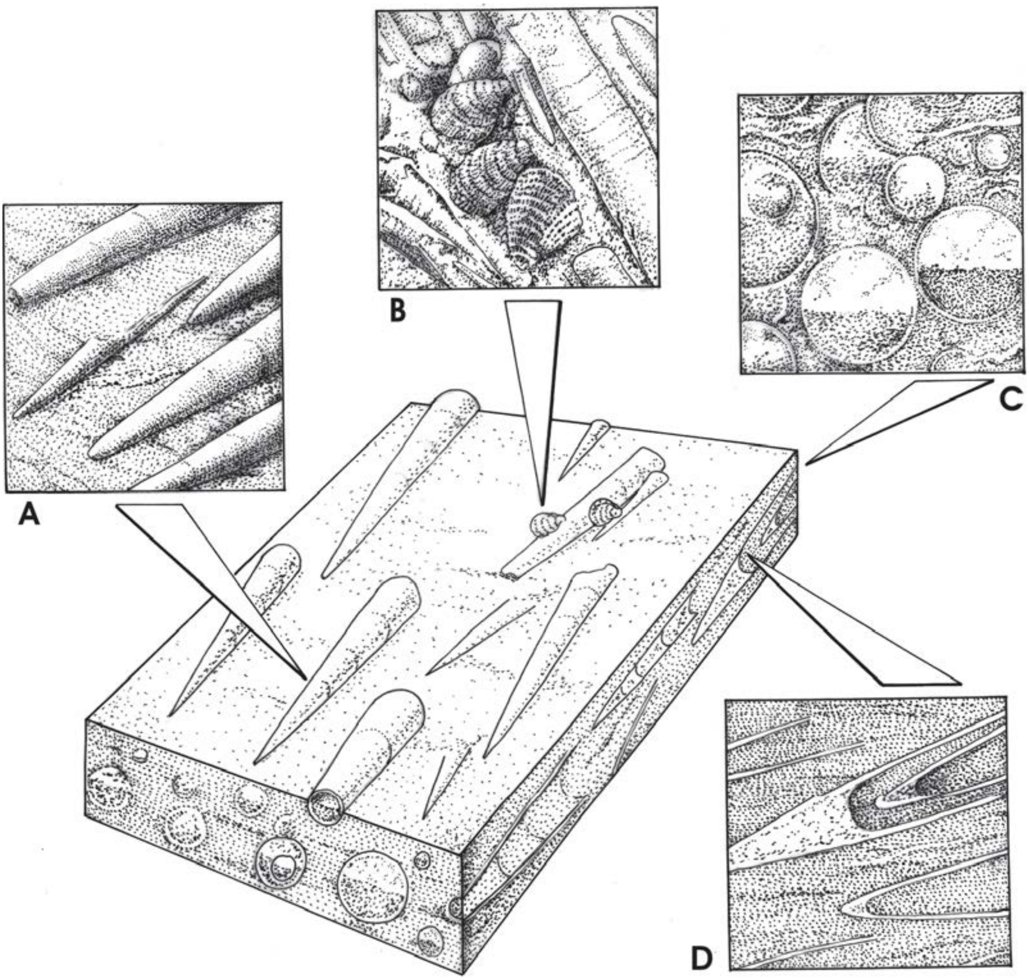


Fig. 2 - Cephalopod limestone main features: A) frequent isorientation of cephalopod shells; B) association between cephalopod shells and bivalve-dominated communities; C) concordant geopetal structures of cephalopod shells; D) “telescoping” (shell-in-shell structure) of cephalopod shells (modified after Ferretti & Kriz, 1995).

are present, possibly reflecting the existence of anomalous oxygen conditions which could not be tolerated by these organisms. Mass occurrences of shells were possibly resulting from regular mass mortalities caused by abiotic conditions (Kriz & Serpagli, 1993).

Flattened rhabdosomes of the Silurian graptolites have been described for a long time from the black shales of classical localities both in southwestern and southeastern Sardinia. Less known is the preservation of graptolites packed together in pseudolenticular limestone bodies, up to 1 m big, developed only in southwestern Sardinia in strict association with the typical cephalopod-dominated limestones. This unusual type of limestone is literally crowded by graptolite rhabdosomes preserved in full three-dimensions (Fig. 3). Graptolites from these bodies document a late Wenlock-early Pridoli age; the age was confirmed also by conodonts. Monospecific or oligospecific graptolite associations are present in each block. Wenlock-Ludlow graptolitic limestones are characterized by species of the straight robust *Monograptus, Colonograptus* or *Saetograptus* together with rare *Bohemograptus*. Early Pridoli associations are dominated by species of "*Monograptus*" (Ferretti & Serpagli, 1996b). Polished slabs obtained from cross-sectioned graptolite limestones revealed centimetric graptolite-packed layers, with sharp base, separated by fine grained calcareous mudstones where sparse graptolite fragments and small cephalopods, with common geopetal infills, are present. Most cephalopods still preserve body chambers which are sometimes filled by graptolites. These concentrations represent discrete event horizons of graptolites which were probably living in an environment close to that of cephalopods and had developed a similar sort of tolerance towards oxygen content and/or other palaeoecological constraints (Ferretti & Serpagli, 1996b). Orientation measurements on the graptolite distribution of some blocks revealed how both random and current oriented concentrations are present, even for graptolites belonging to the same genus or species and having therefore similar hydrodynamic behaviour.

Ferretti (1989) described five different microfacies (Fig. 4) in the Wenlock-upper Ludlow limestones of southwestern Sardinia, related to two main different regimes: a shallow-high energy deposition for the cephalopod-ostracode packstone-wackestones (typical of the "*Orthoceras* limestones"), the graptolitic packstones and the "coated-grains" grainstone-packstones, and a deposition below normal wave-base but probably in areas within storm wave-base for rare Ludlow pre-nodular mudstones with intercalated shell-lags and for dark laminated fossiliferous mudstones found locally. In Pridoli time, a shift to a deeper environment is suggested by dark fossiliferous mudstones, where winnowed shell lags of disarticulated thin-shelled and convex-up bivalves and ostracodes, small orthocones and rare crinoidal fragments are present (Ferretti, 1989).

A crinoidal bioclastic packstone, associated with *Scyphocrinites* loboliths, caps the Fluminimaggiore Fm. The same distinctive horizon is present in many other Gondwana

Fig. 3 - Graptolitic limestone exposed in southwestern Sardinia (Perd'e Fogu locality, Fluminimaggiore area). Coin for scale = 24 mm.

and extra-Gondwana (e.g. China and Arctic Canada) regions. The Silurian/Devonian boundary occurs in the calcareous Fluminimaggiore Fm. immediately below the lobolith-horizon (Gnoli *et al.*, 1990).

The Ockerkalk (25 m thick) is an argillaceous limestone developed in southeastern Sardinia above the Lower Graptolitic Shales, with a blue-grey colour weathering to ochre (so the name) and a peculiar irregular flaser texture. This unit is reported also in Thuringia, Spain, the Carnic Alps and northwestern Czech Republic. Crinoidal stems, all parallel to the bedding, and a few cephalopods (Gnoli, 1993) are the only macrofossils clearly visible in outcrop. Trace fossils and very small solitary corals were reported by Jaeger (1977); loboliths are present in a distinctive level (see below). The Ockerkalk unit is represented by massive sequences of fine micritic limestones with a scattered microscopic fauna of ostracodes, brachiopods, thin-shelled bivalves, trilobite fragments, gastropods, sponge spiculae, phyllocarids (mainly mandibles) and crinoids, sometimes concentrated in millimetric wackestone shell-lags of disarticulated debris. A quiet pelagic environment, below wave-base action, dominated by a fine-grain sedimentation and with bioclastic input variable in time and probably in space, especially in the crinoidal fraction, was proposed by Barca et al. (1995).

The lobolith horizon with the giant pelagic crinoid *Scyphocrinites*, already recorded in the Early Devonian (*woschmidti* conodont Zone) of southwestern Sardinia, extends also to the southeastern sector of Sardinia but with loboliths generally bigger (up to 20 cm compared to 12 cm of southwestern Sardinia) and occurring definitely earlier (*detortus* conodont Zone) (Corradini et al., 1998). The Silurian/Devonian boundary corresponds in southeastern Sardinia to the lithological change from the Ockerkalk limestone to the overlying graptolitic shales.

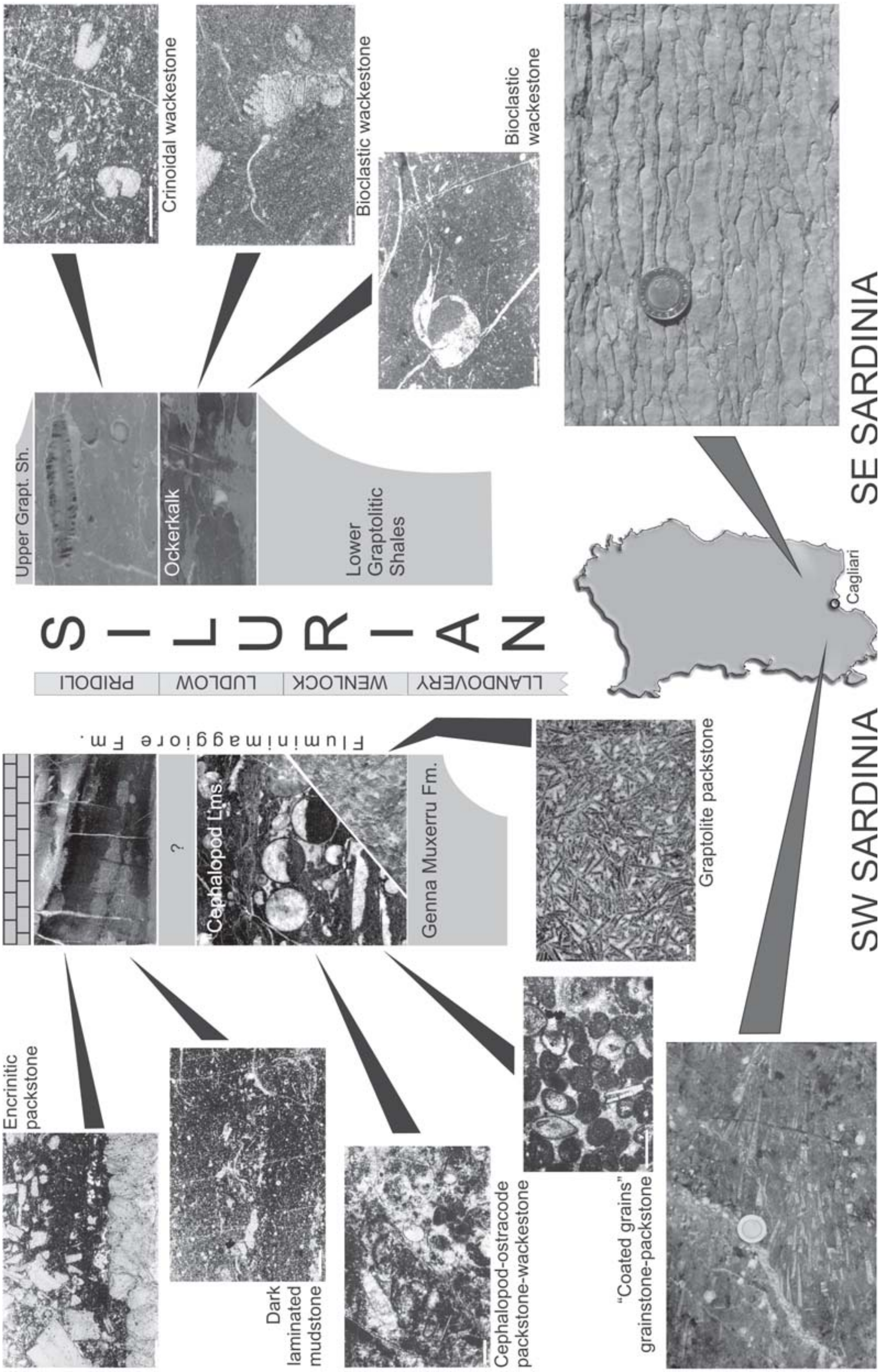
In a project on the Lau event (Jeppsson et al., 2002), $\delta^{13}C$ and $\delta^{18}O$ isotope samples have been collected from the Silius section. Researches are still in progress, but preliminary data, even if slightly weakened by metamorphism, appear useful for documenting variations in a deep water mid-latitude environment.

The explanation for a so different nature of the calcareous units exposed in southeastern and southwestern Sardinia has never been fully given, but certainly should consider also other South-European areas belonging (or close) to the northern Gondwana margin where the two limestone-types have also been reported. Similar facies differences, at least in the limestone development, occur in fact also in the Carnic Alps and in Bohemia and two distinct Silurian facies suites in the Iberian Peninsula were reported by Gutièrrez-Marco et al. (1998). The existence of a multivaried environmental setting in the Silurian appears therefore highly plausible.

Devonian cover

The Fluminimaggiore Fm. of southwestern Sardinia extends up to the earliest Devonian (earliest Lochkovian) and is covered by Devonian nodular and massive limestones, alternating with compact dark siltstones and shales, of the Mason Porcus Formation. In southeastern Sardinia, the calcareous Ockerkalk is followed by graptolitic shales, already

Fig. 4 - Generalized stratigraphical columns, outcrop view of the calcareous units and their main microbiofacies for the Silurian of southwestern and southeastern Sardinia. Microfacies scale bar = 1 mm (modified after Ferretti & Serpagli, 1996a).


Crinoidal wackestone
Bioclastic wackestone
Bioclastic wackestone
Upper Grapt. Sh.
Ockerkalk
Lower Graptolitic Shales
S I L U R I A N
PRIDOLI
LUDLOW
WENLOCK
LLANDOVERY
Fluminimaggiore Fm.
?
Cephalopod Lms.
Genna Muxerru Fm.
Graptolite packstone
Cagliari
SE SARDINIA
SW SARDINIA
Encrinitic packstone
Dark laminated mudstone
Cephalopod-ostracode packstone-wackestone
"Coated grains" grainstone-packstone

Devonian in age, known informally as Upper Graptolitic Shales, composed of alum slates only (Barca & Jaeger, 1990). The thickness of this unit is estimated in about 30 m (Jaeger, 1977). Planktonic graptolites are the only abundant fossils of the black shales, but rare *Ceriatocaris* (Jaeger, 1977) and a single specimen of pterineid bivalve (Barca & Jaeger, 1990) have also been reported from this unit. Crinoidal stems and calyces and possible loboliths (Barca & Jaeger, 1990, fig. 9; Piras et al., 2009) occur in the lower part of the Upper Graptolitic Shales.

Acknowledgements

Funding for this work was provided by MIUR-PRIN 2007 (*Analysis of stratigraphic, palaentological and structural features of the Hercynian basement and the Tertiary cover in Sardinia and Calabria, as a contribution to the geodynamic reconstruction of the central-western Mediterranean basin*).

References

Barca S., Corradini C., Ferretti A., Olivieri R. & Serpagli E. (1995). Conodont biostratigraphy of the "Ockerkalk" (Silurian) from Southeastern Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 100 (1994): 459-476.

Barca S., Ferretti A., Massa P. & Serpagli E. (1992). The Hercynian Arburese Tectonic Unit of SW Sardinia. New stratigraphic and structural data. *Rivista Italiana di Paleontologia e Stratigrafia*, 92 (3): 119-136.

Barca S. & Jaeger H. (1990). New geological and biostratigraphical data on the Silurian in SE-Sardinia. Close affinity with Thuringia. *Bollettino della Società Geologica Italiana*, 108 (1989): 565-580.

Corradini C., Ferretti A. & Serpagli E. (1998). Wenlock and Pridoli conodonts from Argiola, East of Domusnovas. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60 (Special Issue): 194-198.

Corradini C., Ferretti A. & Serpagli E. (2002). The Gerrei tectonic Unit (SE Sardinia, Italy). *In* Cherchi A., Corradini C. & Putzu M.T. (Eds.), Sardinia Field Trip – Palaeontology & Stratigraphy. *Rendiconti della Società Paleontologica Italiana*, 1: 69-76.

Ferretti A. (1989). Microbiofacies and constituent analysis of Upper Silurian-Lowermost Devonian limestones from Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 28 (1): 87-100.

Ferretti A., Corradini C. & Serpagli E. (1998). Wenlock-Ludlow conodonts from Perd'e Fogu (Fluminimaggiore). *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60 (Special Issue): 156-167.

Ferretti A., Gnoli M., Kriz J. & Serpagli E. (1995). The Silurian and early Devonian in south-west Sardinia. *In* Paleobenthos Guidebook. *Rendiconti del Seminario della Facoltà di Scienze dell'Università di Cagliari*, 65 (suppl.): 106-117.

Ferretti A. & Kriz J. (1995). Cephalopod limestone biofacies in the Silurian of the Prague Basin, Bohemia. *Palaios*, 10 (3): 240-253.

Ferretti A. & Serpagli E. (1996a). Geological outline, community sequence and paleoecology of the Silurian of Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 102 (3): 353-362.

Ferretti A. & Serpagli E. (1996b). Unusual graptolitic limestones from the Silurian of SW Sardinia. *In* James Hall Meeting Volume, 2nd International Symposium on the Silurian System, Rochester, New York, August 4-9: 52.

Gnoli M. (1993). Occurrence of middle-late Silurian Nautiloids from S. Basilio area (Gerrei, SE Sardegna). *Bollettino del Museo Regionale di Scienze Naturali di Torino*, 10 (1992): 265-269.

Gnoli M., Parea G.C., Russo F. & Serpagli E. (1980). Palaeoecological remarks on the "*Orthoceras* limestone" of Southwestern Sardinia (Middle-Upper Silurian). *Memorie della Società Geologica Italiana*, 20 (1979): 405-423.

Gutièrrez-Marco J.C., Robardet M. & Piçarra J.M. (1998). Silurian Stratigraphy and Paleogeography of the Iberian Peninsula (Spain and Portugal). *In* Gutièrrez-Marco J.C. & Rábano I. (Eds.), Proceedings 6th International Graptolite Conference (GWG-IPA) & 1998 Field Meeting, IUGS Subcommission on Silurian Stratigraphy. *Temas Geológico-Mineros ITGE*, 23: 13-44.

Jaeger H. (1977). The Silurian-Devonian boundary in Thuringia and Sardinia. *In* Martinsson A. (Ed.), The Silurian/Devonian boundary. IUGS, A (5): 117-125.

Jeppsson L., Mawson R., Simpson A., Talent J.A., Andrew A., Withford D. & Corradini C. (2002). The Lau global extinction Event (late Silurian): lithologic, conodont and isotope data and implications. *In* IPC2002. *Geological Society of Australia*, Abstract series, 68: 222-223.

Kriz, J. (1999). Bivalvia dominated communities of Bohemian type from the Silurian and Lower Devonian carbonate facies. *In* Boucot A.J. & Lawson J.D. (Eds.), Paleocommunities - a case study from the Silurian and Lower Devonian: 229-252. Cambridge University Press.

Kriz J. & Serpagli E. (1993). Upper Silurian and Lowermost Devonian Bivalvia of Bohemian type from Western Sardinia. *Bollettino della Società Paleontologica Italiana*, 32 (3): 289-347.

Loydell, D.K. (1998). Early Silurian sea-level changes. *Geological Magazine*, 135 (4): 447-471.

Melchin M.J., Koren‘ T.N. & Storch P. (1998). Global diversity and survivorship patterns of Silurian graptoloids.- *In* Landing E. & Johnson M.E. (Eds.), Silurian Cycles: linkages of dynamic processes in the atmosphere and oceans. *New York State Museum Bulletin,* 491: 165-182.

Meneghini G. (1857). Paléontologie de l’Ile de Sardaigne. *In* Lamarmora A., Voyage en Sardaigne, 3: 1-584; Imprimerie Royal, Torino.

Ogg J.G., Ogg G. & Gradstein F.M. (2008). The Concise Geologic Time Scale. 177 pp., Cambridge University Press.

Palmer D. & Gnoli M. (1985). A preliminary report on new micropaleontological discoveries in the Silurian of Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 23 (2) (1984): 221-238.

Pittau P. & Del Rio M. (2000). Wenlock Chitinozoans of SE Sardinia (Italy). *Bollettino della Società Paleontologica Italiana*, 39 (3): 257-291.

Pittau P., Del Rio M., Aresu V. & Deidda D. (1998). Wenlock Chitinozoa of the Goni Section. *In* Pittau P. (Ed.), Palynological Research in the Sardinian Basement, Field Trip Guide-book: 69-79.

Serpagli E., ed. (1998). Sardinia Guide-book. Seventh International Conodont Symposium held in Europe. Giornale di Geologia, 60 (Special Issue), 212 pp.

Storch P. (1998). Biostratigraphy, palaeobiogeographical links and environmental interpretation of the Llandovery and Wenlock graptolite faunas of peri-Gondwanan Europe. *In* Gutièrrez-Marco J.C. & Rábano I. (eds), Proceedings 6th International Graptolite Conference (GWG-IPA) & 1998 Field Meeting, IUGS Subcommission on Silurian Stratigraphy. *Temas Geológico-Mineros ITGE*, 23: 126-129.

Storch P. & Piras S. (2009). Silurian graptolites of Sardinia: assemblages and biostratigraphy. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 77-93.

Storch P. & Serpagli E. (1993). Lower Silurian Graptolites from Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 32 (1): 3-57.

Storch P., Serpagli E. & Barca S. (2002). Silurian graptolites of the *spiralis* and *lapworthi* biozones (upper Telychian, Llandovery) in the Sulcis area, SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 41 (2-3): 97-107.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 67-76

Silurian Palaeogeography of northern Gondwana: where was Sardinia at that time?

ANNALISA FERRETTI, GIACOMO OGGIANO, CARLO CORRADINI, PETR STORCH

A. Ferretti - Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia, largo S. Eufemia 19, I-41100 Modena (Italy); ferretti@unimore.it

G.. Oggiano - Dipartimento di Scienze Botaniche Ecologiche e Geologiche, Università di Sassari, Via Muroni 25, 07100 Sassari (Italy); giacoggi@uniss.it

C. Corradini - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); corradin@unica.it

P. Storch - Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojova 269, 165 02 Praha 6 (Czech Republic); Storch@gli.cas.cz

ABSTRACT - An unambiguous collocation of the actual European sectors in Silurian times is still far from accepted. The most recently published data appear to contradict and disprove current models. The position of Sardinia within this ill-defined scenario is still unclear.

KEY WORDS - Silurian, Northern Gondwana, Southern Europe, Palaeogeography.

INTRODUCTION

The present-day geographic configuration of Europe was never in existence at any point during the Palaeozoic. The actual setting arose from a collage of diverse terranes, progressively assembled within the continent of Europe through a long process which culminated in the Alpine Orogeny (Cocks & Torsvik, 2006). In order to reconstruct the principal ancient configurations, different scientific approaches have been traditionally proposed. The analysis of faunal affinity between geographic sectors, as well as studies on palaeomagnetism, sedimentary successions, volcanic suites and structural evidence have been used to produce a kinematically valid series of successive palaeomaps (see for example Fig. 1 after http://www.geodynamics.no/PLATEMOTIONS/500-400).

A multidisciplinary approach, embracing and comparing results across vast time intervals, has recently provided new data for discussion of this intriguing topic and justifies this brief overview. In this still tentative global geographic scenario, the role of Sardinia, as well as that of many adjacent sectors, has not yet been established with certainty.

THE GEOGRAPHIC CONFIGURATION OF EUROPE

The Silurian is the shortest period of the Palaeozoic Era, lasting only 27 Ma, about half the duration of the Cambrian or the Devonian. At that time, the equatorial belt was occupied by a series of large continents, that had maintained a generally consistent position confirmed by palaeomagnetic data. Laurentia was located across the equator, while Baltica was placed in the southern subtropical belt, having the famous limestones and bioherms of Gotland positioned at about 20°S in the Wenlock (Claesson, 1979; Trench & Torsvik, 1991). The opening of the Rheic Ocean caused the detachment of Avalonia (embracing part of eastern North America and part of North Europe) from Gondwana in the Ordovician, as revealed by changing faunal affinities of trilobites and brachiopods (Cocks & Fortey, 1982, 1990) and by palaeomagnetic data. Avalonia occupied tropical palaeolatitudes in the Silurian (Cocks & Torsvik, 2006). The Iapetus Ocean separated Laurentia from Baltica and Avalonia. By the late Silurian (Cocks & Torsvik, 2006), Baltica, Avalonia and Laurentia joined together to give birth to the supercontinent of Laurussia.

One of the most controversial topics in recent palaeogeographic reconstructions of the Silurian regards the very large palaeocontinent of Gondwana and especially its northern margin with a number of derived peri-Gondwanan terranes of little known history and barely identifiable palaeogeographic configuration. Palaeomagnetic data were not able to provide an unequivocal solution as two diverse polar wander paths were proposed (Robardet, 2003). For that time, most of southern Europe has been commonly located at moderately high latitudes, in an ambiguous "northern Gondwana" setting, according to palaeontological affinities and to sedimentological evidence that had documented a glaciation and proximity to the South Pole in the Late Ordovician. A series of peri-Gondwanan terranes, originally integral parts of Gondwana, have been progressively recognized and located North of northern Gondwana along the southern margin of the Rheic Ocean. At various times in the Palaeozoic, these terranes possibly separated and rifted from it. Their existence is today under discussion, as strong criticism has been put forward by so-called "palaeogeographical splitters" (Servais, 2007).

Stampfli & Borel (2002) proposed an integrated approach to Palaeozoic and Mesozoic palaeogeographies, combining the analysis of dynamic plate boundaries, plate buoyancy and ocean spreading rates with major tectonic and magmatic events. They introduced the concept of the Hun Superterrane as a ribbon-like terrane extending for more than 10,000 km, embracing the Variscan terranes spread along the Gondwana margin, and following the opening of a former peri-Gondwanan ocean – the Prototethys. Stampfli et al. (2006) and von Raumer & Stampfli (2008) subsequently post-dated to the Devonian the detachment of these terranes, renaming those composing future European sectors as a Galatian terrane (Fig. 2). These terranes started their drift to Laurussia in the earliest Devonian, following the opening of the Palaeotethys Ocean after a long rifting phase began in the Late Ordovician.

Among those terranes located along the northern margin of Gondwana, Armorica, Perunica and the eastern Alps represent crucial units. Parts of Spain and France, together with minor other geographic sectors, had been included in Armorica or the Armorican Terrane Assembly (ATA), situated North of the northern margin of Gondwana according to palaeomagnetic (Van der Voo, 1979, 1982; Tait et al., 1997) and faunistic data (Fortey & Cocks, 2003). Tait et al. (2000) suggested that Armorica began a 4000 km North drift separating from Gondwana in the Late Ordovician. Robardet (2003), in a critical review of palaeomagnetic data that had supported Armorica's existence and palaeoclimatic and palaeobiogeographic records found no evidence for an ocean between Armorica and Gondwana, suggesting that "the concept of an Armorica microplate can thus be considered a fiction" and that southern European regions remained along the northern margin of the Gondwana mainland till the Devonian. Linnemann et al. (2004) recently confirmed this view by the study of Nd-isotope data of Late Neoproterozoic to Early Carboniferous sedimentary rocks of Saxo-Thuringia, detecting no significant change in sediment provenance from the Neoproterozoic to the Early Carboniferous. According to the authors, several sectors of the pre-Variscan basement in western and Central Europe, usually

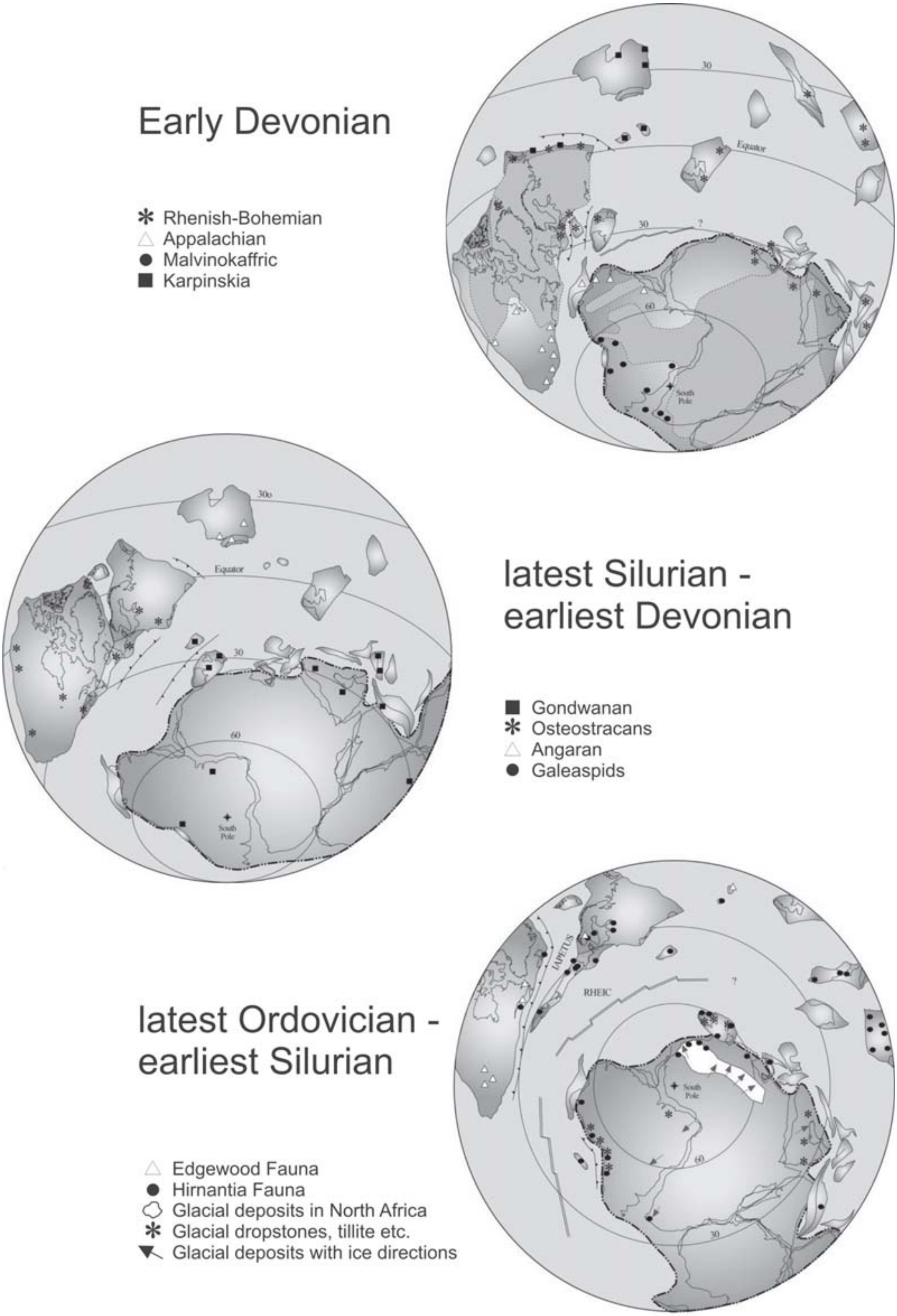


Fig. 1 - Main palaeogeographic reconstructions of the latest Ordovician-Early Devonian (after Torsvik, http://www.geodynamics.no/PLATEMOTIONS/500-400).

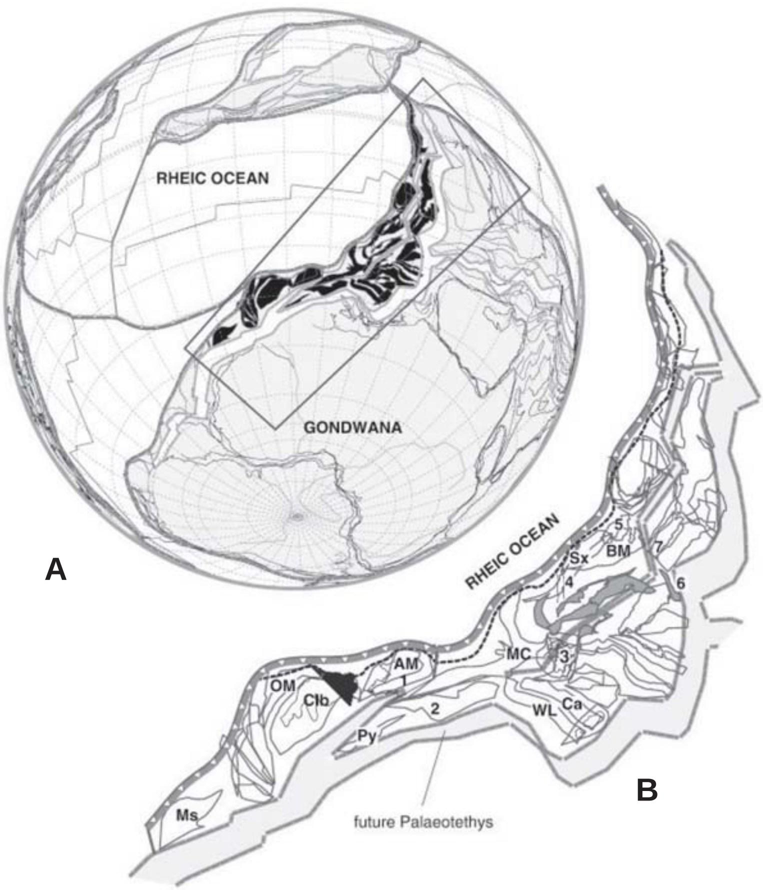


Fig. 2 - A. Global tectonic situation at the beginning of the Devonian. B. Detail of A illustrating the Galatian terrane assemblage. 1: Southern Brittany; 2: North Spain; 3: Sardinia; 4: S. Black Forest; 5: Barrandian; 6: Carnic Alps; 7: Graz Palaeozoic. AM: Armorican Massif; BM: Moldanubian part of the Bohemian Massif; Ca: Cantabrian Zone; CIb: Central Iberia; MC: French Massif Central; Ms: Meseta; OM: Ossa Morena Zone; Py: Pyrenees; Sx: Saxothuringian; WL: Westasturian Leonese Zone (after von Raumer & Stampfli, 2008).

assigned to Armorica, were still attached to Gondwana, “which makes Armorica a remnant of a “Greater Africa” in Gondwanan Europe” (Linneman et al., 2004).

The Perunica microplate, containing the classic Prague Synform in the southeastern Barrandian Region, was originally recognized by Havlicek et al. (1994) on the basis of its peculiar brachiopod and trilobite fauna and by palaeomagnetic data (Krs et al., 1986, 1987; Tait et al., 1994). Comparable to other areas of peri-Gondwana or northern Gondwana, even for Perunica a long drift from high southern to low northern latitudes was supposed after its detachment from the main continent in the Early Ordovician. The existence of Perunica as an independent palaeoplate was recently challenged by Servais & Lehnert (2006) who stated that Perunica was only a part of northern Gondwana.

Sediments of Silurian age are present in the eastern Alps (Austria and northern Italy), with three locations north of an important Alpine structural divide – the Periadriatic Line, and in the Carnic Alps south of the latter, in the present-day northern part of the Italia

Terrane, also called the Apulia Terrane s.l. (Stampfli et al., 1998; Cocks & Torsvik, 2002). Palaeomagnetic data indicates a palaeolatitude of 30–40°S for the Silurian (Schönlaub, 1997). The Proto-Alps in the Late Ordovician were not part of northern Gondwana but a separate (peri-Gondwanan) terrane (Schätz et al., 2002). Histon et al. (2007) recently analyzed 97 K-bentonite levels from the Austrian Carnic Alps, ranging in age from the Late Ordovician to the Early Devonian. They attributed most of the K-bentonites to widespread rifting related volcanism, which possibly persisted till the end of the Middle Devonian, having its source in the peri-Gondwanan area.

THE SARDINIA CORSICA MICROPLATE WITHIN THE SOUTH VARISCAN REALM

As for the Sardinia-Corsica Microplate (SCM), studies so far conducted have not provided an unequivocal position. The SCM was placed either in Armorica (e.g., Cocks & Torsvik, 2002) or in Gondwana according to geological constraints (Matte, 2001).

The present-day arrangement of the South Variscan Realm (SVR) first of all results from a several hundred- kilometre shift of the Variscides away from Bohemia due to the large clockwise rotation-translation of Gondwana towards North America (Bard, 1997). During this shift, which occurred in Westphalian-Stephanian times, several blocks spread out along a strike-slip dextral mega shear zone that displaced the Sardinia-Bohemia Virgation (Fig. 3) (Bellot, 2005). Moreover, during the Alpine cycle, further dispersion resulted from Tethyan oceanization, Alpine collision and opening of the Mediterranean back-arc basins.

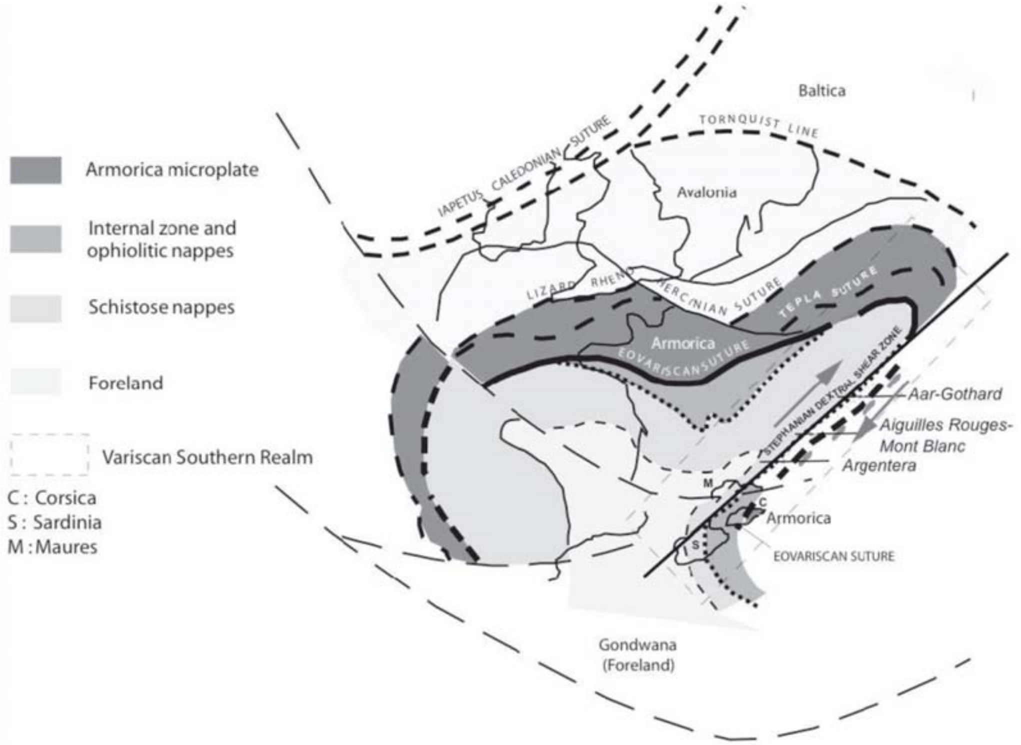


Fig. 3 - Late Carboniferous (Stephanian) arrangement of the Variscan belt (after Rossi et al., in press, mod).

Blocks within the SVR share, however, common characteristics such as the association of low-grade Pan-African-Cadomian basements, Eo-Variscan HP metamorphic events and presence of Mg-K granites. Among these fragments, the Sardinia-Corsica Microplate (SCM) exhibits one of the best-preserved segments of the Variscides. A transect across it gives a remarkable and constructive picture for the reconstruction of the "Southern Variscan Realm" (SVR) from Bohemia through the Alps, the Maures Massif, the SCM and southward to Calabria and Kabylie.

When the SCM is restored to its original position, before the Burdigalian rotation, several fits are found between the Maures Massif and northwestern Sardinia. These concern collision-related, prograde zoneography and a similar post-collision evolution of the Variscan basement (Buzzi et al., 2007). As for the pre-Variscan evolution, several sedimentary and magmatic features are shared by the different units of the Maures and Sardinia including Cambro-Ordovician metasandstones, Lower Ordovician felsic igneous rocks, Upper Ordovician alkaline metabasite, Silurian, graptolite bearing, black shales (Bellot, 2005 and bibliography therein). All these common features allow the Maures, SCM and – after the restoration of the Stephanian dextral shear – also part of Bohemia to be considered as belonging to the same geographic domain.

Von Raumer & Stampfli (2008), besides the report of the well-known calcalkaline Ordovician magmatism, do not consider other evidence from SCM in the reconstruction of the North Gondwana margin evolution. According to their complex pattern, local back-arcs basins, or intra-continental rifts, developed in the Early Cambrian and were followed by Late Cambrian-Early Ordovician closure, and, in turn, by Mid-Ordovician extension, with a large-scale volcanic activity and opening of Palaeotethys. During this time period, the future Hun Superterrane began the drift away from the eastern Gondwana margin. The passive margin of the remaining Gondwana was composed of the Galatian superterranes, constituents of the future Variscan basement areas. This reconstruction hardly fits the field evidence and the geochronological and petrological data of the Sardinia Variscides. Within the Sardinia-Corsica segment of the Variscan chain, Cappelli et al. (1992), Carmignani et al. (1994) and Carmignani (2001), considered the belt marked by the occurrence of MORB-derived eclogites (Posada-Asinara Line) as a tract of the South-Variscan suture, tectonically transported on the Gondwana crust. This belt is sandwiched between the hinterland ("Armorica" crust), cropping in Corsica at Argentella, and the Nappe Zone of the Sardic segment of the Variscan Chain (North Gondwana Margin) and is rooted in the discontinuity, stitched by the Mg-K plutonic association, that actually can separate two different terranes. The age of the Mg-K granites (in the range of 340 My) predates the dextral strike-slip shear zone that displaced Sardinia from Bohemia; as a fact similar Mg-K intrusions crop out from South Bohemia throughout Western Alps down to Corsica, marking the south Variscan suture (Rossi et al., in press).

Before the Variscan collision - bracketed between the Tournasian and Westphalian - according to the sequences exposed in Sardinia, the North Gondwana margin exhibits sedimentary aspects typical of passive margin since the Ediacarian. Then the SCM, comprised in this margin, experienced the onset of an Andean type magmatic arc (Di Pisa et al., 1992; Carmignani et al., 1994; Carmignani, 2001) during the Middle Ordovician. The related calcalkaline products are sub-aerial; they postdate the Sardic phase (post Arenig) and pre-date the Caradoc-Ashgillian transgressive sequence topped with Hirnantian glaciomarine deposits (Leone et al., 1991; Oggiano & Mameli, 2006). Hence no evidence of Cambrian ocean closure and/or evidence for Middle Ordovician rifting originate from the Palaeozoic of Sardinia. Conversely the onset of a rift, after the collapse of the magmatic arc, could have invested the North Gondwana margin starting from Late Ordovician times as testified by alkaline (Ricci & Sabatini, 1978; Di Pisa et al., 1992) metabasalts and epiclastites interbedded within Upper Ordovician and Lower Silurian deposits (Gattiglio & Oggiano, 1990; Oggiano & Mameli, 2006).

If the detachment of "Armorica" or ATA from North Gondwana ever occurred in the Early Palaeozoic, it must be placed in the early Silurian. In any case whether the intervening oceanic space and the related latitudinal gap between Gondwana and "Armorica" shelves was wide enough to support faunal differentiations is to be established. For sure, assuming current spread rates in back arc basin and oceanic rifts, until the early Silurian North Gondwana and its nearby areas - at least those involved in SVR - must be set at high latitude. In fact Late Ordovician glacial deposits occur also in Brittany (Picarra et al., 2002), Corsica (Barca et al., 1996) and Thuringia (Erdtmann, 1991) within crust sectors, which all have to be placed in the ensemble of terranes that detached from Gondwana and accreted to Laurussia.

The rich faunal content of the Silurian sequences, exposed especially in southwestern Sardinia, has enabled palaeobiogeographic considerations. The rich cephalopod fauna collected from southwestern Sardinia reveals clear affinity with Bohemia (Serpagli & Gnoli, 1977; Gnoli, 1987, 1990, 1994, 2003), with 36 species (of 55 total) in common (Gnoli, 1990). Q-mode cluster analysis was applied to estimate faunal similarities between Silurian-Early Devonian nautiloid assemblages from northern Gondwana (Gnoli, 2003). According to these data, major faunal similarity exists between southwestern Sardinia and the Prague Basin (0.89), followed by similarity between southwestern Sardinia, the Prague Basin and the Carnic Alps (0.70).

Similar conclusions had been already suggested by the analysis of bivalves. Gortani (1923) stressed that the bivalve fauna collected in southwestern Sardinia was of the same type as that occurring in the Carnic Alps and Bohemia. Kriz & Serpagli (1993) further detailed the close affinity of the Silurian and earliest Devonian bivalves of southwestern Sardinia and Bohemia, suggesting the existence of direct connections between the two areas, with only minor differences for the late Ludlow-earliest Pridoli attributed to a diverse subsidence of the basin floor in Sardinia.

A gradual faunistic homogenization in the Silurian was documented by a statistical and graphical study on Orthida brachiopods (Tychsen & Harper, 2004) from the major terranes of the Greater Iapetus Ocean Region (including the European Massifs, Core Gondwana, Avalonia, Baltica and Laurentia). This phase was later followed by a successive differentiation in two distinct faunal associations of low-mid and high latitudes. While the peri-Gondwanan European areas appear to have maintained a faunal integrity, remarkable is the loss of affinity of Bohemia with these sectors, possibly indicating a movement of a distinctive terrane.

Graptolites from southeastern Sardinia have been compared with coeval graptolite assemblages recorded in the Saxo-Thuringian Zone of the Bohemian Massif and those from other pelagic deep-water European areas (Barrandian, Alps, Carpato-Balkanids, Ossa Morena Zone, Scania, Bornholm and Great Britain; Barca & Jaeger, 1990). Close links with Barrandian and, in particular, Saxo-Thuringian graptolite faunas are obvious. In turn, some graptolite taxa of Llandovery age, common for North African Silurian shelf, Central Iberian and Ossa Morena zones of Hesperian Massif, and Brittany, are missing in Sardinia, Bohemia and Thuringia (Storch & Massa, 2007). Rickards et al. (1990) recognized a specific graptolite Mediterranean Subprovince neighbouring with Rheic Subprovince in the north and embracing North Africa and the whole Variscan Europe except for Bohemia. Storch (1998) assigned Bohemia and other terranes of the Variscan Europe to "Graptolite province of peri-Gondwanan Europe" with graptolite fauna transitional between low-diversity cold-water, shelfal fauna of North Africa and high-diversity, presumably sub-tropical, fauna of Avalonia and Baltica. Minor faunal differences among the respective terranes may be assigned to depth and nutrient-related constraints on graptolite distribution (Storch, 1998).

If Silurian data appear to indicate a rather cosmopolitan situation, much more defined was the situation in the Late Ordovician. Analysis of the brachiopod fauna (Havlicek et al., 1987) of Katian (early Ashgillian) age revealed substantial differences between the closely-related brachiopod associations of Sardinia and the Carnic Alps from that of the Barrandian area, as the "typical" Mediterranean (Bohemian-Moroccan) elements were subordinate in the first two regions, where invasion of North European warm-water elements was also documented by genera which are completely absent from the North African regions. Similar conclusions were also derived from Late Ordovician conodonts (Ferretti & Serpagli, 1998), stressing strong affinity of Sardinia and the Carnic Alps for the extreme paucity of markers of the Mediterranean Province and the presence of low-latitude genera, already reported in sectors of the conodont British Province (*sensu* Sweet & Bergström, 1984). Vennin et al. (1998) and Villas et al. (1999) had located Sardinia in the Late Ordovician at about 50 degrees South, in strict connection with the eastern Pyrennes, Montagne Noire and Catalonia, on the basis respectively of the main sedimentary facies, and of the *Hirnantia* brachiopod Fauna distribution. The late Katian *Foliomena* brachiopod fauna, that occurs in the Barrandian area and includes many brachiopod and trilobite taxa common in Avalonia and Baltica (Havlicek & Mergl, 1982; Storch & Mergl, 1989), is absent, in turn, in other parts of peri-Gondwanan Europe.

ACKNOWLEDGMENTS

We acknowledge with pleasure Kathleen Histon for critical reading and useful comments and Paolo Serventi for graphic support. This paper represents a contribution to the IGCP Projects n. 499 "Devonian sea-land interactions: evolution of ecosystem and climate" and n. 503, "Ordovician palaeogeography and palaeoclimate".

Funding for this work was provided by MIUR-PRIN2007 (*Analysis of stratigraphic, palaeontological and structural features of the Hercynian basement and the Tertiary cover in Sardinia and Calabria, as a contribution to the geodynamic reconstruction of the central-western Mediterranean basin*).

REFERENCES

BARCA S., DURAND-DELGA M., ROSSI P., STORCH P. (1996). Les micaschistes panafricains de Corse et leur couverture paléozoïque: leur interprétation au sein de l'orogène varisque sud-européen. *Comptes Rendus de l'Académie des Sciences de Paris*, IIa, 322: 981-989.

BARCA S. & JAEGER H. (1990). New geological and lithostratigraphical data on the Silurian of SE Sardinia. Close affinity with Thuringia. *Bollettino della Società Geologica Italiana*, 108: 565-580.

BARD J.-P. (1997). Démembrement anté-mésozoïque de la chaîne varisque d'Europe occidentale et d'Afrique du Nord: rôle essentiel des grands décrochements transpressifs dextres accompagnant la rotation-translation horaire de l'Afrique durant le Stéphanien. *Comptes Rendus de l'Académie des Sciences de Paris*, IIa, 324: 693-704.

BELLOT J.-P. (2005). The Palaeozoic evolution of the Maures massif (France) and its potential correlation with others areas of the Variscan belt: a review. *In* Carosi R., Iacopini D. & Rosenbaum G. (Eds.), The southern Variscan belt. *Journal of the Virtual Explorer*, 19, paper 4, doi:10.3809/jvirtex.2005.00116.

BUZZI L., GAGGERO L., FUNEDDA A., OGGIANO G. & TIEPOLO M. (2007). Zircon geochronology and Sm-Nd isotopic study of the Ordovician magmatic event in the southern Variscides (Sardinia). *Geologie de la France*, 2 (Meeting on Mechanics of Variscan Orogeny: a modern view on orogenic research): 73.

CAPPELLI B., CARMIGNANI L., CASTORINA F., DI PISA A., OGGIANO G. & PETRINI R. (1992). A Hercynian suture zone in Sardinia: geological and geochemical evidence. *Geodinamica Acta*, 7: 31-43.

CARMIGNANI L. (2001). Geologia della Sardegna. *Memorie descrittive della Carta Geologica d'Italia*, LX. Servizio Geologico d'Italia, Roma.

CARMIGNANI L., CAROSI R., DI PISA A., GATTIGLIO M., MUSUMECI G., OGGIANO G. & PERTUSATI P.C. (1994). The Hercynian chain in Sardinia (Italy). *Geodinamica Acta*, 7 (1): 31-47.

CLAESSON K.C. (1979). Early Palaeozoic geomagnetism of Gotland. *Geologiska Föreningens i Stockholm Förhandlingar*, 101: 149–155.

Cocks L.R.M. & Fortey R.A. (1982). Faunal evidence for oceanic separations in the Palaeozoic of Britain. *Journal of the Geological Society of London*, 139: 465-478.

Cocks L.R.M. & Fortey R.A. (1990). Biogeography of Ordovician and Silurian faunas. *In* Mc Kerrow W.S. & Scotese C.R. (Eds.), Palaeozoic Palaeogeography and Biogeography. *Geological Society of London, Memoirs*, 12: 97-104.

Cocks L.R.M. & Torsvik T.H. (2002). Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. *Journal of the Geological Society*, London, 159: 631-644.

Cocks L.R.M. & Torsvik T.H. (2006). European geography in a global context from the Vendian to the end of the Palaeozoic. *In* Gee D.G. & Stephenson R.A. (Eds.), European Lithosphere Dynamics. *Geological Society, London, Memoirs*, 32: 83-95.

Di Pisa A., Gattiglio M. & Oggiano G. (1992). Pre-Hercynian magmatic activity in the nappe zone (internal and external) of Sardinia: evidence of two within plate basaltic cycles. IGCP No. 276, *Newsletter* 5: 107-116.

Erdtmann B.-D. (1991). The post-Cadomian early Palaeozoic tectonostratigraphy of Germany. *Annales Societé Géologique de Belgique*, 114: 19–43.

Ferretti A. & Serpagli E. (1998). Late Ordovician conodont faunas from southern Sardinia, Italy: biostratigraphic and palaeogeographic implications. *Bollettino della Società Paleontologica Italiana*, 37 (2-3): 215-236.

Fortey R.A. & Cocks L.R.M. (2003). Palaeontological evidence bearing on global Ordovician-Silurian continental reconstructions. *Earth Science Reviews*, 61: 245-307.

Gattiglio M. & Oggiano G. (1990). L'unità tettonica di Bruncu Nieddu e i suoi rapporti con le unità della Sardegna Sud-Orientale. *Bollettino della Società Geologica Italiana*, 109: 547-555.

Gnoli M. (1987). Revision and autoecological remarks of the species *Columenoceras grande* (Meneghini, 1857) (Nautiloidea, Orthocerida). *Bollettino della Società Paleontologica Italiana*, 26 (3): 245-250.

Gnoli M. (1990). New evidence for faunal link between Sardinia and Bohemia in Silurian time. *Bollettino della Società Paleontologica Italiana*, 29 (3): 289-307.

Gnoli M. (1994). Remarks on minor elements of the Upper Silurian cephalopod fauna of Southwestern Sardinia. *Atti della Società dei Naturalisti e Matematici di Modena*, 124 (1993): 19-26.

Gnoli M. (2003). Northern Gondwana Siluro-Devonian palaeogeography assessed by cephalopods. *Palaeontologia Electronica*, 5 (2): 19 pp.

Gortani M. (1923). Osservazioni sul Paleozoico della Sardegna. *Bollettino della Società Geologica Italiana*, 41 (1922): 362-369.

Havlicek V., Kriz J. & Serpagli E. (1987). Upper Ordovician brachiopod assemblages of the Carnic Alps, Middle Carinthia and Sardinia. *Bollettino della Società Paleontologica Italiana*, 25 (3) (1986): 277-311.

Havlicek V. & Mergl M. (1982). Deep water shelly fauna in the latest Kralodvorian (upper Ordovician, Bohemia. *Vestnik Ustredniho ustavu geologickeho*, 57 (1): 37-46.

Havlicek V., Vanek J. & Fatka O. (1994). Perunica microcontinent in the Ordovician (its position within the Mediterranean Province, series division, benthic and pelagic associations). *Sbornik Geologickych Ved, Geologie*, 46: 23-56.

Histon K., Klein P., Schönlaub H.P. & Huff W.D. (2007). Lower Palaeozoic K-bentonites from the Carnic Alps, Austria. *Austrian Journal of Earth Sciences*, 100: 26-42.

Kriz J. & Serpagli E. (1993). Upper Silurian and lowermost Devonian Bivalvia of Bohemian type from Western Sardinia. *Bollettino della Società Paleontologica Italiana*, 32 (3): 289-347.

Krs M., Krsova M., Pruner P. & Havlicek V. (1986). Paleomagnetism, palaeogeography and multi-component analysis of magnetisation of Ordovician rocks of the Barrandian in the Bohemian Massif. *Sbornik Geologickych Ved, Uzita Geofyzika*, 22: 9-48.

Krs M., Krsova M., Pruner P., Chvojka R. & Havlicek V. (1987). Palaeomagnetism, palaeogeography and the multi-component analysis of Middle and Upper Cambrian rocks of the Barrandian in the Bohemian Massif. *Tectonophysics*, 139: 1-20.

Leone F., Hammann W., Laske R., Serpagli E. & Villas E. (1991). Lithostratigraphic units and biostratigraphy of the post-sardic Ordovician sequence in south-west Sardinia. *Bollettino della Società Paleontologica Italiana*, 30 (2): 201-235.

Linnemann U., McNaughton N.J., Romer R.L., Gehmlich M., Drost K. & Tonk C. (2004). West African provenance for Saxo-Thuringia (Bohemian Massif): did Armorica ever leave pre-Pangean Gondwana?– U/Pb-SHRIMP zircon evidence and the Nd-isotopic record. *International Journal of Earth Sciences* (*Geologische Rundschau*), 93: 683-705.

Matte P. (2001). The Variscan collage and orogeny (480-290 Ma) and the tectonic definition of the Armorica microplate: a review. *Terra Nova*, 13: 122-128.

Oggiano G. & Mameli P. (2006). Diamictite and oolitic ironstones, a sedimentary association at Ordovician-Silurian transition in the north Gondwana margin: New evidence from the inner nappe of Sardinia Variscides (Italy). *Gondwana Research*, 9: 500-511.

Piçarra J.M., Robardet M., Bourahrouh A., Paris F., Pereira Z., Le Menn J., Gouvernnec R., Oliveira T. & Lardeux H. (2002). Le passage Ordovicien-Silurien et la partie inférieure du Silurien (Sud-Est du Massif Armoricain, France). *Comptes Rendus Geoscience*, 334: 1177-1183.

Ricci C.A. & Sabatini G. (1978). Petrogenetic affinity and geodynamic significance of metabasic rocks from Sardinia, Corsica and provence. *Neues Jahrbuch fur Geologie und Palaeontologie Monatschefte*: 23-38.

Rickards R.B., Rigby S. & Harris J.H. (1990). Graptoloid biogeography: recent progress, future hopes. *In* McKerrow W.S. & Scotese C.R. (Eds.), Palaeozoic palaeogeography and biogeography. *Geological Society of London, Memoir*, 12: 139-145.

Robardet M. (2003). The Armorica "microplate": fact or fiction? Critical review of the concept and contradictory palaeobiogeographical data. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 195: 125-148.

Rossi P., Oggiano G. & Cocherie A. A restored section of the "South Variscan realm" across the Corsica Sardinia Microcontinent. *CRAS Geoscience* [In press].

Schatz M., Reischmann T., Tait J., Bachtadse V., Bahlburg H. & Martin U. (2002). The Early Palaeozoic break-up of northern Gondwana, new palaeomagnetic and geochronological data from the Saxothuringian Basin, Germany. *International Journal of Earth Sciences*, 91 (5): 838-849.

Schönlaub H.P. (1997). IGCP-421 Inaugural Meeting Vienna, Guidebook. *Berichte der Geologischen Bundesanstalt*, 40: 1-134.

Serpagli E. & Gnoli M. (1977). Upper Silurian cephalopods from Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 16 (2): 153-196.

Servais T. (2007). The proliferation of early Palaeozoic peri-Gondwanan terranes: the productive work of splitters. Lyell Meeting 2007, Early Palaeozoic peri-Gondwana terranes: new insights from tectonics and biogeography, London, 21 February 2007. Programme: 16.

Servais T. & Lehnert O. (2006). Good and bad terranes: Are some methods better than others for inferring palaeogeography? *In* Programme: Abstracts and Field Excursion Guides of the Annual Meeting of project IGCP 503, Changing palaeogeographical and palaeobiogeographical patterns in the Ordovician and Silurian, Glasgow, 28 August to 4 September 2006: 44.

Stampfli G.M. & Borel G.D. (2002). A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones. *Earth and Planetary Science Letters*, 196 (1-2): 17-33.

Stampfli G.M., Hochard C. & von Raumer J. (2006). Reconstructing the Palaeozoic Gondwana margin and its redistribution – new aspects. *Geophysical Research Abstracts*, 8: 02708.

Stampfli G.M., Mosar J., Marquer D., Marchant R., Baudin T. & Borel G. (1998). Subduction and obduction processes in the Swiss Alps. *Tectonophysics*, 296 (1-2): 159-204.

Storch P. (1998). Biostratigraphy, palaeobiogeographical links and environmental interpretation of the Llandovery and Wenlock graptolite faunas of peri-Gondwanan Europe. *In* Gutiérrez-Marco J.C. & Rábano I. (Eds.), Proceedings of the Sixth International graptolite Conference of the GWG (IPA) and the SW Iberia Field Meeting 1998 of the International Subcommission on Silurian Stratigraphy (ICS-IUGS). *Temas Geológico-Mineros ITGE*, 23: 126-129.

Storch P. & Massa D. (2007). Middle Telychian (upper Llandovery, Silurian) graptolites from boreholes of northwestern Libya: Their biostratigraphic significance and palaeogeographical implication. *Geobios*, 40 (4): 535-540.

Storch P. & Mergl M. (1989). Králodvor/Kosov boundary and the late Ordovician environmental changes in the Prague Basin (Barrandian, Bohemia). *Sbornik Geologickych Ved, Geologie*, 44: 117-153.

Sweet W.C. & Bergström S.M. (1984). Conodont provinces and biofacies of the Late Ordovician. *Geological Society of America Special Paper*, 196: 69-87.

Tait J., Bachtadse V., Franke W. & Soffel H.C. (1997). Geodynamic evolution of the European Variscan fold belt: palaeomagnetic and geological constraints. *Geologische Rundschau*, 86: 585-598.

Tait J., Bachtadse V. & Soffel H. (1994). New palaeomagnetic constraints on the position of Bohemia during Early Ordovician times. *Geophysical Journal International*, 116: 131-140.

Tait J., Schatz M., Bachtadse V. & Soffel H.C. (2000). Palaeomagnetism and Palaeozoic palaeogeography of Gondwana and European terranes. *In* Franke W., Haak V., Oncken O. & Tanner D. (Eds.), Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geological Society, London: 21-34.

Trench A. & Torsvik T.H. (1991). The Lower Palaeozoic apparent polar wander path for Baltica: palaeomagnetic data from Silurian limestones of Gotland, Sweden. *Geophysical Journal International*, 107 (2): 373-379.

Tychsen A. & Harper D.A.T. (2004). Ordovician-Silurian distribution of Orthida (Palaeozoic Brachiopoda) in the Greater Iapetus Ocean Region. *Palaeontologia Electronica*, 7 (3): 15 pp.

Van der Voo R. (1979). Palaeozoic assembly of Pangea: a new plate tectonic model for the Taconic, Caledonian and Hercynian orogenies. *Eos Transactions of the AGU*, 60: 241.

Van der Voo R. (1982). Pre-Mesozoic paleomagnetism and plate-tectonics. *Annual Review of Earth and Planetary Sciences*, 10: 191-200.

Vennin E., Álvaro J.J. & Villas E. (1998). High-latitude pelmatozoan-bryozoan mud-mounds from the late Ordovician Northern Gondwana Platform. *Geological Journal*, 33: 121-140.

Villas E., Lorenzo S. & Gutiérrez-Marco J.C. (1999). First record of a *Hirnantia* Fauna from Spain, and its contribution to the Late Ordovician palaeogeography of northern Gondwana. *Transactions of the Royal Society of Edinburgh*, 89: 187-197.

von Raumer J.F. & Stampfli G.M. (2008). The birth of the Rheic Ocean – Early Palaeozoic subsidence patterns and subsequent tectonic plate scenarios. *Tectonophysics*, 461 (1-4): 9-20.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 77-93

Silurian graptolites of Sardinia: assemblages and biostratigraphy

Petr Storch, Sergio Piras

P. Storch - Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojova 269, 165 02 Praha 6 (Czech Republic); storch@gli.cas.cz
S. Piras - Dipartimento di Scienze della Terra, Università di Cagliari, Via Trentino 51, I-09127 Cagliari (Italy); piras_srg@hotmail.com

Abstract - 155 taxa of planktic graptolites are reported from the Silurian pelagic succession of southern Sardinia, and 24 graptolite assemblage biozones are recognized and briefly described. The *Cyrtograptus insectus, Monograptus riccartonensis, Pristiograptus dubius* and *Cyrtograptus ramosus – Cyrtograptus ellesae* biozones are recorded for the first time in Sardinia; most other biozones are redefined. This is the first compilation on Sardinian graptolites that comprises critically assessed published data combined with new records.

Key words - Graptolites, Silurian, Sardinia, biostratigraphy, assemblages.

Introduction and historical overview

Offshore, largely anoxic or dysoxic Silurian sedimentary rocks, exposed discontinuously in southern Sardinia, are rich in diverse graptolite associations. Together with Corsica, Sardinia belongs to a collisional chain of Variscan Europe with strong faunal affinities to other parts of northwestern Gondwana. Lower Palaeozoic rocks were affected by Variscan tectonic deformation, metamorphism and magmatic activity. Southwestern Sardinia exhibits Silurian facies suite similar to the Barrandian area of Bohemia (Gnoli et al., 1990); southeastern Sardinia seems to have close affinities to the basinal facies of Thuringia (Helmcke, 1973; Jaeger, 1976; a.o.). This difference justifies separate treatment of the western and eastern parts of southern Sardinia. Fossiliferous localities are concentrated in the Iglesiente and Sulcis regions in the South-West, and in the Gerrei and Sarrabus subregions of the southeastern part of the island (Fig. 1).

Sardinian graptolites have been known since 1838 when General Alberto La Marmora found graptolite-bearing black shales in Goni. Those graptolites were described and figured in a monographic paper by Meneghini (1857). The wide distribution of Silurian graptolitic black shales in the Gerrei, Iglesiente and Fluminese areas was demonstrated by Taricco (1911, 1922) and Novarese & Taricco (1922). Gortani (1923a, b) published a well-illustrated monograph of the then-known Silurian graptolites of Sardinia. Biostratigraphical work based upon bed by bed sampling was carried out by Helmcke (1973) and Helmcke & Koch (1974). Jaeger (1976) correlated the graptolite-bearing Silurian sections of Sardinia with Thuringia and other parts of Variscan Europe.

Jaeger & Barca (1990) summarized graptolite records from southeastern Sardinia and recognized the *Lituigraptus convolutus* Biozone with *Cephalograptus cometa* Subzone, *Spirograptus turriculatus* Biozone with *Rastrites linnaei* Subzone, *Streptograptus crispus-Monoclimacis griestoniensis* Biozone, *Cyrtograptus lundgreni* Biozone with *Testograptus*

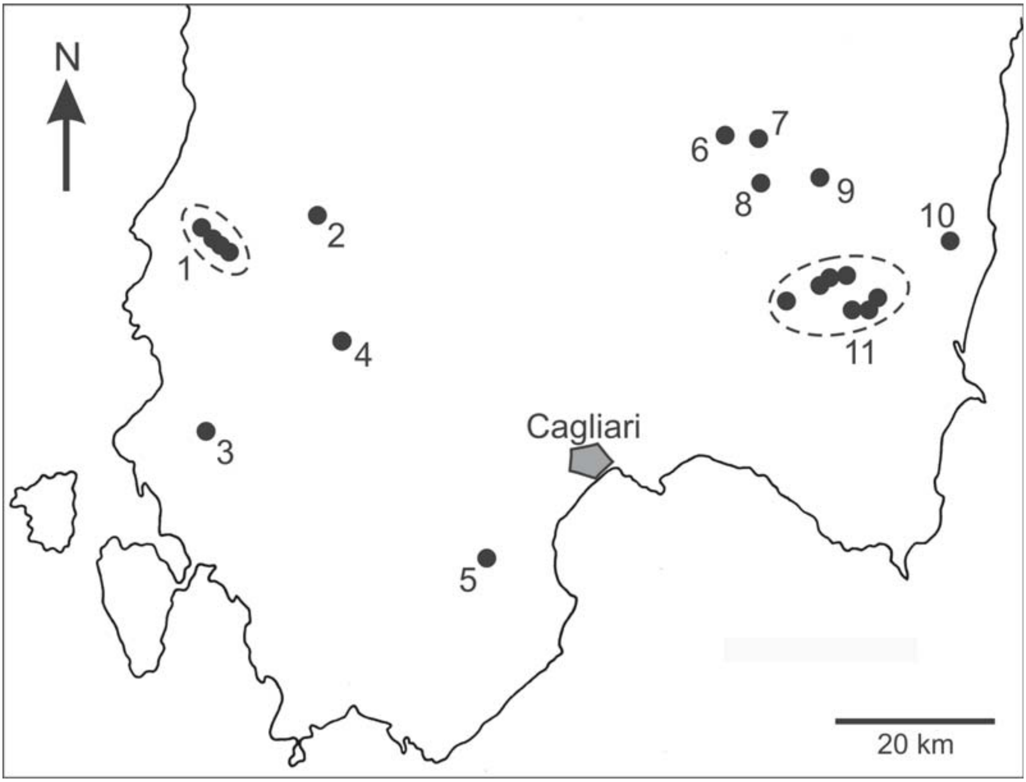


Fig. 1 - Location map of the graptolite-bearing outcrops referred to in the text: 1) Fluminimaggiore area (Cantoniera Flumini, Galemmu, Genna Quadroxius, northern outskirts of the village, Sentiero Flumini, road-cut to Mason Porcus, Terra Murus); 2) Genna Muxerru (GMX A, GMX F, GMX P); 3) Monte Cortoghiana Becciu; 4) Argiola; 5) Punta S‘Omu de Is Abis; 6) Sedda de S’Ortu; 7) Goni; 8) Cungiareddu (A and B); 9) Lantini Tunnel (Ballao-Muravera road cutting E of the tunnel); 10) Baccu Scottis, 11) Rio Ollastu Area (Baccu sa Rutta, Baccu Perdaccia, Rio Brabaisu-Rio Ollastu confluence, Rio Minderri, road section above Rio Ollastu, road-cut S of Mt. Bisaccu, Sarcilloni, SE of Punta 324, WSW of Punta 324).

testis Subzone, *Pristiograptus parvus* Biozone, *Pristiograptus dubius – Gothograptus nassa* Biozone, *Colonograptus praedeubeli* Biozone and *Colonograptus deubeli* Biozone. Their lists of graptolites were supplemented by illustrations of selected material.

Gnoli et al. (1990), followed by Storch & Serpagli (1993), paid attention to southwestern Sardinia. The latter authors described 44 lower Silurian graptolite taxa and recognized the *Parakidograptus acuminatus* Biozone, *Cystograptus vesiculosus-Coronograptus cyphus* Biozone, *Demirastrites triangulatus* Biozone, *Lituigraptus convolutus* Biozone, *Spirograptus turriculatus* Biozone, probable *Streptograptus crispus* Biozone, and *Monoclimacis griestoniensis* Biozone from the Fluminimaggiore area, Monte Cortoghiana Becciu near Barbusi, and Genna Muxerru near Gonnosfanadiga. Rickards et al. (1995) reviewed new and earlier finds of largely upper Silurian graptolites. Storch et al. (2002) described the upper Llandovery *Oktavites spiralis* and *Cyrtograptus lapworthi* biozones from a large Variscan olistolith in Sulcis area.

LOCALITIES AND PRESERVATION

Flattened Silurian graptolites are the only macrofossils preserved in the more or less siliceous, organic-rich Lower Graptolitic Shales (Barca & Jaeger, 1990; a.o.) of southeastern Sardinia. The anoxic succession of this, essentially informal lithostratigraphical unit has been subsequently affected by cleavage and/or contact-metamorphosed to various degrees. As a result, graphitic slates, siliceous shales and silicites predominate in the lower Silurian succession of this region. The Pridoli Series and most of the Ludlow are formed of peculiar, deep-water nodular limestones, the so-called Ockerkalk (e.g. Jaeger, 1976). No graptolites were found in the limestone.

Soft clayey graphitic shales and/or slates have been termed alum slates in Sardinia (Jaeger, 1976; Barca & Jaeger, 1990); highly siliceous rocks are known as lydites. Black, bedded siliceous slates are common throughout the Llandovery and Wenlock succession in the southeastern part of the island, while typical massive lydites with conchoidal fractures are confined to the Llandovery. Alum slates are present in the upper Llandovery and Wenlock.

Graptolites are common to abundant in the black shales and silicites of southeastern Sardinia. The best preserved graptolites come predominantly from siliceous shales because larger rhabdosomes and/or rhabdosome fragments are inaccessible in lydites due to the irregular conchoidal splitting which is not bedding parallel. In the alum slates, even though the graptolite rhabdosomes are commonly large and complete, tectonic deformation may prevent or complicate their identification. Thick stipes of robust monograptids without any apparent thecal detail, can be found in many exposures. All dimensions of the graptolite rhabdosome may be considerably enlarged in the alum slates, by comparison with flattened rhabdosome of the same taxon preserved in siliceous rock or limestone. Despite this tendency, fairly well preserved graptolites occur in the alum shales and slates in the Goni, Cungiareddu, Sarcilloni and Sedda de S'Ortu sections.

Silurian rocks with graptolites are widespread also in southwestern Sardinia. The Llandovery is represented by the Genna Muxerru Formation (Gnoli et al., 1990): a rather monotonous succession of black, carbon-rich shales and/or slates affected by cleavage, faulting and small-scale folding. Graptolite rhabdosomes are flattened and usually deformed in the alum slates which are exposed at several places in the vicinity of Fluminimaggiore (Terra Murus, Cantoniera Flumini, Genna Quadroxius). The specimens are silver-coloured on black bedding planes or preserved as shallow imprints infilled by black oxide on glossy grey, sheared bedding planes. At Genna Muxerru hill, near Gonnosfanadiga, the graphitic slates are often so much sheared that graptolites are undeterminable. In the same locality (outcrop GMX A of Storch & Serpagli, 1993) a distinct part of the *Spirograptus turriculatus*-*Streptograptus crispus* Biozone is developed in the form of black, fine grained greywacke with limonitized graptolite rhabdosomes preserved in partial relief. Little tectonized black shales, with well preserved flattened, almost undeformed graptolites of the *Akidograptus ascensus*-*Parakidograptus acuminatus* Biozone, are known from Monte Cortoghiana Becciu in the Barbusi – Caput Aquas area (Storch & Serpagli, 1993).

The upper Wenlock through Lower Devonian Fluminimaggiore Formation (Gnoli et al., 1990), recognized in southwestern Sardinia, consists of predominantly black, often lenticular beds of cephalopod limestones intercalated with sheared graphitic slates. Low diversity graptolite assemblages preserved in partial relief are known from the cephalopod-bearing limestones at Sentiero Flumini and Terra Murus in the Fluminimaggiore area (Gnoli & Palmer, 1985), and from Argiola, east of Domusnovas (Rickards et al., 1995).

Loose, displaced boulders of pale-coloured sparitic limestones of early Pridoli age, densely packed with monospecific three-dimensional rhabdosomes of "*Monograptus*" *parultimus* Jaeger, have been found in Fluminimaggiore (e.g. Rickards et al., 1995; see also Ferretti & Serpagli, 1996). Graptolitic limestones crowded with colonograptids and straight saetograptids originate from the same outcrop area. A similar microfacies with *Saetograptus jaegeri* Rickards, Holland & Serpagli, of mid-Ludlow age, is known from Argiola (Ferretti, 1989; Rickards et al., 1995).

In the Sulcis area of southwestern Sardinia (Punta S'Omu de Is Abis locality) a sequence of Telychian (upper Llandovery) siliceous black shales has been preserved in a large olistolith within a Culm-type Sulcis flysch complex of Variscan age (Storch et al., 2002). Shales are not affected by cleavage and yield flattened, badly to moderately well-preserved graptolites assigned to *Oktavites spiralis* and *Cyrtograptus lapworthi* biozones, along with a poor record of the *S. turriculatus* Biozone.

GRAPTOLITE ASSEMBLAGES AND BIOSTRATIGRAPHY

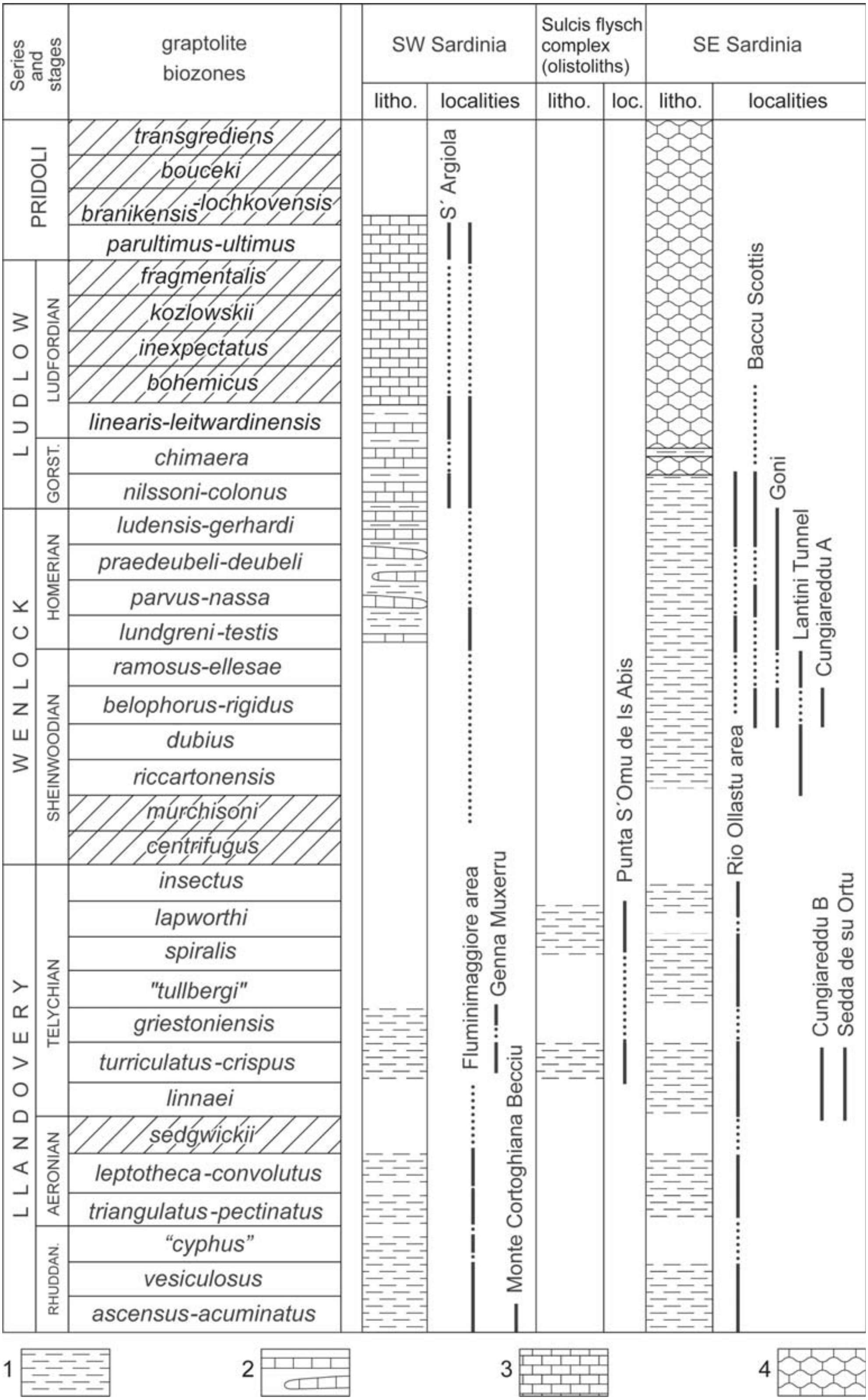
All of the Silurian shaly successions of Sardinia are affected by faulting and are often also complicated by small-scale folding and/or shear-zones. Some graptolite assemblages were found in thin, commonly lenticular bodies of less tectonically affected black shales within intensively sheared successions (e.g. Genna Muxerru GMX P). The upper and lower limits of the biozones cannot be delimited accurately due to strong tectonic deformation. Bed-by-bed sampling is further complicated by the highly variable preservation of graptolites in the alum slates and by the exceptional hardness of the lydites. Only a limited number of relatively complete and thus determinable rhabdosomes was picked up from the less tectonized siliceous shales and the lydites full of well preserved graptolites.

Taxon-range zones, in the sense of International Stratigraphic Guide (Salvador, 1994 ed.), are not applicable in such circumstances, since their recognition requires well exposed, continuous sections with common and well preserved graptolites.

The graptolite biozones described in this and all other papers on the Silurian biostratigraphy of Sardinia (see Jaeger, 1976; Barca & Jaeger, 1990; Storch & Serpagli, 1993; Rickards et al., 1995; Storch et al., 2002) are assemblage zones. Assemblage zones are distinguished by their total graptolite content, with particular importance placed on some characteristic age-diagnostic species. Each zone is named after a zonal-index taxon that is known also from other, well established European graptolite biozonations. Due to limited graptolite material and/or preservation, some classical biozones with similar assemblages had to be combined in a single, composite biozone in Sardinia (e.g. the *Akidograptus ascensus – Parakidograptus acuminatus* Biozone, *Spirograptus turriculatus – Streptograptus crispus* Biozone a.o.). Biozones in quotation marks indicate an insufficient faunal record with tentatively determined or missing zonal-index species.

Some of the 155 graptolite taxa recorded to date are left in open nomenclature; cf. and aff. are used when: 1) these qualifiers were used in the original source of reference or 2) the morphology recorded by the present authors was only comparable with or similar to

Fig. 2 - Graptolite biozonation of the Silurian formations of Sardinia with schematic lithofacies and stratigraphical ranges of the localities. Unrecorded parts of the supposed zonal scheme are hatched. Unconfirmed parts of supposed locality ranges are dotted. 1) black shales and lydites; 2) cephalopod limestone lenses; 3) platy cephalopod limestones; 4) marly nodular limestone (Ockerkalk). So far unknown intervals of the sedimentary succession are blank.


Series and stages
graptolite biozones
SW Sardinia
Sulcis flysch complex (olistoliths)
SE Sardinia
litho.
localities
litho.
loc.
litho.
localities
PRIDOLI
LUDLOW
LUDFORDIAN
GORST.
WENLOCK
HOMERIAN
SHEINWOODIAN
LLANDOVERY
TELYCHIAN
AERONIAN
RHUDDAN.
transgrediens
bouceki
branikensis-lochkovensis
parultimus-ultimus
fragmentalis
kozlowskii
inexpectatus
bohemicus
linearis-leitwardinensis
chimaera
nilssoni-colonus
ludensis-gerhardi
praedeubeli-deubeli
parvus-nassa
lundgreni-testis
ramosus-ellesae
belophorus-rigidus
dubius
riccartonensis
murchisoni
centrifugus
insectus
lapworthi
spiralis
"tullbergi"
griestoniensis
turriculatus-crispus
linnaei
sedgwickii
leptotheca-convolutus
triangulatus-pectinatus
"cyphus"
vesiculosus
ascensus-acuminatus
S' Argiola
Fluminimaggiore area
Genna Muxerru
Monte Cortoghiana Becciu
Punta S'Omu de Is Abis
Baccu Scottis
Goni
Lantini Tunnel
Cungiareddu A
Rio Ollastu area
Cungiareddu B
Sedda de su Ortu
1
2
3
4

the species concerned. Those taxa whose determinations are based upon poorly preserved material, are suffixed with a question mark.

Graptolite assemblages are mostly composite records from several localities. The primary source of reference has been cited for the respective localities. "Pers. obs." means that the present authors checked the original illustrations and/or specimens. "Unpubl. pers. obs." refers to thus far unpublished data based on material collected by the authors and their fellow workers from the University of Modena and Reggio Emilia and University of Cagliari.

Akidograptus ascensus – Parakidograptus acuminatus Biozone

Well preserved and moderately diverse graptolites of the basal Silurian biozone were found in several isolated exposures and subcrops at Monte Cortoghiana Becciu in southwestern Sardinia (Storch & Serpagli, 1993). Hirnantian strata are missing in the neighborhood and the graptolite assemblage analyzed by Storch (1996) indicates that the lowermost and the uppermost parts of the biozone are probably missing at this site, presumably cut-off by tectonics. The faunal assemblage of the middle part of the biozone, with *Akidograptus ascensus* Davies, *Parakidograptus acuminatus* (Nicholson), and *Neodiplograptus lanceolatus* Storch & Serpagli was reported also by Helmcke & Koch (1974) from southeastern Sardinia (Riu Ollastu area). However, a single specimen of *Cystograptus ancestralis* Storch which they found, was determined as *Cystograptus vesiculosus* (Nicholson) by Jaeger (1976) and Barca & Jaeger (1990), hence the whole assemblage with *A. ascensus* and *P. acuminatus* was assigned by mistake to the *vesiculosus* Biozone. A poor *ascensus-acuminatus* Biozone assemblage is known also from the Fluminimaggiore area (Storch & Serpagli, 1993).

Graptolite fauna: *Normalograptus angustus* (Perner), *Normalograptus ajjeri* (Legrand) (= *N. normalis* of Storch & Serpagli, 1993), *Normalograptus crassus* Storch & Feist (= *N. medius* of Storch & Serpagli, 1993), *Normalograptus trifilis* (Manck), *Normalograptus longifilis* (= *N. trifilis* of Storch & Serpagli, 1993, Pl. 4, fig. 8, text-fig. 7H, I, K), *Neodiplograptus parajanus* (Storch), *Neodiplograptus lanceolatus* (= *Diplograptus modestus* of Helmcke & Koch, 1974; Jaeger, 1976 and Barca & Jaeger, 1990), *Neodiplograptus apographon* Storch, *Cystograptus ancestralis* Storch (= *C. vesiculosus* of Jaeger, 1976 and Barca & Jaeger, 1990), *Sudburiagraptus cortoghianensis* (Storch & Serpagli), *Akidograptus ascensus* and *Parakidograptus acuminatus*.

Localities: Monte Cortoghiana Becciu and Fluminimaggiore area (Terra Murus) (Storch & Serpagli, 1993), Rio Ollastu area (Baccu sa Rutta) (Jaeger, 1976; Barca & Jaeger, 1990).

Cystograptus vesiculosus Biozone

Alum slate exposed along the unpaved road at Terra Murus (southwestern Sardinia) yielded some graptolites of which the zonal index *Cystograptus vesiculosus* (Nicholson) and *Rhaphidograptus toernquisti* (Elles & Wood) are the most prominent forms. Juvenile rhabdosomes of *Cyst. vesiculosus*, typified by its large sicula, were recovered, together with the species listed below, from bedded lydites at Riu Minderri in southeastern Sardinia.

Graptolite fauna: *Normalograptus normalis* (Lapworth)?, *Normalograptus rectangularis* (McCoy), *Cystograptus vesiculosus*, *Neodiplograptus lautus* Storch & Feist?, *Sudburiagraptus cortoghianensis* and *Atavograptus* cf. *gracilis* Hutt.

Localities: Fluminimaggiore area (Terra Murus, road cutting to Mason Porcus) (Storch & Serpagli, 1993), Rio Ollastu area (Rio Minderri) (unpubl. pers. obs., *non* Baccu sa Rutta reported by Barca & Jaeger, 1990).

“Coronograptus cyphus Biozone*”*

A poorly preserved graptolite fauna assignable, with some reservation, to the upper Rhuddanian *cyphus* Biozone has been reported from both southwestern (Jaeger, 1976; Barca & Jaeger, 1990) and the southeastern (Storch & Serpagli, 1993) part of Sardinia.

Graptolite fauna: *Normalograptus* cf. *normalis* (Lapworth), *Rhaphidograptus toernquisti*, *Atavograptus* sp., *Coronograptus cyphus* (Lapworth)?, *Coronograptus gregarius* (Lapworth)?, *“Monograptus” austerus* Törnquist? and *“Monograptus”* ex gr. *revolutus* Kurck.

Localities: Fluminimaggiore area (Genna Quadroxius) (Storch & Serpagli, 1993), ?Rio Ollastu area (Rio Brabaisu-Rio Ollastu confluence) (Jaeger, 1976; Barca & Jaeger, 1990).

Demirastrites triangulatus – Demirastrites pectinatus Biozone

Poor preservation in the Fluminimaggiore area and modest material from the hard lydites of Riu Ollastu area do not allow further subdivision of the lower Aeronian succession, previously referred to broad *gregarius* Biozone by Jaeger (1976).

Graptolite fauna: *Normalograptus normalis* (Lapworth)?, *Metaclimacograptus hughesi* (Nicholson), *Neodiplograptus thuringiacus* (Kirste)?, *Rhaphidograptus toernquisti*, *Pseudorthograptus* cf. *insectiformis* (Nicholson), *Petalolithus ovatoelongatus* (Kurck)?, *Coronograptus gregarius* (Lapworth), *Demirastrites triangulatus* (Harkness), *Demirastrites pectinatus* (Richter)? and *Rastrites* sp.

Localities: Fluminimaggiore area (Genna Quadroxius) (Storch & Serpagli, 1993), Rio Ollastu area (Rio Brabaisu-Rio Ollastu confluence, road section above Rio Ollastu) (Barca & Jaeger, 1990).

Pribylograptus leptotheca – Lituigraptus convolutus Biozone

Middle and upper Aeronian graptolites are present but poorly preserved in southwestern Sardinia (Storch & Serpagli, 1993). In the siliceous shales and lydites of southeastern Sardinia the specimens are only slightly deformed, but are few and fragmentary. All typical constituents of the *convolutus* Biozone assemblage were recovered by Barca & Jaeger (1990). This original *convolutus* Biozone was subdivided by Storch (1998) into two biozones in Bohemia: 1) The *convolutus* Biozone *s.s.*, characterized by the eponymous species, *Rastrites peregrinus* Barrande and *Cephalograptus cometa* (Geinitz), represents the upper part of the former biozone; and 2) the *leptotheca* Biozone which correlates with its lower part, below the first appearance of *Lituigraptus convolutus* (Hisinger). The *leptotheca* Biozone is distinguished by its index taxon, *Petalolithus praecursor* Boucek & Pribyl, *Campograptus millepeda* (McCoy), *Rastrites approximatus* Perner a.o. Both biozones are present in the Rio Ollastu area but random sampling and specimens coming from float do not allow recognition of original associations. This is why in Sardinia the two biozones are combined in a single *leptotheca – convolutus* Biozone which corresponds to the original *convolutus* Biozone of Barca & Jaeger.

Graptolite fauna: *Normalograptus scalaris* (Hisinger), *Glyptograptus* ex gr. *tamariscus* (Nicholson), *Pseudorthograptus insectiformis* (Nicholson), *Rivagraptus bellulus* (Törnquist), *Petalolithus praecursor*, *Cephalograptus cometa*, *Pseudoretiolites perlatus* (Nicholson), *Coronograptus gregarius* (Lapworth), *Pribylograptus leptotheca* (Lapworth), *Pristiograptus* cf. *regularis* Törnquist, *“Monograptus” limatulus* Törnquist, *Campograptus lobiferus* (McCoy), *Campograptus* cf. *millepeda* (McCoy), *Torquigraptus decipiens* (Törnquist)?, *Torquigraptus magnificus* (Pribyl & Münch), *Rastrites* cf. *approximatus* Perner, *Rastrites peregrinus* and *Lituigraptus convolutus*.

Localities: Fluminimaggiore area (Genna Quadroxius) (Storch & Serpagli, 1993), Rio Ollastu area (Rio Brabaisu-Rio Ollastu confluence, road section above Rio Ollastu, Rio Minderri) (Barca & Jaeger, 1990 and pers. obs.).

RASTRITES LINNAEI BIOZONE

Rich graptolite faunas of the *Rastrites linnaei* Biozone have been collected from several outcrops in southeastern Sardinia. In all of these sections the eponymous species is associated with *Spirograptus guerichi* Loydell, Storch & Melchin which designates a closely similar stratigraphical interval in British Isles and elsewhere. The easily distinguishable *R. linnaei* is the preferred zonal index taxon in tectonized alum slates of Sardinia where *S. guerichi* is very difficult to distinguish from the morphologically similar *Spirograptus turriculatus* (Barrande), which characterizes the overlying biozone. Several successive assemblages encountered in a large tectonized exposure at Sedda de S'Ortu suggest that most of the biozone is present, including the *Paradiversograptus runcinatus* - *Monograptus gemmatus* and *Parapetalolithus hispanicus* subzones recognized in Spain (Gutiérrez-Marco & Storch, 1998). Tentative intrazonal correlation is possible also with Wales (Loydell, 1991) and Bohemia (Storch, 1994).

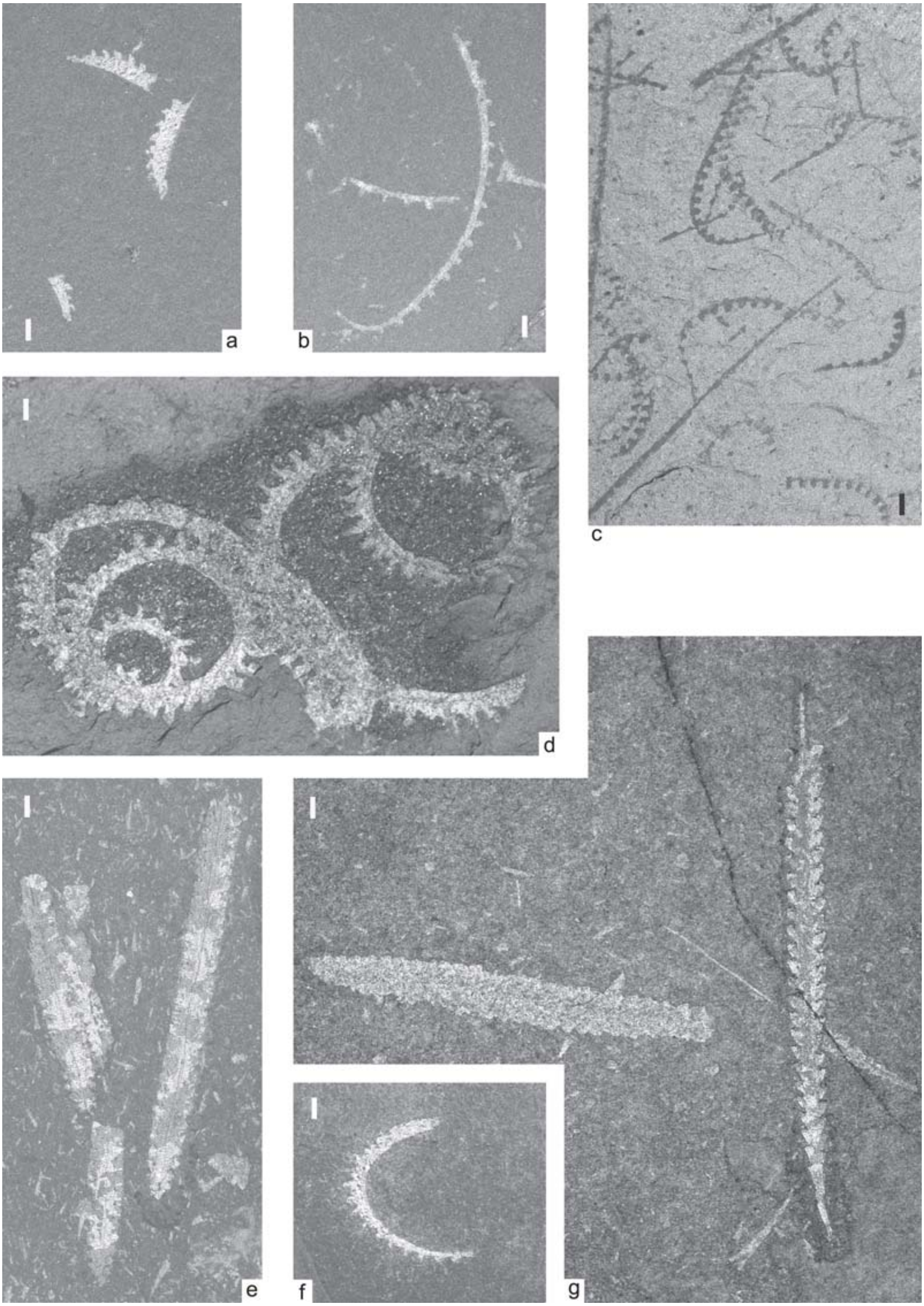
Graptolite fauna: *Glyptograptus* sp. (= "*Orthograptus ultimus*" *sensu* Manck), *Parapetalolithus ovatus* (Barrande), *Parapetalolithus elongatus* (Boucek & Pribyl), *Parapetalolithus* cf. *hispanicus* (Haberfelner), *Parapetalolithus* sp., *Pristiograptus variabilis* (Perner), *Pristiograptus pristinus* Pribyl, *Pristiograptus* cf. *renaudi* Phillipot, *Stimulograptus becki* (Barrande), *Stimulograptus halli* (Barrande), *Streptograptus* cf. *plumosus* (Baily), *Streptograptus* aff. *storchi* Loydell, *Paradiversograptus runcinatus* (Lapworth)?, *Monograptus gemmatus* (Barrande), "*Monograptus*" cf. *capillaris* (Carruthers), *Rastrites linnaei*, *Rastrites schaueri* Storch & Loydell, *Rastrites abbreviatus* Lapworth, *Rastrites fugax* Barrande, *Torquigraptus planus* (Barrande), *Torquigraptus obtusus* (Schauer), *Torquigraptus contortus* (Perner) and *Spirograptus guerichi*.
Localities: Cungiareddu B and Sedda de S'Ortu (unpubl. pers. obs.), Rio Ollastu area (Rio Brabaisu – Rio Ollastu confluence, Rio Minderri) (Barca & Jaeger, 1990).

SPIROGRAPTUS TURRICULATUS – *STREPTOGRAPTUS CRISPUS* BIOZONE

The lower part of the biozone is marked by a low diversity graptolite assemblage which correlates with the post-extinction fauna of Loydell (1994). Rare *Torquigraptus planus*? and *Pristiograptus* cf. *pristinus* survived from the previous biozone. The appearances of *Monograptus* cf. *galaensis* Lapworth, *Torquigraptus proteus* (Barrande), *Streptograptus* cf. *storchi* Loydell and *Streptograptus exiguus* (Lapworth) characterize the middle part of combined *turriculatus* - *crispus* Biozone whilst *S. turriculatus* occurs almost throughout. *Cochlograptus veles* (Richter) and *Torquigraptus* cf. *arcuatus* (Boucek)

Fig. 3 - a) *Monograptus pseudocultellus* Boucek, *insectus* Biozone, Sarcilloni; b) *Mediograptus* cf. *vittatus* Storch, *insectus* Biozone, Sarcilloni; c) *Streptograptus loydelli* Storch & Serpagli and *Monoclimacis griestoniensis* (Nicol)?, *griestoniensis* Biozone, Genna Muxerru GMX; d) *Oktavites spiralis* (Geinitz), *spiralis* Biozone, Rio Minderri; e) *Normalograptus crassus* Storch & Feist, *ascensus-acuminatus* Biozone, Monte Cortoghiana Becciu; f) *Cyrtograptus insectus* Boucek, *insectus* Biozone, Sarcilloni; g) *Parakidograptus acuminatus* (Nicholson) and *Neodiplograptus lanceolatus* Storch & Serpagli, *ascensus-acuminatus* Biozone, Monte Cortoghiana Becciu. Scale bars = 1 mm.

appear in the upper part of the biozone, as does *Streptograptus crispus* (Lapworth). The similar ranges of many significant species, incomplete and/or tectonized sections and limited material prevented recognition of two separate biozones in this interval.



Graptolite fauna: *Parapetalolithus tenuis* (Barrande), *Parapetalolithus altissimus* Elles & Wood?, *Pristiograptus* cf. *pristinus*, *Pristiograptus* cf. *bjerringus* Bjerreskov, *Monograptus* ex gr. *priodon* (aff. *marri* Perner), *Monograptus* cf. *galaensis*, *Spirograptus turriculatus*, *Torquigraptus proteus*, *Torquigraptus planus*?, *Torquigraptus* cf. *arcuatus*, *Cochlograptus veles*, *Streptograptus exiguus*, *Streptograptus crispus*, *Streptograptus* cf. *storchi* and *Diversograptus* sp. (extremely slender).

Localities: Sedda de S'Ortu (unpubl. pers. obs.), Genna Muxerru (GMX A and GMX F of Storch & Serpagli, 1993), Punta S'Omu de Is Abis (unpubl. pers. obs.), Rio Ollastu area (Rio Minderri, Baccu sa Rutta) (Barca & Jaeger, 1990 and unpubl. pers. obs.).

MONOCLIMACIS GRIESTONIENSIS BIOZONE

Slightly cleaved alum shale, encountered in an otherwise heavily tectonized Llandovery succession at Genna Muxerru, yielded a moderately well preserved fauna, dominated by *Streptograptus loydelli* Storch & Serpagli. Diverse torquigraptids [*Torquigraptus arcuatus* Boucek?, *Torquigraptus australis* Storch and *Torquigraptus pragensis* (Pribyl)] associated with slender *Monoclimacis griestoniensis* (Nicol)? enable correlation with the *griestoniensis* Biozone of Spain (Gutiérrez-Marco & Storch, 1998), Wales (Zalasiewicz, 1994), and Bohemia (Storch, 1994a).

Graptolite fauna: *Retiolites angustidens* Elles & Wood, *Pristiograptus initialis* Kirste, *Torquigraptus arcuatus*?, *Torquigraptus australis*, *Torquigraptus pragensis*, *Monograptus priodon* (Bronn), *"Monograptus"* cf. *speciosus* Tullberg, *Monograptus*? sp. (with flexuous rhabdosome), *Monoclimacis griestoniensis*? and *Streptograptus loydelli*.

Locality: Genna Muxerru (GMX P of Storch & Serpagli, 1993).

”*TORQUIGRAPTUS TULLBERGI* BIOZONE”

Barca & Jaeger (1990) reported *Torquigraptus tullbergi* (Boucek) from the Riu Ollastu area in association with a large form of *Streptograptus exiguus* (Nicholson) (apparently similar to *Streptograptus loydelli*). *T. tullbergi* is a common and prominent associate of the less abundant *Monoclimacis crenulata* Elles & Wood in the Barrandian area of Bohemia and the Central Iberian Zone of Spain (Storch, 1994; Gutiérrez-Marco & Storch, 1998). In both regions the *tullbergi* Biozone has formally replaced the *crenulata* Biozone. The same, easily determinable zonal index can be used for this interval in Sardinia.

Graptolite fauna: *Pseudoplegmatograptus* ex gr. *obesus* (Lapworth), *Monograptus* ex gr. *priodon* (Bronn), *Torquigraptus tullbergi* and *Streptograptus* aff. *loydelli* Storch & Serpagli.

Locality: Rio Ollastu area (float near unpaved road above Rio Ollastu) (Barca & Jaeger, 1990).

OKTAVITES SPIRALIS BIOZONE

The lower-middle part of the *spiralis* Biozone with *Oktavites spiralis* (Geinitz), *"Monograptus" flagellaris* Törnquist, *Streptograptus anguinus* (Pribyl), *Streptograptus* cf. *sartorius* Törnquist a.o., was reported by Barca & Jaeger (1990) from the Rio Ollastu area. The middle-upper part of the biozone with the eponym, *Oktavites excentricus* (Bjerreskov), *Streptograptus* aff. *nodifer* (Törnquist), *Monoclimacis geinitzi* (Boucek) and *Diversograptus ramosus* Manck, was found in a large olistolith of lower Silurian black siliceous shales at Punta S`Omu de Is Abis; a similar fauna was recently encountered at Rio Minderri.

Graptolite fauna: *Retiolites geinitzianus* Barrande, *Retiolites angustidens* Elles & Wood?, *Pristiograptus* ex gr. *dubius* (Suess), *Monoclimacis vomerina* (Nicholson)?, *Monoclimacis geinitzi*, *Monoclimacis* cf. *linnarssoni* (Tullberg), *Monograptus priodon*, *"Monograptus" flagellaris*, *Oktavites spiralis*, *Oktavites falx* (Suess), *Oktavites excentricus*, *Streptograptus anguinus*, *Streptograptus* cf. *sartorius* Törnquist, *Streptograptus* aff. *nodifer*, *Lapworthograptus* cf. *grayae* (Lapworth), *Diversograptus pergracilis* (Boucek)? and *Diversograptus ramosus*.

Localities: Rio Ollastu area (road-cut South of Mt. Bisaccu, Rio Minderri) (Barca & Jaeger, 1990 and unpubl. pers. obs.), Punta S'Omu de Is Abis (Storch et al., 2002).

CYRTOGRAPTUS LAPWORTHI BIOZONE

Storch et al. (2002) assigned the uppermost part of the Llandovery succession exposed at Punta S'Omu de Is Abis to the lower half of *Cyrtograptus lapworthi* Biozone. In the uppermost layer, a single, poorly preserved specimen of *Cyrtograptus* (*Cyrtograptus lapworthi* Tullberg?) was found in association with *Streptograptus* aff. *nodifer* and large *Stomatograptus grandis* (Suess). The latter species indicates a level corresponding to the *S. grandis* Subzone of the upper *lapworthi* Biozone in the sense of Storch (2006).

Graptolite fauna: *Retiolites geinitzianus* Barrande, *Stomatograptus grandis*, *Monoclimacis geinitzi*, *Monograptus priodon*, *Oktavites spiralis*, *Streptograptus* aff. *nodifer*, *Diversograptus ramosus* and *Cyrtograptus lapworthi*?.

A graptolite fauna that includes *Monograptus pseudocultellus* Boucek, *Monoclimacis geinitzi*, *Oktavites spiralis*, *Oktavites falx*? and *Cyrtograptus lapworthi*, and corresponds with the upper part of the biozone, has been recorded from the Rio Ollastu area.

Localities: Punta S'Omu de Is Abis (Storch et al., 2002), Sarcilloni in Rio Ollastu area (unpubl. pers. obs.).

CYRTOGRAPTUS INSECTUS BIOZONE

A large and well preserved graptolite fauna referable to the *Cyrtograptus insectus* Biozone was found by one of us (S.P.) at Sarcilloni, in alum slates immediately above the *lapworthi* Biozone. The fossiliferous interval assigned to the *insectus* Biozone (probably just the lower part of the biozone) is about 20 cm thick.

Graptolite fauna: *Retiolites geinitzianus* (Barrande), *Retiolites angustidens* Elles & Wood, *Pristiograptus largus* (Perner), *Mediograptus* cf. *vittatus* Storch, *Mediograptus* ?*morleyae* Loydell & Cave, *Mediograptus* sp., *Monograptus priodon* (Bronn), *Monograptus praecedens* Boucek, *Monograptus pseudocultellus* Boucek, *Monoclimacis geinitzi* (Boucek), *Cyrtograptus insectus* Boucek and *Barrandeograptus pulchellus* (Tullberg).
Locality: Sarcilloni in Rio Ollastu area (unpubl. pers. obs.).

MONOGRAPTUS RICCARTONENSIS BIOZONE

The zonal index *Monograptus riccartonensis* Lapworth is reported for the first time from Sardinia. Common rhabdosomes, typified by a blunt, slightly dorsally curved proximal end, and associated with robust pristiograptids of the *dubius* Group, have been collected from thin-bedded calcareous black slates in the road-cut Ballao-Muravera, c. 50 m from the eastern mouth of the Lantini Tunnel.

Graptolite fauna: *Pristiograptus dubius* (Suess), *Pristiograptus latus* (Boucek)?, *Monograptus riccartonensis*.

Locality: Lantini Tunnel (unpubl. pers. obs.).

Pristiograptus dubius Biozone

The overlying beds E of the Lantini Tunnel yield abundant but uniform pristiograptid rhabdosomes. *M. riccartonensis* has already vanished in this level and the assemblage equates with that of the *dubius* Interval Biozone described by Boucek (1953) and Storch (1994) in Bohemia.

Graptolite fauna: *Pristiograptus dubius* and *Pristiograptus latus.*

Locality: Lantini Tunnel (unpubl. pers. obs.).

Monograptus belophorus – Cyrtograptus rigidus Biozone

Southeastern Sardinia has been considered a reference area for mid-Wenlock graptolites since the early works by Meneghini (1857) and Gortani (1923a). Several important species were first described from Goni. The section is of particular importance as a type locality of the zonal index *Monograptus belophorus* (Meneghini). Considerable variability in the S-shaped proximal flexure of its rhabdosome, commonly enhanced by tectonic deformation, led Meneghini and Gortani to distinguish several morphospecies within this taxon. Elles (1900) recognized *Monograptus flexilis* - a closely similar species that became a zonal-index of the eponymous biozone in British Isles and elsewhere. Close morphological similarity and the similar/equal stratigraphical range of *M. belophorus* and *M. flexilis* has raised some doubts as to whether the two taxa are closely similar successive members of a single clade, are geographic subspecies, or are morphological variants of the same taxon. All of the Sardinian specimens at our disposal may be well assigned to a single, morphologically variable species – *M. belophorus* (Meneghini, 1857), which is the senior synonym. A combined *belophorus – rigidus* Biozone has been introduced in this paper because of the large overlap in the occurrences of *M. belophorus* and *Cyrtograptus rigidus* Tullberg in the pig-paddock section at Goni (see also Barca & Jaeger, 1990 and Rickards et al., 1995) and in the gorge North of Baccu Scottis. A similar association has been observed at Kosov section in Bohemia (pers. obs.).

Graptolite fauna: *Pristiograptus dubius*, *Pristiograptus meneghinii* (Gortani), *Monograptus flemingii* (Salter), *Monograptus belophorus*, *Monoclimacis flumendosae* (Gortani), *Monoclimacis hemipristis* (Meneghini)?, *"Streptograptus" antennularius* (Meneghini), *Streptograptus retroflexus* (Tullberg) and *Cyrtograptus rigidus*.

Localities: Goni and Baccu Scottis (Barca & Jaeger, 1990 and pers. obs.), Cungiareddu A and Lantini Tunnel (unpubl. pers. obs.).

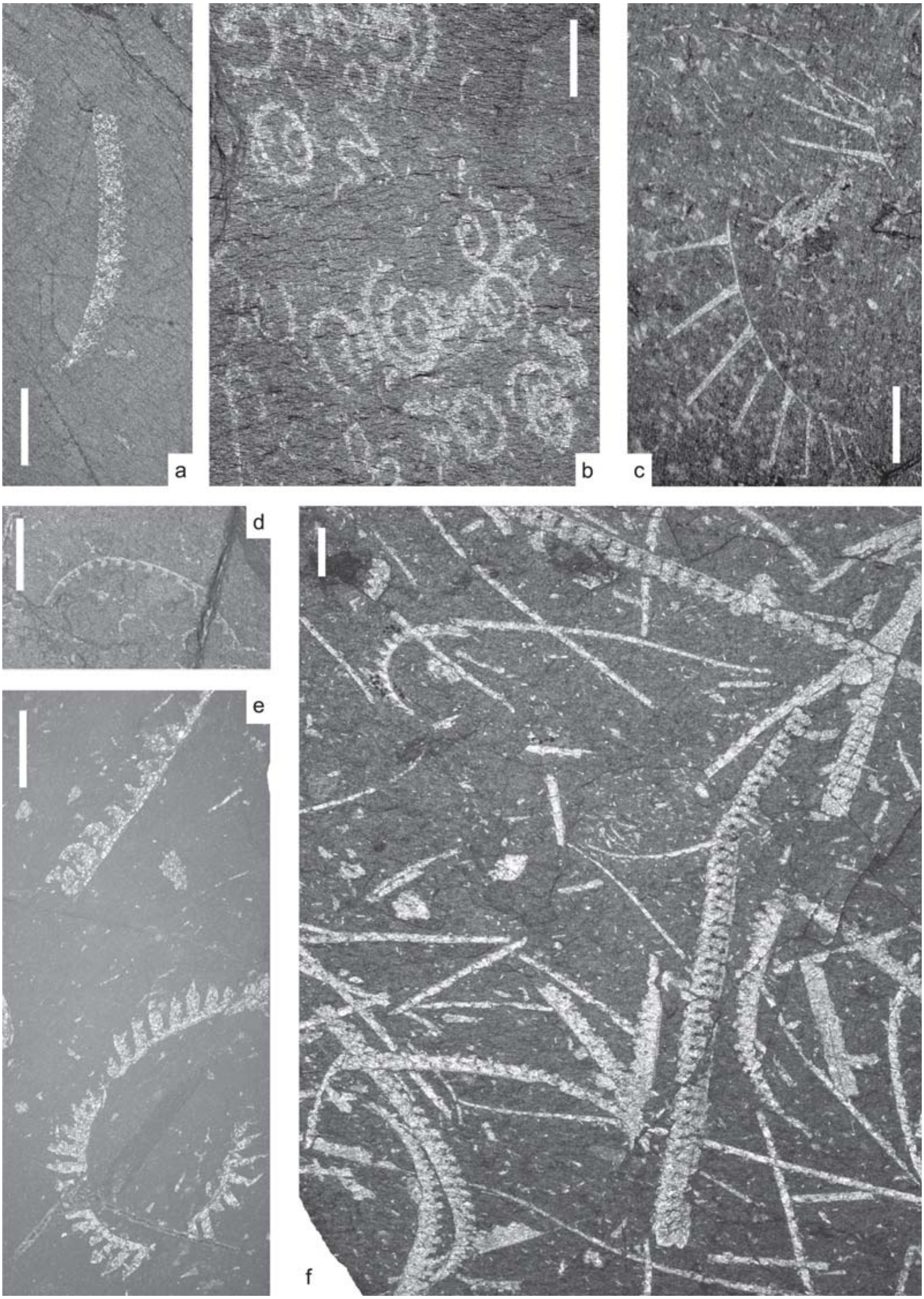
Cyrtograptus ramosus – Cyrtograptus ellesae Biozone

Several graptolite species indicating the stratigraphical interval between the *belophorus* Biozone below and *lundgreni-testis* Biozone above have been recovered from the Ballao-Muravera road-cut East of Lantini Tunnel. The oligospecific assemblage comprises

Fig. 4 - a) *Monograptus riccartonensis* Lapworth, *riccartonensis* Biozone, Lantini Tunnel; b) *Spirograptus guerichi* Loydell, Storch & Melchin, *linnaei* Biozone, Cungiareddu B; c) *Rastrites linnaei* Barrande and *Torquigraptus planus* (Barrande), *linnaei* Biozone, Cungiareddu B; d) *Streptograptus crispus* (Lapworth), *turriculatus-crispus* Biozone, Rio Minderri; e) *Lituigraptus convolutus* (Hisinger) and *Campograptus lobiferus* (McCoy), *leptotheca-convolutus* Biozone, road section above Rio Ollastu; f) *Monograptus belophorus* (Meneghini), *"Streptograptus" antennularius* (Meneghini) and *Cyrtograptus rigidus* Tullberg, *belophorus–rigidus* Biozone, Goni. Scale bars = 5 mm.

pristiograptids, accompanied by slender cyrtograptids, a relatively common diversograptid, rare monoclimacid and flexuous streptograptid.

Graptolite fauna: *Pristiograptus pseudodubius* Boucek, *Pristiograptus dubius*,



Monoclimacis flumendosae?, *Streptograptus* cf. *retroflexus* (Tullberg), *Cyrtograptus ramosus* Boucek or *Cyrtograptus ellesae* Gortani and *Diversograptus gracilis* (Boucek).

Locality: Lantini Tunnel (unpubl. pers. obs.).

Cyrtograptus lundgreni – *Testograptus testis* Biozone

A typical graptolite assemblage of the lower Homerian *lundgreni* Biozone comes from the pig-paddock section in Goni (Barca & Jaeger, 1990). Barca & Jaeger and the present authors recorded a similar assemblage typified by *Testograptus testis* (Barrande), in the Rio Ollastu area. By comparison with Bohemian sections (Storch, 1994; see also Jaeger, 1991), abundant *T. testis* appears to indicate the upper part of the *lundgreni* Biozone, designated the *testis* Subzone.

Graptolite fauna: *Paraplectograptus eiseli* (Manck), *Gothograptus* aff. *pseudospinosus* (Eisenack), *Pristiograptus dubius*, *Pristiograptus pseudodubius*, *Monograptus flemingii*, *Monoclimacis flumendosae*?, *Monoclimacis hemipristis*?, *Testograptus testis*, *Cyrtograptus lundgreni* Tullberg and *Cyrtograptus* aff. *perneri* Boucek.

Localities: Goni, Rio Ollastu area (Baccu Perdaccia, SE of Punta 324, South of Mt. Bisaccu, Sarcilloni) (Barca & Jaeger, 1990 and unpubl. pers. obs.) and probably Galemmu in the Fluminimaggiore area (Kriz & Serpagli, 1994).

Pristiograptus parvus – *Gothograptus nassa* Biozone

A uniform graptolite association that survived the severe extinction event at the end of the *lundgreni* Biozone (see e.g. Jaeger, 1993 and Melchin et al., 1998) was identified by Barca & Jaeger (1990) in the pig-paddock section at Goni and in the gorge North of Baccu Scottis. *Pristiograptus parvus* Ulst, that occurs in the lower part of this biozone, is a dwarf form, easily distinguishable from *Pristiograptus pseudodubius*, which is typical of early Homerian strata.

Graptolite fauna: *Gothograptus nassa* (Holm), *Pristiograptus parvus* and *Pristiograptus dubius* (Suess)?.

Localities: Goni and Baccu Scottis (gorge) (Barca & Jaeger, 1990).

Colonograptus praedeubeli – *Colonograptus deubeli* Biozone

Barca & Jaeger (1990) recorded that the Goni succession continued with an oligospecific assemblage typified by *Gothograptus nassa* and *Colonograptus praedeubeli* (Jaeger) which is replaced by *Colonograptus deubeli* (Jaeger) in the upper part of the interval. The same combined *preadeubeli – deubeli* Biozone was applied by Kozlowska-Dawidziuk et al. (2002) in the Barrandian area of Bohemia.

Graptolite fauna: *Gothograptus nassa*, *Pristiograptus dubius*, *Colonograptus deubeli* and *Colonograptus praedeubeli.*

Locality: Goni (Barca & Jaeger, 1990).

Colonograptus ludensis – *Colonograptus gerhardi* Biozone

The uppermost Wenlock strata are characterized by a low diversity graptolite assemblage of *Pristiograptus dubius*, *Colonograptus* cf. *ludensis* (Murchison) and *Colonograptus gerhardi* (Kuehne). The latter two species are difficult to distinguish from each other. *C. gerhardi* with its lobate thecal apertures seems to be more common in Sardinia than *C. ludensis* which is marked by simple distal thecal apertures of pristiograptid appearance.

Localities: Rio Ollastu area (SE of Punta 324), Goni and Baccu Scottis (gorge) (Barca & Jaeger, 1990) and probably road-cut 150 m E of Lantini Tunnel (unpubl. pers. obs.)

NEODIVERSOGRAPTUS NILSSONI – *COLONOGRAPTUS COLONUS* BIOZONE

A small fauna of the lowermost Ludlow graptolite biozone, including the zonal index *Neodiversograptus nilssoni* (Lapworth), was recovered by Barca & Jaeger (1990) from southeastern Sardinia. In southwestern Sardinia the same interval is marked by abundant colonograptids preserved in graptolitic limestones exposed in the northern vicinity of Fluminimaggiore (Palmer & Gnoli, 1985) in association with cephalopod limestone lenses. Kriz et al. (1993) used the *Colonograptus colonus* Biozone as an equivalent of the *N. nilssoni* Biozone in the limestone dominated sections of the Barrandian area. We combine here the two different, but roughly coeval graptolite assemblages in a single *nilssoni – colonus* Biozone.

Graptolite fauna: *Plectograptus macilentus* (Törnquist), *Spinograptus spinosus* (Wood), *Pristiograptus dubius*, *Colonograptus colonus* (Barrande), *Colonograptus roemeri* (Barrande), *Monograptus uncinatus* Tullberg, *Bohemograptus bohemicus* (Barrande) and *Neodiversograptus nilssoni*.

Localities: Rio Ollastu area (WSW of Punta 324) and Baccu Scottis (gorge) (Barca & Jaeger, 1990), Fluminimaggiore area (Sentiero Flumini) (Palmer & Gnoli, 1985 and pers. obs.).

SAETOGRAPTUS CHIMAERA BIOZONE

Kriz and Serpagli (1994) reported the upper Gorstian zonal index species *Saetograptus chimaera* (Barrande) from dark-coloured cephalopod limestones at Galemmu near Fluminimaggiore.

SAETOGRAPTUS LINEARIS – *SAETOGRAPTUS LEINTWARDINENSIS* BIOZONE

Early Ludfordian graptolites, herein assigned to the combined *linearis - leintwardinensis* Biozone, originated from scattered loose and displaced blocks of dark-coloured, largely cephalopod limestones of the Fluminimaggiore Formation (Rickards et al., 1995). Some species, such as *Saetograptus linearis* (Boucek), *Saetograptus leintwardinensis* (Hopkinson) and *Saetograptus jaegeri* Rickards, Holland & Serpagli, are abundant. *Bohemograptus tenuis* (Boucek) and *”Monograptus” dalejensis* Boucek? are rare, but all indicate an early Ludfordian age, prior to the *kozlowskii* extinction Event of Urbanek (1993) and Melchin et al. (1998).

Localities: Fluminimaggiore area (Sentiero Flumini) (Palmer & Gnoli, 1985 and pers. obs.), Argiola (Rickards et al., 1995).

MONOGRAPTUS PARULTIMUS – *MONOGRAPTUS ULTIMUS* BIOZONE

Loose slabs and boulders of both dark- and pale-coloured limestones, densely packed with three-dimensional rhabdosomes of *“Monograptus” parultimus* Jaeger?, have been found at the northern periphery of Fluminimaggiore (e.g. Rickards et al., 1995; Ferretti & Serpagli, 1996). Rickards et al. (1995) reported a single specimen, tentatively refered to *M. parultimus*, from Argiola, East of Domusnovas. *”M.” parultimus* is the latest Silurian graptolite so far recorded in Sardinia.

STATE OF ART AND PERSPECTIVE

The vast majority of the 155 graptolite species recorded from the Silurian succession of southern Sardinia to date, is known also from black shale dominated Silurian formations in other parts of Variscan, i.e. peri-Gondwanan Europe (i.e. Barrandian area of Bohemia, Thuringia and Saxony, French Montagne Noire, Ossa Morena Zone of Iberian Peninsula). Our knowledge of Sardinian graptolite assemblages has been affected by the poor preservation of graptolites in the heavily sheared sedimentary rocks rather than by true palaeoenvironmental diversity controls.

Despite the tectonic and metamorphic effects, the current graptolite fauna enables detailed correlation with graptolite-based biozonations of Silurian sections in Europe and worldwide.

The proposed biozonal scheme (Fig. 2) consists of 24 graptolite biozones. The standard upper Aeronian *Stimulograptus sedgwickii* Biozone, lower Sheinwoodian *Cyrtograptus centrifugus* and *Cyrt. murchisoni* biozones, middle and upper Ludfordian biozones and all Pridoli biozones except for the *M. praeultimus – M. ultimus* Biozone have not yet been encountered in southern Sardinia. Only the upper Silurian graptolite record may have been limited by environmental factors, suggested by the monospecific taphocoenoses of colonograptid and saetograptid rhabdosomes in nautiloid limestones. No graptolites are known from the Ockerkalk of southeastern Sardinia. It is obvious that further field investigations, new road-cuts, building excavations and other exposures in black shales, may bring to light less heavily sheared blocks that enable more detailed biostratigraphical subdivision than the present scheme or exhibit so far unrecovered parts of the stratigraphical succession.

Acknowledgements

E. Serpagli is deeply acknowledged for his long-term logistical and scientific support and encouragement. Logistical support in the field was also provided by C. Corradini and S. Barca at various times. D.K. Loydell is thanked for helpful comments and for improving the English. S. Piras research was funded by Region Sardinia (research program Master and Back 2006 rif. B 20), P. Storch received funding through research program AV 0Z30130516.

References

Barca S. & Jaeger H. (1990). New geological and biostratigraphical data on the Silurian in SE-Sardinia. *Bollettino della Società Geologica Italiana*, 108 (1989): 565-580.

Boucek B. (1953). Biostratigraphy, Development and Correlation of the Zelkovice and Motol Beds of the Silurian of Bohemia. *Sborník Ustredního Ustavu geologického, Oddíl paleontologicky* 20: 421-484.

Elles G.L. (1900). The zonal classification of the Wenlock Shales of the Welsh Borderland. *Quarterly Journal of the Geological Society of London*, 56: 370-414.

Ferretti A. (1989). Microbiofacies and constituent analysis of Upper Silurian – Lowermost Devonian limestones from Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 28 (1): 87-100.

Ferretti A. & Serpagli E. (1996). Geological outline, community sequence and paleoecology of the Silurian of Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 102 (3): 353-362.

Gnoli M., Kriz J., Leone F., Olivieri R., Serpagli E. & Storch P. (1990). Lithostratigraphic units and biostratigraphy of the Silurian and early Devonian of Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 11-23.

Gortani M. (1923a). Faune Paleozoiche della Sardegna. Parte 1: Le graptoliti di Goni. *Palaeontographia Italica*, 28: 51-67.

Gortani M. (1923b). Faune Paleozoiche della Sardegna. Parte 2: Graptoliti della Sardegna orientale. *Palaeontographia Italica*, 28: 85-111.

Gutiérrez-Marco J.C. & Storch P. (1998). Graptolite biostratigraphy of the lower Silurian (Llandovery) shelf deposits of the Western Iberian Cordillera, Spain. *Geological Magazine*, 135 (1): 71-92.

Helmcke D. (1973). Schichtgebundene NE-Metall- und F-Ba-Lagerstätten im Sarrabus-Gerrei-Gebiet, SE-Sardinien. II. Bericht: Zur Stratigraphie des Silur und Unterdevon der Lägerstättenprovinz Sarrabus-Gerrei. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte* 1973-H9: 529-544.

Helmcke D. & Koch G. (1974). Schichtgebundene NE-Metall- und F-Ba-Lagerstätten im Sarrabus-Gerrei-Gebiet, SE-Sardinien. III. Bericht: Zur Altersstellung der Porphyroide in der Lägerstättenprovinz Sarrabus-Gerrei. *Zeitschrift der Deutschen geologischen Gesellschaft*, 125: 91-98.

Jaeger H. (1976). Das Silur und Unterdevon vom thüringischen Typ in Sardinien und seine regionalgeologische Bedeutung. *Nova Acta Leopoldina*, 45 (224): 263-299.

Jaeger H. (1991). Neue Standard-Graptolithenzonenfolge nach der "Grossen Krise" an der Wenlock/Ludlow Grenze (Silur). *Neues Jahrbuch für Geologie ind Paläontologie, Abhandlungen*, 182 (3): 303-354.

Kozlowska-Dawidziuk A., Lenz A.C. & storch P. (2001). Upper Wenlock and Lower Ludlow (Silurian) graptolites; Všeradice section, Barrandian area, Czech Republic. *Journal of Paleontology*, 75: 147-164.

Kriz J., Dufka P., Jaeger H. & Schönlaub H.P. (1993). The Wenlock/Ludlow Boundary in the Prague Basin (Bohemia). *Jahrbuch der Geologischen Bundesanstalt*, 136 (4): 809-839.

Kriz J. & Serpagli E. (1994). Upper Silurian and Lowermost Devonian Bivalvia of Bohemian type from Western Sardinia. *Bollettino della Società Paleontologica Italiana*, 33 (3): 289-347.

Loydell D.K. (1991). The biostratigraphy and formational relationships of the Upper Aeronian and lower Telychian (Llandovery, Silurian) formations of western mid-Wales. *Geological Journal*, 26: 209-244.

Loydell D.K. (1994). Early Silurian changes in graptoloid diversity and sea level. *Geological Journal*, 29: 355-368.

Melchin M.J., Koren T.N. & Storch P. (1998). Global diversity and survivorship patterns of Silurian graptoloids. *In* Landing E. & Johnson M.E. (eds.): Silurian Cycles: linkages of dynamic processes in the atmosphere and oceans. *New York State Museum Bulletin*, 491: 165-182.

Meneghini G. (1857). Paléontologie de l'Ile de Sardaigne. *In* La Marmora A., Voyage en Sardaigne. 584pp. Imprimaire Royal, Turin-Paris.

Novarese V. & Taricco M. (1922). Cenni sommari sul Paleozoico dell'Iglesiente. *Bollettino della Società Geologica Italiana*, 41: 316-325.

Palmer D. & Gnoli M. (1985). A preliminary report on new micropalaeontological discoveries in the Silurian of Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 23 (2): 221-238.

Rickards R.B., Holland C.H. & Serpagli E. (1995). Aspects of Silurian and Lower Devonian graptolite faunas and stratigraphy in southern Sardinia. *Bollettino della Società Paleontologica Italiana*, 34 (1): 67-80.

Salvador A., ed. (1994). International Stratigraphic Guide, 2nd. edition: 214 pp. The IUGS and The Geological Society of America Inc. Boulder.

Storch P. (1994). Graptolite biostratigraphy of the Lower Silurian (Llandovery and Wenlock) of Bohemia. *Geological Journal*, 29: 137-165.

Storch P. (1996). The basal Silurian *Akidograptus ascensus - Parakidograptus acuminatus* Biozone in peri-Gondwanan Europe: graptolite assemblages, stratigraphical ranges and palaeobiogeography. *Bulletin of the Czech Geological Survey*, 71: 171-178.

Storch P. (1998). Graptolites of the *Pribylograptus leptotheca* and *Lituigraptus convolutus* biozones of Tman (Silurian, Czech Republic). *Journal of the Czech Geological Society*, 43 (4): 209-272.

Storch P. (2006). Facies development, depositional settings and sequence stratigraphy across the Ordovician-Silurian boundary: a new perspective from Barrandian area of the Czech Republic. *Geological Journal*, 41: 163-192.

Storch P. & Serpagli E. (1993). Lower Silurian graptolites from Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 32 (1): 3-57.

Storch P., Serpagli E. & Barca S. (2002). Silurian graptolites of the *spiralis* and *lapworthi* biozones (upper Telychian, Llandovery) in the Sulcis area, SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 41 (2-3): 97-107.

Taricco M. (1911). Osservazioni geologico-minerarie sui dintorni di Gadoni e sul Gerrei. *Bollettino della Società Geologica Italiana*, 30: 113-150.

Taricco M. (1922). Sul Paleozoico del Fluminese (Sardegna). *Bollettino del Regio Comitato geologico d'Italia*, 48: 1-22.

Urbanek A. (1993). Biotic crises in the history of Upper Silurian graptoloids: a palaeobiological model. *Historical Biology*, 7: 29-50.

Zalasiewicz J. (1994). Middle to late Telychian (Silurian, Llandovery) graptolite assemblages of central Wales. *Palaeontology*, 37(2): 375-396.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 95-107

Silurian conodonts from Sardinia: an overview

Maria G. Corriga, Carlo Corradini, Annalisa Ferretti

M.G. Corriga - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); maria.corriga@unica.it
C. Corradini - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); corradin@unica.it
A. Ferretti - Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia, largo S. Eufemia 19, I-41100 Modena (Italy); ferretti@unimore.it

Abstract - A general review of Silurian conodont data from Sardinia is here presented. Main features of the conodont associations, with special attention to their biostratigraphical implications, are briefly highlighted. All papers dealing with Silurian conodonts from Sardinia are listed, as well as a complete summary of productive localities is given in the appendix.

Key words - Silurian, Sardinia, Conodonts, Biostratigraphy.

Introduction and historical overview

Conodonts are by long the better known and more documented fossil group from the Silurian of Sardinia. Starting from the first report by Serpagli (1967), more than 35 papers have dealt with this fossil group (for a complete list see appendix 1). Most of the researches, mainly carried out by the palaeontological group of Modena University lead by Enrico Serpagli, were devoted to solving geological and stratigraphical problems in highly tectonized sequences. Only in a few papers a taxonomic and systematic approach to these fossils was made. Nevertheless, several new taxa have been established in Sardinia (Pl. 1).

About thirty localities yielded Silurian conodonts (Figs. 1, 2; appendix 2). For a long time field work was mainly limited to the "*Orthoceras* limestone" occurrences (Fluminimaggiore Formation) of southwestern Sardinia. Only in the last fifteen years researches moved to the southeastern part of the island, where the Ockerkalk limestones there exposed in continuous sections have been the subject of an intensive study. A dozen of sections from the Gerrei tectonic Unit have been investigated and placed in the late Silurian time frame.

Conodont fauna

Forty-three conodont species and subspecies belonging to sixteen genera (*Amydrotaxis*, *Ancoradella*, *Aspidognathus*, *Belodella*, *Dapsilodus*, *Kockelella*, *Oulodus*, *Ozarkodina*, *Panderodus*, *Pedavis*, *Pelekysgnathus*, *Polygnathoides*, *Pseudooneotodus*, *Pterospathodus*, *Wurmiella* and *Zieglerodina*) have been reported from the Silurian of Sardinia (Fig. 3).

Conodont abundance is in general quite high, with an average of about 30 elements/kg. The preservation varies from time to time and from area to area, but in general it is moderately good. The Colour Alteration Index is constantly between 4.5 and 5.5.

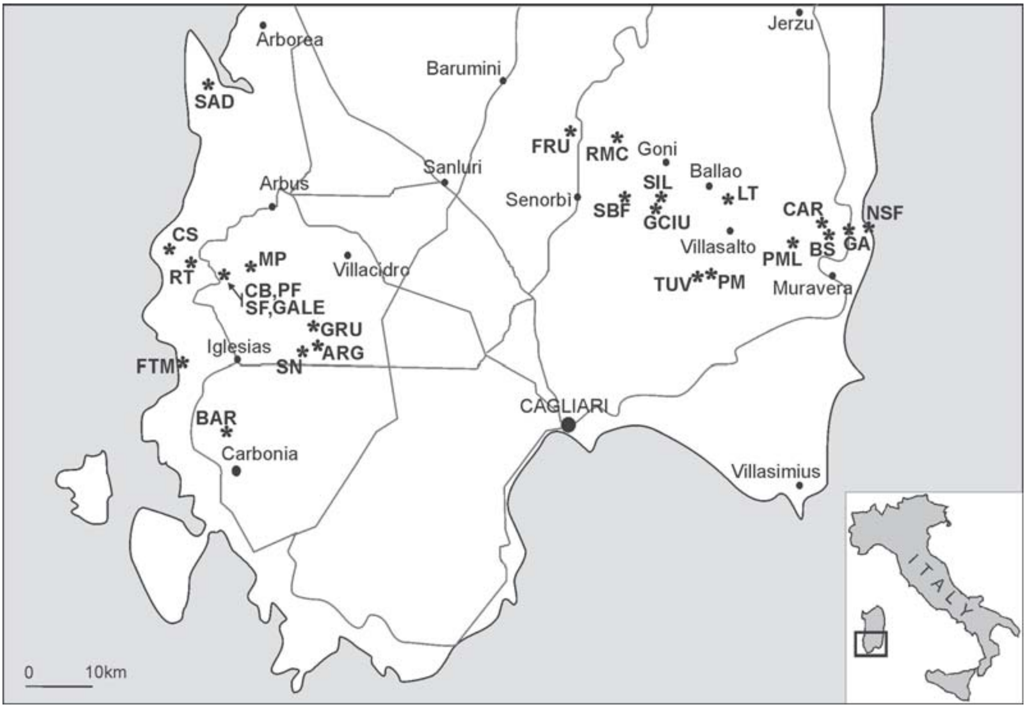


Fig. 1 - Location map of the localities yielding Silurian conodonts in Sardinia. Locality abbreviations: ARG: Argiola; BAR: Barbusi; BS: Baccu Scottis; CAR: Punta Carroga; CB: Corti Baccas; FTM: Funtanamare; FRU: Monte Fruccas; GA: Genna Arrela; GALE: Galemmu; GCIU: Genna Ciuerciu; GRU: Gruttixedda; LT: Lantini Tunnel; MP: Mason Porcus; NSF: Nuraghe su Franzesu; PF: Perd'e Fogu; PM: Pala Manna; PML: Ponte Monte Lora; RMC: Rio Murru de Callus; RT: Roia is Tintionis; SAD: Sant'Antonio Donigala; SBF: San Basilio Fenugu; SF: Sentiero Flumini; SIL: Silius; SN: Su Nuargi; TUV: Tuviois.

Ozarkodinids are almost always largely dominant in the conodont faunas and in several samples *Wurmiella excavata* may represent more than half of the association. Within this range, also *Ozarkodina sagitta sagitta*, *Oz. confluens* and *"Oz." eosteinhornensis* are common.

The genus *Kockelella* is abundant in the Gorstian and early Ludfordian, when it became extinct within the *siluricus* Zone, in connection with the Lau event. A revision of Kockelellids, based on rich collections from Sardinia, was proposed by Serpagli & Corradini (1999). The authors revised the phylogeny of the genus, proposed a reconstruction of the apparatuses of *K. variabilis variabilis* and *K. crassa*, and described three new taxa: *K. variabilis ichnusae*, *K. maenniki* and *K. absidata sardoa* (Pl. 1).

The long ranging *Dapsilodus obliquicostatus* is relatively abundant in the late Silurian. Serpagli (1971) proposed for the first time a reconstruction of the apparatus of this species, based on material from Sentiero Flumini, in the Fluminimaggiore area.

Pseudooneotodus has very irregular occurrences, being in some levels very abundant and in some others, even stratigraphically very close, completely absent. Corradini (2008) suggested a possible ecological control to explain such irregular distribution.

Beside *Dapsilodus* and *Pseudooneotodus*, other coniform conodonts (mainly Panderodids) are curiously quite rare in the Silurian conodont associations reported from Sardinia.

Anomalous conodont elements, mainly ramiforms with branched processes or extra bars, were collected from several sections, always from the *siluricus* Zone. Corradini et al. (1996) referred these occurrences to "pre-event" P-episodes, characterized by abundant and diverse planktonic communities.

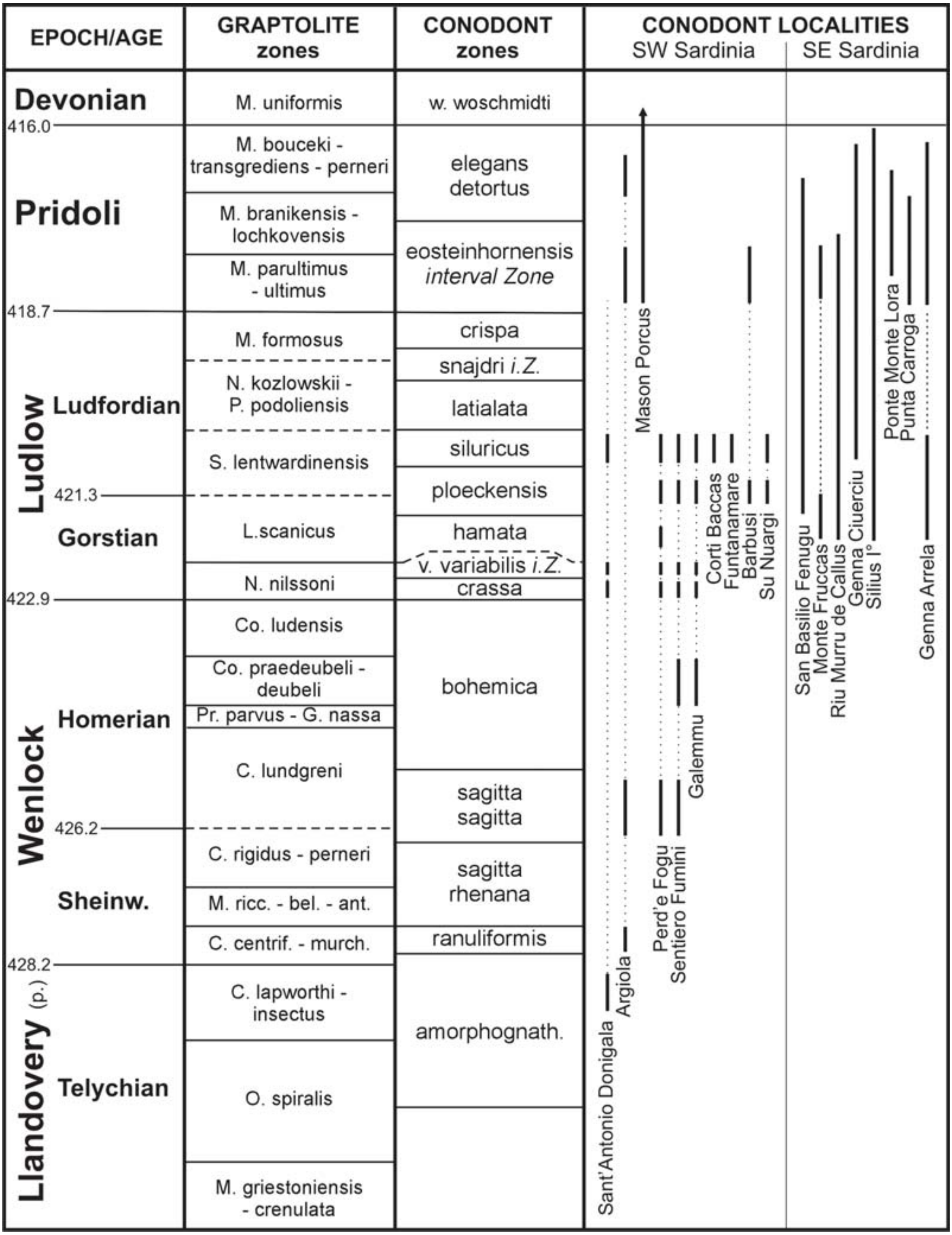


Fig. 2 - Age of main conodont localities in Sardinia. Numerical age and graptolite zonation after Ogg et al. (2008); conodont zones modified after Corradini & Serpagli (1999).

BIOSTRATIGRAPHY

A Silurian conodont zonation based on Sardinian data was proposed by Corradini & Serpagli (1998, 1999). The authors discriminated fifteen biozones in the top Llandovery-end Pridoli interval, with a much more detail for the Ludlow than any other scheme. The authors proved that the Sardinian conodont zonation is widely usable worldwide and claimed that it is "of pratical use for Silurian biostratigraphy, and therefore more generally useful than extremely detailed schemes, sometimes based on not yet defined or endemic taxa" (Corradini & Serpagli, 1999, p. 270). Following these considerations, the same authors (Corradini & Serpagli, 2000) proposed their scheme as a Standard Silurian Conodont Zonation, even if the base of Silurian is not included. A perfect timing between conodont and graptolite zonations was possible in some intervals thanks to some joint occurrences in the graptolite limestones of the Fluminimaggiore area (Corradini & Serpagli, 1999).

The lower part of the scheme, up to the *K. variabilis* interval Zone, is based on reports from several localities in southwestern Sardinia, whereas data from the upper part mainly derive from the Ockerkalk limestones of southeastern Sardinia, integrated with a few of Pridoli age from the Fluminimaggiore Fm.

Recently, the upper part of the Sardinian biozonation scheme has been updated by means of a graphic correlation method (Gouwy & Corradini, 2006), demonstrating that the *detortus* Zone, the final zone of the Silurian, is definitely longer in Sardinia than elsewhere. Later on, an analogous longer range of *Oul. el. detortus* was documented from the Czech Republic and Bavaria by Carls et al. (2007).

The scheme by Corradini & Serpagli (1998, 1999) is slightly updated here (Fig. 2) in respect of the lower Pridoli interval: their "*Oz. rem. remscheidensis* interval Zone" is here named "*eosteinhornensis* s.l. interval Zone" after a recent taxonomical revision of late Silurian Ozarkodinids by Murphy et al. (2004) and Carls et al. (2007). According to the new, restricted, definition of *Zieglerodina remscheidensis* (Ziegler), the species is missing

Plate 1

Holotypes of conodont taxa established in Sardinia. All specimens x80.

Fig. 1 - *Kockelella maenniki* Serpagli & Corradini, 1998, Pa element; sample GCIU 3; upper (a) and lower (b) views of the holotype.

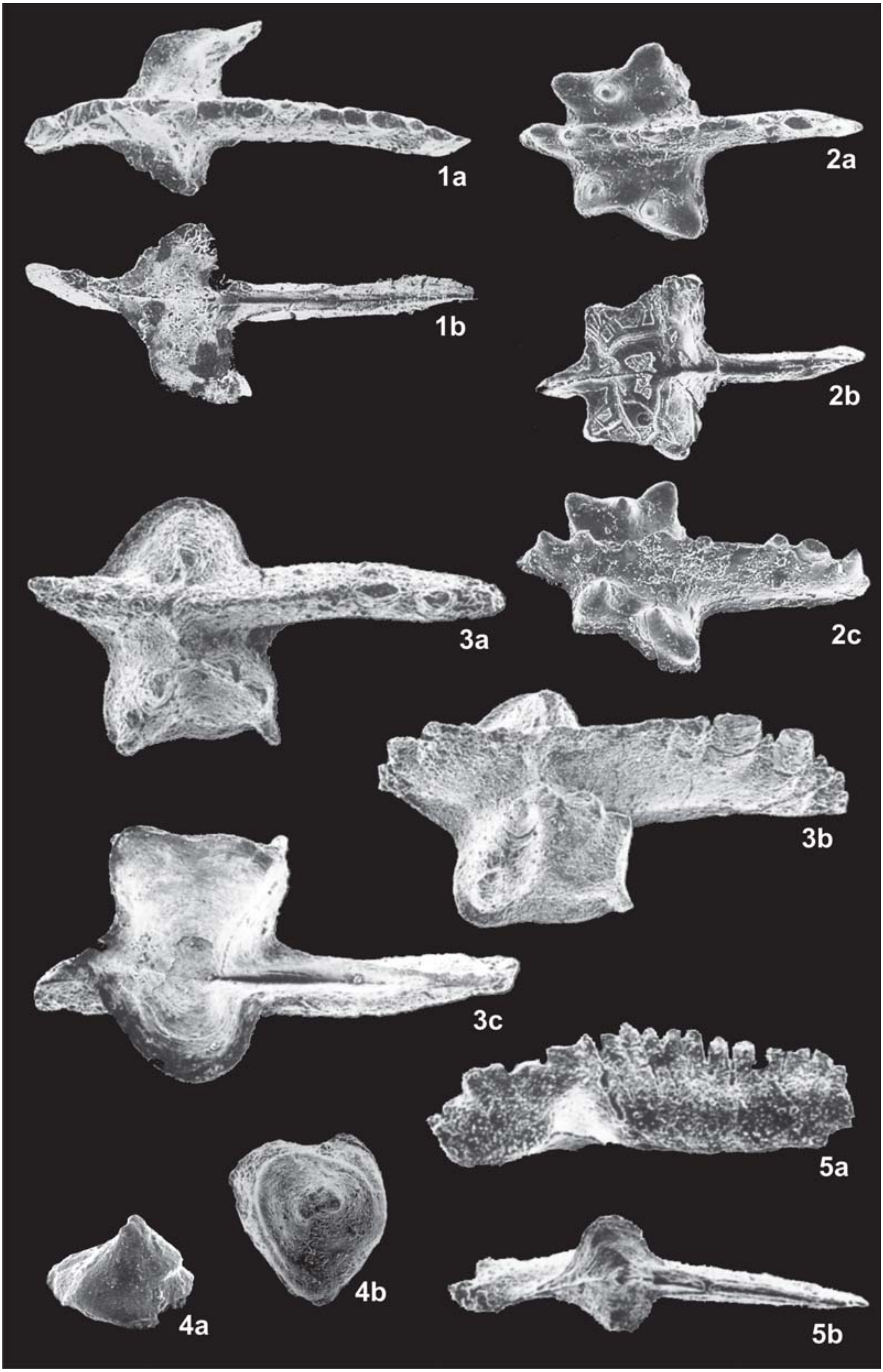
Fig. 2 - *Kockelella crassa* (Walliser, 1964), Pa element; sample SAD-BK 2; upper (a), lower (b) and upper-lateral (c) views of the Pa element [specimen figured as *K. circaquadra* n. sp. in Serpagli & Corradini, 1998, and then identified as Pa element of *K. crassa* by Serpagli & Corradini, 1999].

Fig. 3 - *Kockelella variabilis ichnusae* Serpagli & Corradini, 1998, Pa element; sample SIL 5; upper (a), upper-lateral (b) and lower (c) views.

Fig. 4 - *Pseudooneotodus bicornis contiguus* Corradini, 2008, Pa element; sample SIL 23; upper (a) and upper-lateral (b) views.

Fig. 5 - *Kockelella absidata sardoa* Serpagli & Corradini, 1999, Pa element; sample GCIU 3; lateral (a) and lower (b) views.

1-3 refigured after Serpagli & Corradini (1998); 4 refigured after Corradini (2008); 5 refigured after Serpagli & Corradini (1999).


1a
2a
1b
2b
2c
3a
3b
3c
5a
4b
4a
5b

in the lower part of the Pridoli. As a consequence, it is not appropriate to name a zone by an absent taxon. It should be pointed out, nevertheless, that this name variation does not change the biostratigraphical meaning of the zone.

LLANDOVERY-WENLOCK

Early Silurian conodonts are quite rare in Sardinia: Llandovery and Wenlock sediments are in fact mainly represented by black graptolitic shales, with some scattered calcareous lenses only in southwestern Sardinia.

The oldest Silurian conodonts have documented the *amorphognathoides* Zone from one isolate block in the Capo Frasca area (Barca et al., 1992). Also the next zone, the *ranuliformis* Zone, is reported from only one isolated block at Argiola, near Domusnovas (Corradini et al., 1998a). No other Sheinwoodian data are up to now available.

Early Homerian data from the *sagitta sagitta* Zone are relatively abundant, mainly from Argiola (Corradini et al., 1998a) and the Fluminimaggiore area (Serpagli, 1971; Ferretti et al., 1998; unpubl. data). However, the fauna is not very differentiated and only a few taxa are reported, even if the abundance is relatively high.

In contrast with the *sagitta sagitta* Zone, records of the following *bohemica* Zone are limited to a few loose blocks in the Fluminimaggiore area.

LUDLOW

Ludlow sediments are definitely better exposed and well documented both in soutwestern and in southeastern Sardinia. More precisely, Gorstian and early Ludfordian conodonts occur in the Fluminimaggiore Fm., while good and continuous upper Gorstian-Pridoli sections are well exposed in southeastern Sardinia as Ockerkalk limestones.

The conodont zonation is very detailed, being the Ludlow subdivided into eight zones, with a time average of about 0.5 Ma *per* zone.

The *crassa* Zone is well documented both in the *Orthoceras* and in the graptolitic limestones of the Fluminimaggiore Fm. either in some localities of the Fluminimaggiore area (Serpagli, 1971; Ferretti et al., 1998; unpubl. data) or the Capo Frasca area (Barca et al., 1992). Among other taxa, representatives of the genus *Kockelella* start to be abundant and differentiated within this interval.

The same localities where the *crassa* Zone is documented yielded also conodonts from the *variabilis* Interval Zone. This zone is defined as the interval "between the last occurrence of *Po. crassus* [now *K. crassa*] and the first occurrence of *Oz. excavata hamata* [now *Wurmiella hamata*], without any really characteristic taxon, except *Kockelella v. variabilis…*" (Corradini & Serpagli, 1999, p. 262).

The *hamata* Zone is documented both in southwestern and southeastern Sardinia, respectively from a few blocks, both *Orthoceras* and graptolitic limestones, of the Fluminimaggiore area (Ferretti et al., 1998) and from the base of the Ockerkalk in a few sections (Corradini & Olivieri, 1997; Serpagli et al., 1998).

The following *ploeckensis* and *siluricus* zones are probably the better documented in Sardinia, being reported in several localities either in the southwestern or in the southeastern of the island. Conodont associations of the *ploeckensis* Zone are characterized by abundance of specimens of *Kockelella* and *Wurmiella*. *Wurmiella posthamata* occurs only in the lower part of the Zone, where *W. inflata* has its last occurrence. Within the *siluricus* Zone, conodont abundance and diversity decrease progressively, due to the effects of the Lau Event. *Kockelella maenniki* is exclusive of the lower part of the zone, where also the other last representatives of the genus (*K. variabilis ichnusae* and *K. absidata sardoa*)

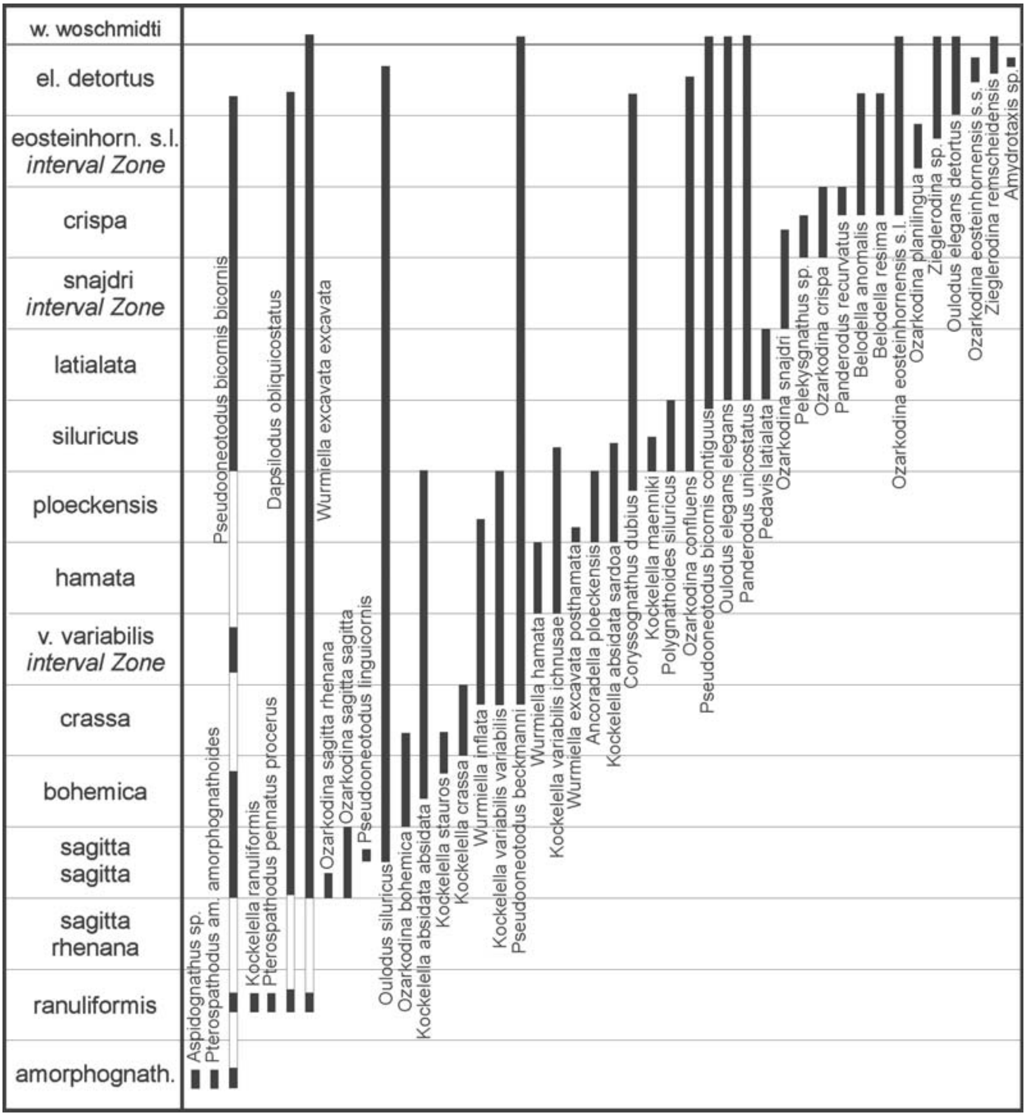


Fig. 3 - Distribution of Silurian conodont taxa in Sardinia, plotted against the conodont zonation.

became extinct. *Ozarkodina confluens*, an important taxon for the late Ludlow and Pridoli, makes its entry in the lower part of the zone.

The other three upper Ludlow conodont zones (*latialata*, *snajdri* i.Z. and *crispa*) are documented in southwestern Sardinia only, and all are represented by low sedimentation rate intervals (less than 2.5 metres of limestone include the three zones). Diversity is relatively high in these intervals, without significant faunal variation, apart from the marker occurrences. In the lower part of the *crispa* Zone, a peculiar *Pelekysgnathus* is present, unfortunately left up to now in open nomenclature owing to the scarcity of the material. Similar forms have been recently reported in the Carnic Alps from the same stratigraphical position (Corriga & Corradini, in press), suggesting a possible biostratigraphical significance for this taxon. Higher in the zone *Belodella anomalis* enters: curiously no other representatives of the genus are present in older Silurian rocks in Sardinia. Also *"Oz." eosteinhornensis* s.l. has its first occurrence within the same zone.

The extinction of *Ozarkodina crispa* is considered to mark the Ludlow-Pridoli boundary.

PRIDOLI

Pridoli is subdivided in two conodont zones: the *eosteinhornensis* s.l. interval Zone and the *detortus* Zone. Conodonts are quite abundant in the Ockerkalk limestones of southeastern Sardinia (Barca et al., 1995; Corradini et al., 1998b; Corradini & Olivieri, 1997; Serpagli et al., 1998; unpubl. data), and have been reported also in a few localities of southwestern Sardinia (Gnoli et al., 1981; Olivieri & Serpagli, 1990; Corradini et al., 1998a; unpubl. data).

The *eosteinhornensis* s.l. interval Zone is defined as the interval between the Last Occurrence of *Oz. crispa* and the First Occurrence of *Oulodus elegans detortus*. *"Oz." eosteinhornensis* s.l. is the most characteristic taxon of this interval, together with *Oulodus el. elegans*.

Plate 2

Fig. 1 - *Zieglerodina remscheidensis* (Ziegler, 1960), Pa element; sample ARG 03; lateral view, x65.
Fig. 2 - *Oulodus elegans detortus* (Walliser, 1964), Sc element; sample MP 10E; lateral view, x80.
Fig. 3 - *Ozarkodina eosteinhornensis* s.s. (Walliser, 1964), Pa element; sample MP 11; upper view, x80.
Fig. 4 - *Ozarkodina crispa* (Walliser, 1964), Pa element; sample GCIU 11; upper view, x50.
Fig. 5 - *Ozarkodina confluens* (Branson & Mehl, 1934), Pa element; sample SBF 4; lateral view, x50.
Fig. 6 - *Polygnathoides siluricus* Branson & Mehl, 1934, Pa element; sample SF 9; upper-lateral view, x50.
Fig. 7 - *Ancoradella ploeckensis* Walliser, 1964, Pa element; sample SBF 5; upper view, x50.
Fig. 8 - *Coryssognathus dubius* (Rhodes, 1953), Sc element; sample SBF 9; lateral view, x80.
Fig. 9 - *Pseudooneotodus bicornis bicornis* (Drygant, 1974); sample ARG 01; upper view, x80.
Fig. 10 - *Wurmiella inflata* (Walliser, 1964), Pa element; sample SIL 4; lateral view, x80.
Fig. 11 - *Kockelella variabilis variabilis* Walliser, 1957, Pa element; sample GALE-BK 23; upper view, x66.
Fig. 12 - *Ozarkodina bohemica* (Walliser, 1964), Pa element; sample SAD-BK 2; lateral view, x90.
Fig. 13 - *Dapsilodus obliquicostatus* (Branson & Mehl, 1933), Sa element; sample PF 1A; lateral view, x80.
Fig. 14 - *Ozarkodina sagitta sagitta* (Walliser, 1964), Pa element; sample PF 1; lateral view, x80.
Fig. 15 - *Pterospathodus pennatus procerus* (Walliser, 1964), Pa element; sample ARG C; upper view, x90.
Fig. 16 - *Kockelella ranuliformis* (Walliser, 1964), Pa element; sample ARG C; upper view, x80.

1, 9, 15-16 refigured after Corradini et al. (1998b); 2-3 refigured after Olivieri & Serpagli (1990); 4 refigured after Corradini et al. (1998b); 5, 7-8 refigured after Corradini et al. (2001); 10 refigured after Serpagli et al. (1998); 11 refigured after Serpagli & Corradini (1999); 12 refigured after Barca et al. (1992); 13-14 refigured after Serpagli (1971).


1


2


3


4

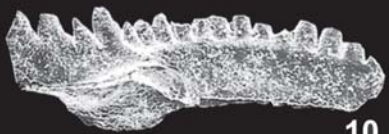

5


6


7


8


9


10

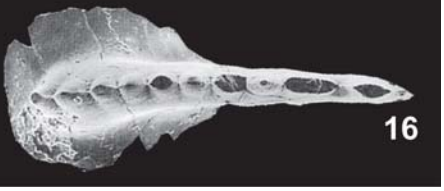

11


12


13


14


15


16

As already pointed out above, the *detortus* Zone is longer in Sardinia than in other regions, and, consequently, the use of *Oul. el. detortus* for long distance correlations could be inappropriate (Gouwy & Corradini, 2006). Very useful for this purpose is *"Oz." eosteinhornensis* s.s., that marks a narrow interval in the upper part of the zone.

Several taxa have their last occurrence in Sardinia within the *detortus* Zone, however it could not be excluded that at least a few may have a longer range. Earliest Devonian conodont data are, in fact, still scarce in Sardinia due to a facies change to typical shaley sediments in southeastern Sardinia and to the existence of only one mainly calcareous section in the southwestern spanning the Silurian/Devonian boundary (Mason Porcus; Gnoli et al., 1988; Olivieri & Serpagli, 1990).

ACKNOWLEDGEMENTS

Funding for this work was provided by MIUR-PRIN2007 (*Analysis of stratigraphic, palaentological and structural features of the Hercynian basement and the Tertiary cover in Sardinia and Calabria, as a contribution to the geodynamic reconstruction of the Central-western Mediterranean basin*).

REFERENCES

BARCA S., CORRADINI C., FERRETTI A., OLIVIERI R. & SERPAGLI E. (1995). Conodont biostratigraphy of the "Ockerkalk" (Silurian) from southeastern Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia,* 100 (4) (1994): 459-476.

BARCA S., FERRETTI A., MASSA P. & SERPAGLI E. (1992). The Hercynian Arburese Tectonic Unit of SW Sardinia. New stratigraphic and structural data. *Rivista Italiana di Paleontologia e Stratigrafia,* 98 (2): 119-136.

CARLS P., SLAVIK L. & VALENZUELA-RIOS J.I. (2007). Revision of conodont biostratigraphy across the Silurian-Devonian boundary. *Bulletin of Geosciences,* 82: 145-164.

CORRADINI C. (2008). The conodont Genus *Pseudooneotodus* Drygant from the Silurian and Lower Devonian of Sardinia and the Carnic Alps (Italy). *Bollettino della Società Paleontologica Italiana,* 36 (2-3): 139-148.

CORRADINI C., FERRETTI A. & SERPAGLI E. (1998a). Wenlock and Pridoli conodonts from Argiola, East of Domusnovas. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia,* 60, Spec. Issue: 194-198.

CORRADINI C., FERRETTI A., SERPAGLI E. & BARCA S. (1998b). The Ludlow-Pridoli Section "Genna Ciuerciu" west of Silius. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia,* 60, Spec. Issue: 112-118.

CORRADINI C., LEONE F., LOI A. & SERPAGLI E. (2001). Conodont Stratigraphy of a highly tectonised Siluro-Devonian Section in the San Basilio area (SE Sardinia). *Bollettino della Società Paleontologica Italiana,* 40 (3): 315-323.

CORRADINI C. & OLIVIERI R. (1997). Conodont biostratigraphy of some supplementary sections in the Sardinian "Ockerkalk" (Upper Silurian). *Bollettino del Museo regionale di Scienze Naturali di Torino,* 15: 89-100.

CORRADINI C., OLIVIERI R. & SERPAGLI E. (1996). Possible relationship between anomalous conodonts and Silurian oceanic episodes. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte,* 1996-H.12: 737-746.

CORRADINI C. & SERPAGLI E. (1998). A Late Llandovery-Pridoli (Silurian) conodont biozonation in Sardinia. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia,* 60, Spec. Issue: 85-88.

CORRADINI C. & SERPAGLI E. (1999). A Silurian conodont zonation from late Llandovery to end Pridoli in Sardinia. *Bollettino della Società Paleontologica Italiana,* 38 (2-3): 255-273.

CORRADINI C. & SERPAGLI E. (2000). A new (standard?) Silurian conodont zonation. *Silurian Times,* 8: 25-28.

CORRIGA M.G. & CORRADINI C. (2009). Upper Silurian and Lower Devonian conodonts from the Monte Cocco II Section (Carnic Alps, Italy). *Bulletin of Geosciences,* 84 (1): 155-168.

FERRETTI A., CORRADINI C. & SERPAGLI E. (1998). Wenlock-Ludlow conodonts from Perd'e Fogu (Fluminimaggiore). *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia,* 60, Spec. Issue: 156-167.

GNOLI M., LEONE F., OLIVIERI R. & SERPAGLI E. (1988). The Mason Porcus Section as reference section for Uppermost Silurian-Lowermost Devonian in SW Sardinia. *Bollettino della Società Paleontologica Italiana,* 27 (3): 323-334.

GNOLI M., MASTANDREA A. & OLIVIERI R. (1981). Osservazioni sedimentologiche e biostratigrafiche sui calcari di Gruttixedda nella Sardegna sud occidentale. *Rendiconti della Società Geologica Italiana,* 4: 329-332.

GOUWY S. & CORRADINI C. (2006). Graphic correlation of the Sardinian Ockerkalk (Late Silurian): implications on the conodont biostratigraphy. *GFF,* 128: 103-108.

Murphy M.A., Valenzuela-Rios J.I. & Carls P. (2004). On classification of Pridoli (Silurian)-Lochkovian (Devonian) Spathognathodontidae (Conodonts). *University of California, Riverside Campus Museum Contribution*, 6: 1-25.

Ogg J.G., Ogg G. & Gradstein F.M. (2008). The Concise Geologic Time Scale. 177 pp., Cambridge University Press.

Olivieri R. & Serpagli E. (1990). Latest Silurian-early Devonian conodonts from Mason Porcus Section near Fluminimaggiore, Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 59-76.

Serpagli E. (1967). Prima segnalazione di conodonti del Siluriano della Sardegna e relative osservazioni stratigrafiche. *Rendiconti della Accademia Nazionale dei Lincei, Classe Scienze fisiche matematiche e naturali*, s. 8, 42: 856-858.

Serpagli E. (1971). Uppermost Wenlockian-Upper Ludlowian (Silurian) Conodonts from Western Sardinia. *Bollettino della Società Paleontologica Italiana*, 9 (1): 76-96.

Serpagli E. & Corradini C. (1999). Taxonomy and evolution of *Kockelella* (Conodonta) from Silurian of Sardinia. *Bollettino della Società Paleontologica Italiana*, 38 (2-3): 275-298.

Serpagli E., Corradini C. & Ferretti A. (1998). Conodonts from a Ludlow-Pridoli section near the Silius Village. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 104-111.

Appendix 1 - List of papers related to Silurian conodonts in Sardinia, arranged by year of publication.

Serpagli E. (1967). Prima segnalazione di conodonti del Siluriano della Sardegna e relative osservazioni stratigrafiche. *Rendiconti della Accademia Nazionale dei Lincei, Classe Scienze fisiche matematiche e naturali*, s. 8, 42: 856-858.

Serpagli E. (1971). Uppermost Wenlockian-Upper Ludlowian (Silurian) Conodonts from Western Sardinia. *Bollettino della Società Paleontologica Italiana*, 9 (1): 76-96.

Serpagli E. & Mastandrea A. (1980). Conodont assemblages from the Silurian-Devonian boundary beds of southwestern Sardinia. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1980-H.1: 37-42.

Gnoli M., Mastandrea A. & Olivieri R. (1981). Osservazioni sedimentologiche e biostratigrafiche sui calcari di Gruttixedda nella Sardegna sud occidentale. *Rendiconti della Società Geologica Italiana*, 4: 329-332.

Serpagli E. (1983). The conodont apparatus of *Icriodus woschmidti woschmidti* Ziegler. *Fossil and Strata*, 15: 155-161.

Barca S., Gnoli M., Olivieri R. & Serpagli E. (1986). New stratigraphic data and evidence of Lower and Upper Devonian based on conodonts in Sarrabus area (Southeastern Sardinia). *Rivista Italiana di Paleontologia e Stratigrafia*, 92 (3): 299-320.

Gnoli M., Leone F., Olivieri R. & Serpagli E. (1988). The Mason Porcus Section as reference section for Uppermost Silurian-Lowermost Devonian in SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 27 (3): 323-334.

Gnoli M., Kriz J., Leone F., Olivieri R., Serpagli E. & Storch P. (1990). Lithostratigraphic units and biostratigraphy of the Silurian and early Devonian of Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 11-23.

Olivieri R. & Serpagli E. (1990). Latest Silurian-early Devonian conodonts from Mason Porcus Section near Fluminimaggiore, Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 59-76.

Barca S. & Olivieri R. (1991). Age and source of calcareous blocks resedimented into Hercynian Flysch type sediments of the Sarrabus area (Southeastern Sardinia). *Atti della Società dei Naturalisti e Matematici di Modena*, 122: 46-66.

Barca S., Ferretti A., Massa P. & Serpagli E. (1992). The Hercynian Arburese Tectonic Unit of SW Sardinia. New stratigraphic and structural data. *Rivista Italiana di Paleontologia e Stratigrafia*, 98 (2): 119-136.

Barca S., Corradini C., Ferretti A., Olivieri R. & Serpagli E. (1995). Conodont biostratigraphy of the "Ockerkalk" (Silurian) from southeastern Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 100 (4) (1994): 459-476.

Corradini C., Olivieri R. & Serpagli E. (1996). Possible relationship between anomalous conodonts and Silurian oceanic episodes. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1996-H.12: 737-746.

Ferretti A. & Serpagli E. (1996). Geological outline, community sequence and paleoecology of the Silurian of Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 102: 353-362.

Corradini C. & Olivieri R. (1997). Conodont biostratigraphy of some supplementary sections in the Sardinian "Ockerkalk" (Upper Silurian). *Bollettino del Museo regionale di Scienze Naturali di Torino*, 15: 89-100.

Serpagli E., Corradini C. & Olivieri R. (1997). Occurrence and range of the Silurian conodont *Coryssognathus dubius* (Rhodes 1953) in southern Sardinia. *Bollettino della Società Paleontologica Italiana*, 35(3) (1996): 239-243.

Ferretti A., Corradini C. & Serpagli E. (1998). The Silurian and Devonian sequence in SW Sardinia. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 57-61.

Corradini C., Ferretti A. & Serpagli E. (1998). The Silurian and Devonian sequence in SE Sardinia. *In* Serpagli E. (Ed.), Sardinia Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 71-74.

Serpagli E. & Corradini C. (1998). New taxa of *Kockelella* (Conodonta) from Late Wenlock-Ludlow (Silurian) of Sardinia. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 79-83.

Corradini C. & Serpagli E. (1998). A Late Llandovery-Pridoli (Silurian) conodont biozonation in Sardinia. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 85-88.

Serpagli E., Corradini C. & Ferretti A. (1998). Conodonts from a Ludlow-Pridoli section near the Silius Village. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 104-111.

Corradini C., Ferretti A., Serpagli E. & Barca S. (1998). The Ludlow-Pridoli Section "Genna Ciuerciu" west of Silius. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 112-118.

Ferretti A., Corradini C. & Serpagli E. (1998). Wenlock-Ludlow conodonts from Perd'e Fogu (Fluminimaggiore). *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 156-167.

Corradini C., Ferretti A. & Serpagli E. (1998). Wenlock and Pridoli conodonts from Argiola, East of Domusnovas. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 194-198.

Corradini C. & Serpagli E. (1999). A Silurian conodont zonation from late Llandovery to end Pridoli in Sardinia. *Bollettino della Società Paleontologica Italiana*, 38 (2-3): 255-273.

Serpagli E. & Corradini C. (1999). Taxonomy and evolution of *Kockelella* (Conodonta) from Silurian of Sardinia. *Bollettino della Società Paleontologica Italiana*, 38 (2-3): 275-298.

Corradini C. & Serpagli E. (2000). A new (standard?) Silurian conodont zonation. *Silurian Times*, 8: 25-28.

Corradini C., Ferretti A. & Serpagli E. (2000). Correlazioni biostratigrafiche negli "Ockerkalk" (Siluriano sup.) della Sardegna sud-orientale. *In* Cherchi A. & Corradini C. (Eds.), Crisi biologiche, radiazioni adattative e dinamica delle piattaforme carbonatiche. *Accademia Nazionale di Scienze Lettere Arti di Modena, Collana di Studi*, 21: 87-92.

Corradini C. (2001). Il genere *Pseudooneotodus* Drygant (Conodonta) nel Siluriano e Devoniano Inferiore della Sardegna. *In* Perri M.C. (Ed.), Giornate di Paleontologia 2001. *Giornale di Geologia*, ser. 3a, 62, Suppl.: 23-29.

Corradini C., Leone F., Loi A. & Serpagli E. (2001). Conodont Stratigraphy of a highly tectonised Siluro-Devonian Section in the San Basilio area (SE Sardinia). *Bollettino della Società Paleontologica Italiana*, 40 (3): 315-323.

Corradini C., Ferretti A. & Serpagli E. (2002). The Gerrei Tectonic Unit (SE Sardinia, Italy). *Rendiconti della Società Paleontologica Italiana*, 1: 69-76.

Corradini C., Ferretti A. & Serpagli E. (2002). The "Ockerkalk" limestone in the Genna Ciuerciu Section (SE Sardinia, Italy). *Rendiconti della Società Paleontologica Italiana*, 1: 255-260.

Corradini C., Ferretti A. & Serpagli E. (2004). The "Ockerkalk" limestone (late Silurian) of the Silius area: palaeobiological content and biostratigraphy. *In* Barca S., Carannante G., Cassinis G., Cherchi A., Corradini C., Cortesogno L., Del Rio M., Durand M., Ferretti A., Fontana D., Funedda A., Gaggero L., Garau A.M., Leone F., Macciotta G., Marchi M., Matteucci R., Murru M., Neri C., Loi A., Pillola G.L., Pittau P., Ronchi A., Salvadori I., Sarria E., Schroeder R., Serpagli E., Simone L. & Stefani C., Sardinian Paleozoic basement and its meso-cainozoic covers (Italy). 32 IGC - Field Trip Guide Book - P39: 18-20.

Gouwy S. & Corradini C. (2006). Graphic correlation of the Sardinian Ockerkalk (Late Silurian): implications on the conodont biostratigraphy. *GFF*, 128: 103-108.

Corradini C. (2007). Scisti a Graptoliti. *In* Carta Geologica d'Italia 1:50000 – Catalogo delle Formazioni; fascicolo VI – Unità tradizionali e/o storiche. *Quaderni*, s.III, 7: 293-297.

Corradini C. (2008). The conodont Genus *Pseudooneotodus* Drygant from the Silurian and Lower Devonian of Sardinia and the Carnic Alps (Italy). *Bollettino della Società Paleontologica Italiana*, 36 (2-3): 139-148.

Corradini C. & Ferretti A. (2009). The Silurian of the External Nappes (southeastern Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (1): 43-49.

Corradini C., Corriga M.G., Ferretti A. & Leone F. (2009). The Silurian of the Foreland Zone (southwestern Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (1): 51-56.

Corriga M.G., Corradini C. & Ferretti A. (2009). Silurian conodonts from Sardinia: an overview. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 95-107.

Storch P., Piras S. & Corriga M.G. (2009). Wenlockian graptolites and the Lower Graptolitic Shales-Ockerkalk transition East of Lantini Tunnel near Ballao (SESardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 187-190.

Corradini C., Ferretti A., Corriga M.G. & Serpagli E.. (2009). The reference section of the Sardinian Ockerkalk: the Silius Section. *Rendiconti della Società Paleontologica Italiana*, 3 (2): 209-216.

Corradini C., Ferretti A., Corriga M.G. & Serpagli E. (2009). Loboliths (crinoids) and conodont biostratigraphy of the Genna Ciuerciu Section (SE Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 217-224.

Pillola G.L., Ferretti A., Corriga M.G. & Corradini C. (2009). Highly tectonized Silurian and Lower Devonian sediments at Funtanamare (SW Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 247-252.

Ferretti A., Corradini C., Kriz J., Piras S. & Serpagli E. (2009). The Perd’e Fogu outcrop: a classical exposure of “*Orthoceras* limestone” in the Fluminimaggiore area (SW Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 253-264.

Appendix 2 - Index of localities

ARG:	Argiola; 39°20’02"N, 8°41’50"E, about 4 km East of Domusnovas. Locality described by Corradini et al. (1998).
BAR:	Barbusi; 39°12’20"N, 8°30’11"E, about 500 m East of Barbusi.
BS:	Baccu Scottis; 39°27’38"N, 9°34'21"E, about 2 km North of Villaputzu.
CAR:	Punta Carroga; 39°29'02"N, 9°33’47"E, about 4.6 km North of San Vito.
CB:	Corti Baccas; 39°26’49"N, 8°29’34"E, about 1 km North of Fluminimaggiore.
CS:	Case Scivu; 39°26'01"N, 8°24’59"E, about 1 km North of Fluminimaggiore.
FTM:	Funtanamare; 39°17’30"N, 8°26’20"E, about 2.3 km South of Nebida.
FRU:	Monte Fruccas; 39°37’26"N, 9°11’19"E, about 2.2 km North of Siurgus Donigala. Locality described by Corradini & Olivieri (1997).
GA:	Genna Arrela; 39°28’31"N, 9°36’19"E, about 4.5 km North of Villaputzu, in a road cut. Locality described by Corradini & Olivieri (1997).
GALE:	Galemmu; 39°26’42"N, 8°29’47"E, about 700 m North of Fluminimaggiore.
GCIU:	Genna Ciuerciu; 39°30’53"N, 9°17’01"E, about 900 m West of Silius. Locality described by Barca et al. (1995) and Corradini et al. (1998, 2002).
GRU:	Gruttixedda; 39°22’45"N, 8°41’03"E about 6.5 km North-West of Domusnovas. Locality described by Gnoli et al. (1981).
LT:	Lantini Tunnel; 39°32’21"N, 9°23’19"E, about 2.5 km East-South-East of Ballao.
NSF:	Nuraghe su Franzesu; 39°28’41"N, 9°38’36"E, about 6.8 km North-East of Villaputzu.
MP:	Mason Porcus; 39°26'51"N, 8°31'19"E, about 2.1 km East-North-East of Fluminimaggiore. Locality described by Gnoli et al. (1988), Olivieri & Serpagli (1990).
PF:	Perd’e Fogu; 39°26’37"N, 8°30’02"E, about 600 m North-East of Fluminimaggiore. Locality described by Ferretti et al. (1998).
PM:	Pala Manna; 39°23’35"N, 9°20’23"E, about 5.6 km North of Burcei. Locality described by Barca et al. (1986).
PML:	Ponte Monte Lora; 39°28’45"N, 9°29’24"E, about 6 km North-West of San Vito. Locality described by Corradini & Olivieri (1997).
RMC:	Rio Murru de Callus; 39°35’53"N, 9°13’25"E, about 3 km East of Siurgus Donigala.
RT:	Roia is Tintionis; 39°27'18"N, 8°28'35"E, about 2.5 km North-West of Fluminimaggiore.
SAD:	Sant’Antonio Donigala; 39°41’58"N, 8°29’37"E, about 1.6 km South of Sant’Antonio di Santadi. Locality described by Barca et al. (1992).
SBF:	San Basilio Fenugu; 39°32’03"N, 9°12’43"E, about 1.2 km East of San Basilio. Locality described by Corradini et al. (2001).
SF:	Sentiero Flumini; 39°26’32"N, 8°30’20"E, about 800 m North-East of Fluminimaggiore. Locality described by Serpagli (1971).
SIL I°:	Silius I°; 39°31’02"N, 9°17’13"E, about 500 m West of Silius. Locality described by Barca et al. (1995) and Serpagli et al. (1998).
SN:	Su Nuargi; 39°19’37"N, 8°40’25"E, about 2 km East of Domusnovas.
TUV:	Tuviois; 39°23’27"N, 9°19’25"E, about 5.9 km North of Burcei. Locality described by Barca & Olivieri (1991).

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 109-118

Silurian nautiloid cephalopods from Sardinia: the state of the art

Maurizio Gnoli, Paolo Serventi

Maurizio Gnoli - Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia, largo S. Eufemia 19, I-41100 Modena (Italy); maurizio.gnoli@unimore.it
Paolo Serventi - Dipartimento del Museo di Paleobiologia e dell'Orto Botanico, via Università 4, I-41100 Modena (Italy); paolo.serventi@unimore.it

Abstract - The complete faunal list of nautiloid cephalopods from the Silurian of Sardinia has been compiled herein. A history leading to the present state of knowledge on this fossil group, achieved after forty years of extensive study, is reviewed.
A total of 61 species assigned to 38 genera are known from the Wenlock-Pridoli of southern Sardinia. The fauna strongly supports links with coeval associations of Bohemia and, to a lesser extent, with the Carnic Alps.

Key words - Silurian, Sardinia, Cephalopods, Palaeogeography.

Introduction

This paper represents the nautiloid cephalopod sum up of more than forty years of scientific activity within the informal International Group on the Palaeozoic Palaeontology headed by Prof. Enrico Serpagli, who devoted most of his research to the Italian Palaeozoic outcrops mainly in two areas, the Carnic Alps and southern Sardinia. During these years, many field trips have been carried out in Sardinia allowing the collection of an enormous amount of samples studied in detail in their palaeontological (either taxonomic or biostratigraphical) content by Italian, German, English, Irish, Spanish, Swedish and Czech members of the research team. Such a multidisciplinary approach involved also a formal definition of the lithostratigraphical units in the post-Sardic Ordovician (Leone et al., 1991) and in the Silurian-Lower Devonian of southwestern Sardinia (Gnoli et al., 1990). The aim of this paper is to report the present knowledge on the Sardinian Silurian nautiloid cephalopods.

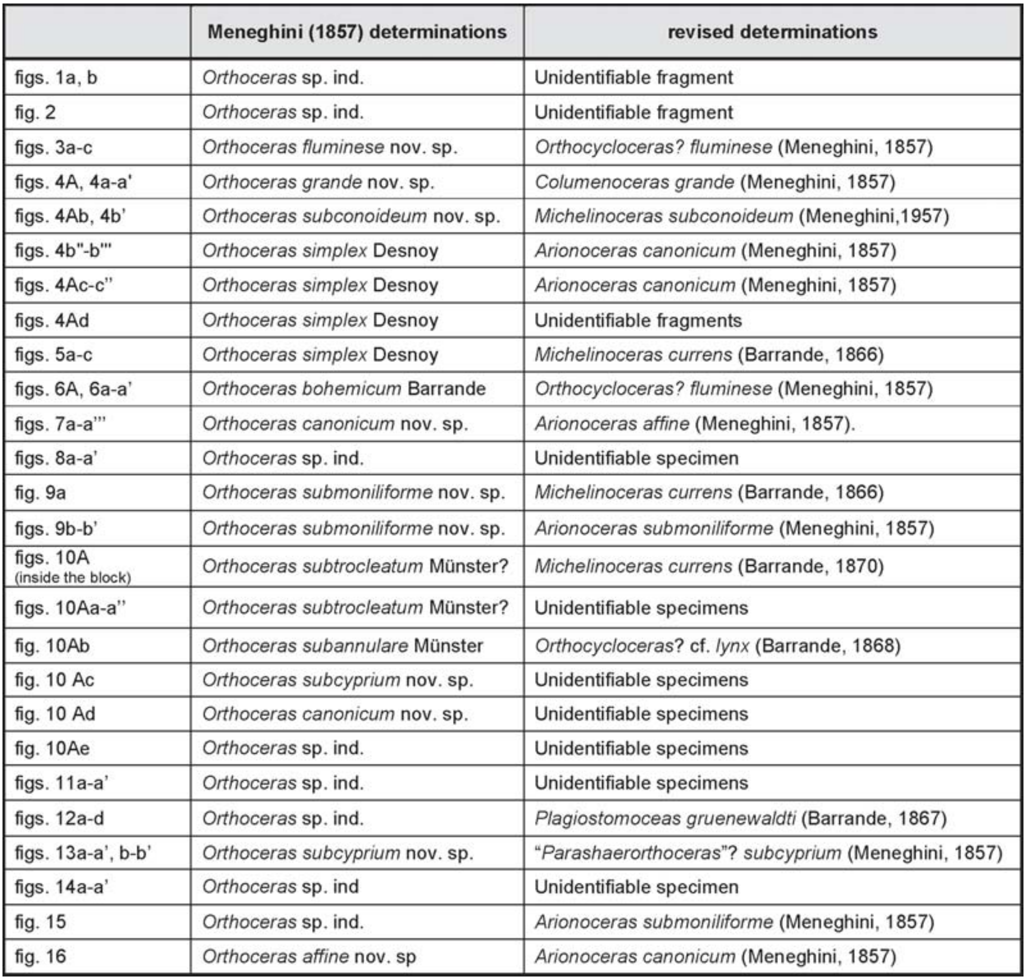
Nautiloid cephalopod fauna

The first description and illustration of these fossils in Sardinia is that of Meneghini (1857) who published the palaeontological part of La Marmora's "Voyage en Sardaigne". Twenty nautiloid species were described from outcrops in the Fluminimaggiore and San Nicolò Gerrei areas. Meneghini's original fauna (Fig. 1) has been later restudied by Gnoli & Serpagli (1977) and its updated list is reported in Tab. 1.

Later on, after the publication of Meneghini's pioneering contribution, some other mainly geological papers (Canavari, 1899; Novarese, 1922; Novarese & Taricco, 1923) mentioned the occurrence of orthoconic nautiloids (a summary of these old studies, including faunal lists, was published by Comaschi-Caria, 1949, 1974). In the sixties, Ristedt (1968) described and illustrated several juvenile stages of Sardinian Silurian nautiloids from the Fluminese area.

Along with the revision of Meneghini's original fauna by Gnoli & Serpagli (1977) and the collection of new material from the Fluminimaggiore area, Serpagli & Gnoli (1977) published a large monograph with 9 plates on Silurian cephalopods from southwestern Sardinia. In that paper, still representing a milestone in our knowledge of the Silurian of Sardinia, 38 species of 21 genera were described and illustrated. New taxa were introduced and important systematic emendations were suggested. Furthermore, representatives of actinoceroid and cyrthoceraconic genera were mentioned in the Mediterranean area for the first time (Serpagli & Gnoli, 1977). As a whole, a strong affinity with the Barrandian nautiloid fauna was highlighted.

Gnoli (1987) revised "*Orthoceras*" *grande* Meneghini, 1857 as a true *Columenoceras* because of its inner features, and included it in the Family Geisonoceratidae Zhuravleva, 1959. Further contributions to a refinement of previous taxonomic knowledge were



	Meneghini (1857) determinations	**revised determinations**
figs. 1a, b	*Orthoceras* sp. ind.	Unidentifiable fragment
fig. 2	*Orthoceras* sp. ind.	Unidentifiable fragment
figs. 3a-c	*Orthoceras fluminese* nov. sp.	*Orthocycloceras? fluminese* (Meneghini, 1857)
figs. 4A, 4a-a'	*Orthoceras grande* nov. sp.	*Columenoceras grande* (Meneghini, 1857)
figs. 4Ab, 4b'	*Orthoceras subconoideum* nov. sp.	*Michelinoceras subconoideum* (Meneghini,1957)
figs. 4b"-b"'	*Orthoceras simplex* Desnoy	*Arionoceras canonicum* (Meneghini, 1857)
figs. 4Ac-c"	*Orthoceras simplex* Desnoy	*Arionoceras canonicum* (Meneghini, 1857)
figs. 4Ad	*Orthoceras simplex* Desnoy	Unidentifiable fragments
figs. 5a-c	*Orthoceras simplex* Desnoy	*Michelinoceras currens* (Barrande, 1866)
figs. 6A, 6a-a'	*Orthoceras bohemicum* Barrande	*Orthocycloceras? fluminese* (Meneghini, 1857)
figs. 7a-a"'	*Orthoceras canonicum* nov. sp.	*Arionoceras affine* (Meneghini, 1857).
figs. 8a-a'	*Orthoceras* sp. ind.	Unidentifiable specimen
fig. 9a	*Orthoceras submoniliforme* nov. sp.	*Michelinoceras currens* (Barrande, 1866)
figs. 9b-b'	*Orthoceras submoniliforme* nov. sp.	*Arionoceras submoniliforme* (Meneghini, 1857)
figs. 10A (inside the block)	*Orthoceras subtrocleatum* Münster?	*Michelinoceras currens* (Barrande, 1870)
figs. 10Aa-a"	*Orthoceras subtrocleatum* Münster?	Unidentifiable specimens
fig. 10Ab	*Orthoceras subannulare* Münster	*Orthocycloceras*? cf. *lynx* (Barrande, 1868)
fig. 10 Ac	*Orthoceras subcyprium* nov. sp.	Unidentifiable specimens
fig. 10 Ad	*Orthoceras canonicum* nov. sp.	Unidentifiable specimens
fig. 10Ae	*Orthoceras* sp. ind.	Unidentifiable specimens
figs. 11a-a'	*Orthoceras* sp. ind.	Unidentifiable specimens
figs. 12a-d	*Orthoceras* sp. ind.	*Plagiostomoceas gruenewaldti* (Barrande, 1867)
figs. 13a-a', b-b'	*Orthoceras subcyprium* nov. sp.	"*Parashaerorthoceras*"? *subcyprium* (Meneghini, 1857)
figs. 14a-a'	*Orthoceras* sp. ind	Unidentifiable specimen
fig. 15	*Orthoceras* sp. ind.	*Arionoceras submoniliforme* (Meneghini, 1857)
fig. 16	*Orthoceras affine* nov. sp	*Arionoceras canonicum* (Meneghini, 1857)

Tab. 1 - Revision of specimens figured by Meneghini (1857).

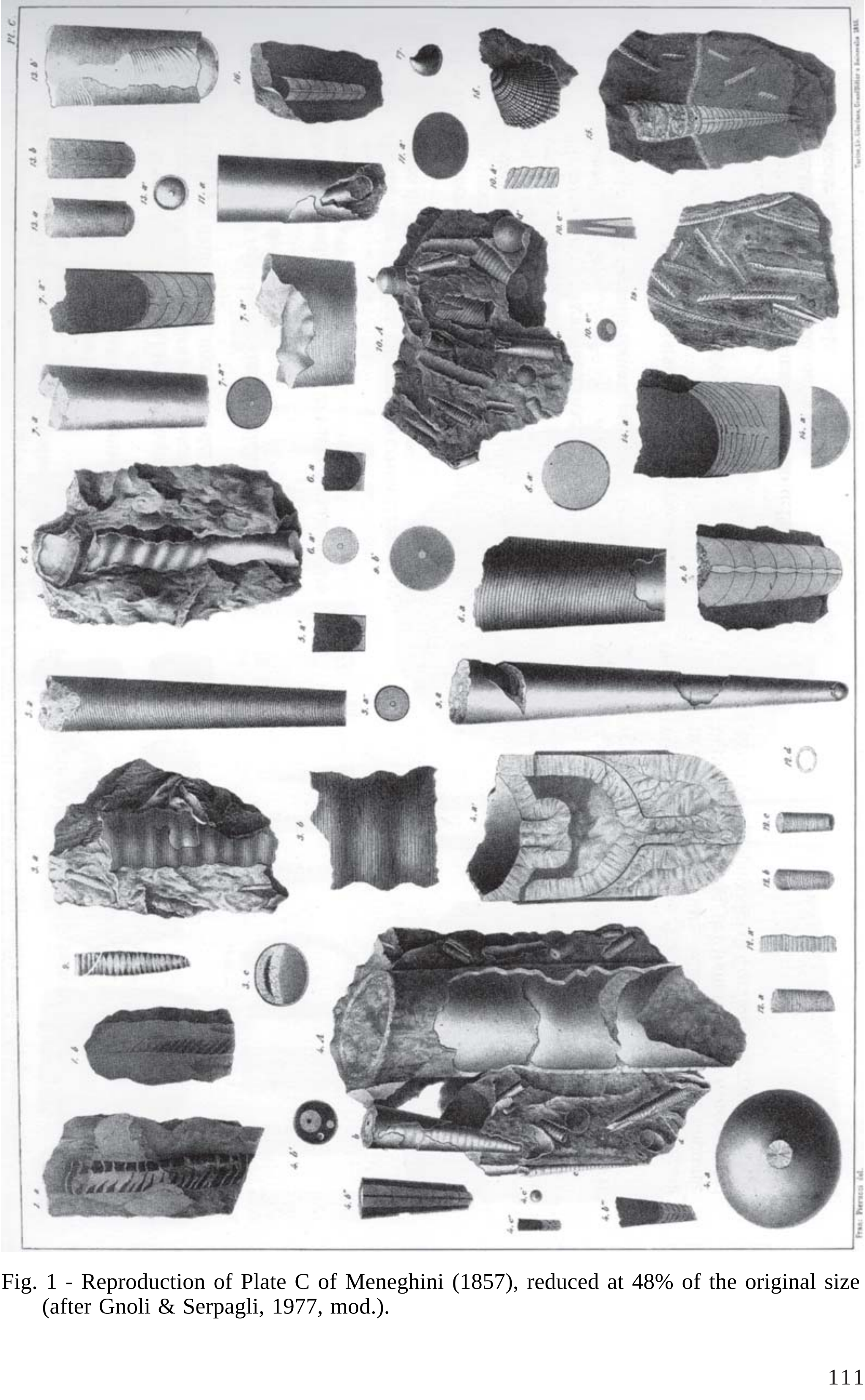


Fig. 1 - Reproduction of Plate C of Meneghini (1857), reduced at 48% of the original size (after Gnoli & Serpagli, 1977, mod.).

submitted by Gnoli (1990, 1994, 1996, 1998), Kiselev & Gnoli (1992), Gnoli & Kiselev (1994), Holland (2000) and Gnoli & Serventi (2006). At the same time, *O. pseudocalamiteum* Barrande was regarded as a type species of the new genus *Calorthoceras* (Chen et al., 1981).

At present the complete Nautiloidea faunal content of the Sardinian Silurian is listed below. In all, 61 taxa are identified at the species level, belonging to 12 higher taxa at family or subfamily level, belonging in turn to the orders Orthocerida, Actinocerida and Oncocerida. No Pseudorthocerida have been identified till now.

The systematic scheme adopted by the Treatise Part K Mollusca 3 (1964) is here followed, with integrations by T. Engeser's Data Retrieval System Nautiloidea. Dzik's 1984 "Phylogeny of Nautiloidea" was also taken in account.

Phylum MOLLUSCA Linnaeus, 1758
Class Cephalopoda Couvier, 1797
Subclass Nautiloidea Agassiz, 1847

Order Orthocerida Kuhn, 1940
Fam. Orthoceratidae M'Coy, 1844
Subfam. Michelinoceratinae Flower, 1945 amend. Kiselev & Gnoli, 1992
Hemicosmorthoceras laterculum Ristedt, 1968
Hemicosmorthoceras semiannulatum (Barrande, 1870)
Hemicosmorthoceras aff. *serratulum* (Barrande, 1867)
Hemicosmorthoceras sp. *sensu* Serpagli & Gnoli, 1977
Kopaninoceras jucundum (Barrande, 1870)
Kopaninoceras? *thyrsus* (Barrande, 1870)
Mericoceras? cf. *sericatum* (Barrande, 1868)
Mericoceras? cf. *simois* (Barrande, 1867)
Michelinoceras (*Michelinoceras*) *currens* (Barrande, 1866)
Michelinoceras (*Michelinoceras*) *michelini* (Barrande, 1866)

Plate 1

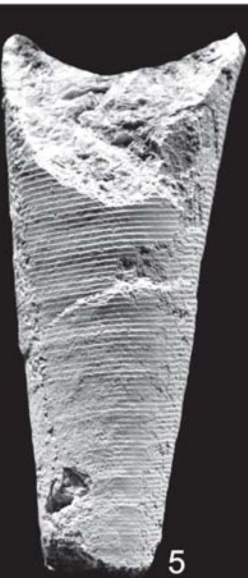
Fig. 1 - *Michelinoceras* (*Michelinoceras*) *michelini* (Barrande, 1866), young specimen in lateral view (IPUM 18987); Fluminimaggiore area, upper Silurian; x2.
Fig. 2 - *Arionoceras submoniliforme* (Meneghini, 1857), lateral view of a juvenile specimen (IPUM 19066); Fluminimaggiore area, upper Silurian; x10.
Fig. 3 - *Orthocycloceras*? *fluminese* (Meneghini, 1857), lateral view (IPUM 19046); Fluminimaggiore area, upper Silurian; x1.
Fig. 4 - *Hemicosmorthoceras* sp., lateral view (IPUM 18977); Fluminimaggiore area, upper Silurian; x5.
Fig. 5 - *Pseudocycloceras transiens* (Barrande, 1866), lateral view (IPUM 21655)~~V~~ "Sentiero Flumini" locality, lower Ludlow; x2.
Fig. 6 - *Columenoceras*? *degener* (Barrande, 1870), lateral view (IPUM 21661); "Mason Porcus" section, Pridoli; x1.
Fig. 7 - *Columenoceras* cf. *columen* (Barrande, 1867), dorsoventral section to show inner features (IPUM 19074); Fluminimaggiore area, upper Silurian; x1.
Fig. 8 - *Geisonoceras* cf. *socium* (Barrande, 1859), lateral view (IPUM 21665); "Galemmu" locality, lower Ludlow; x1.


1

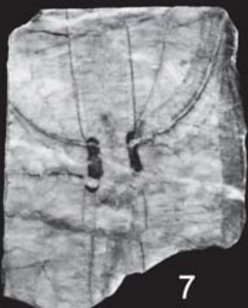

2


3


4


5


6


7


8

Michelinoceras (*Michelinoceras*) *subconoideum* (Meneghini, 1857)
Michelinoceras (*Michelinoceras*) sp. 1 *sensu* Serpagli & Gnoli, 1977
Michelinoceras (*Michelinoceras*) sp. 2 *sensu* Serpagli & Gnoli, 1977
Michelinoceras (*Michelinoceras*) sp. 3 *sensu* Serpagli & Gnoli, 1977
Michelinoceras (*Sphaerorthoceras*) *beatum* (Ristedt, 1968)
Michelinoceras (*Sphaerorthoceras*) *curvum* (Ristedt, 1968)
Michelinoceras (*Sphaerorthoceras*) *teicherti* (Ristedt, 1968)
Michelinoceras (*Sphaerorthoceras*) sp. *sensu* Serpagli & Gnoli, 1977
«*Parasphaerorthoceras*» sp. B *sensu* Ristedt, 1968
«*Parasphaerorthoceras*» sp. H *sensu* Ristedt, 1968
«*Parasphaerorthoceras*» sp. J *sensu* Ristedt, 1968
«*Parasphaerorthoceras*» sp. K *sensu* Ristedt, 1968

Subfam. Protobactritinae Chen, 1981
Plagiostomoceras gruenewaldti (Barrande)
Plagiostomoceras cf. *pleurotomum* (Barrande)
Protobactrites? sp. *sensu* Serpagli & Gnoli, 1977

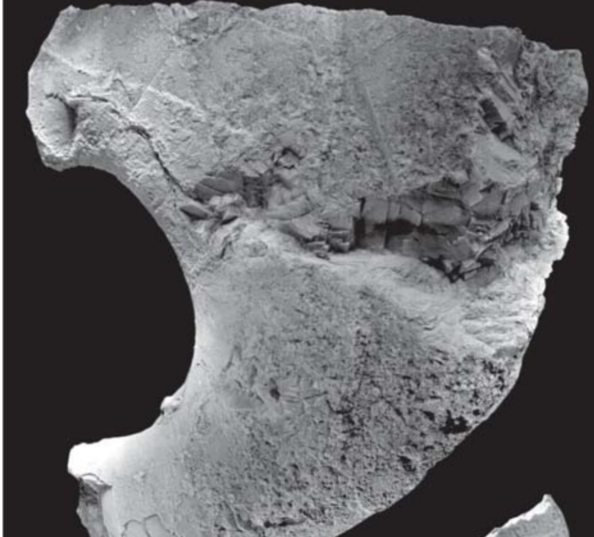
Subfam. Leurocycloceratinae Sweet, 1964
Akrosphaerorthoceras gregale Ristedt, 1968
Calorthoceras pseudocalamiteum (Barrande in Quenstedt, 1851)
Orthocycloceras fluminese (Meneghini, 1857)
Orthocycloceras cf. *lynx* (Barrande)
Merocycloceras declive Ristedt, 1968
Pseudocycloceras transiens (Barrande, 1866)

Subfam. Kionoceratinae Hyatt in Zittel, 1900
Kionoceras doricum (Barrande, 1868)
Parakionoceras originale (Barrande, 1868)
Vericeras ambigena (Barrande)

Fam. Geisonoceratidae Zhuravleva, 1959
Arionoceras canonicum (Meneghini, 1857)
Arionoceras? *repetitum* (Barrande, 1866)

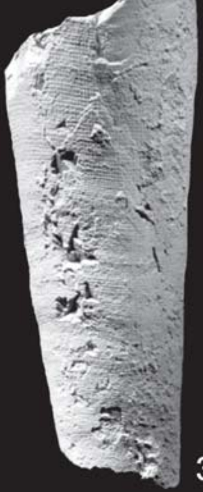
Plate 2

Fig. 1 - *Phragmoceras broderipi subleve* (Barrande, 1865), lateral view (IPUM 21677); “Sentiero Flumini” locality, upper Wenlock; x0,75.
Fig. 2 - *Protophragmoceras minus* (Barrande, 1865), lateral view (IPUM 21678); “Galemmu” locality, lower Ludlow; x1.
Fig. 3 - *Mericoceras*? cf. *sericatum* (Barrande, 1868), ventral view (IPUM 21653); “Sentiero Flumini” locality, lower Wenlock; x2.
Fig. 4 - *Oonoceras acinaces elongatum* (Barrande, 1866), view of the polished longitudinal middle section (IPUM 33100); “Argiola” locality, Pridoli; x1,5.
Figs. 5-6 - *Sphooceras truncatum* (Barrande, 1860).
5. ventral view enlarged to show “finger print” type ornament of the outer truncature callus (IPUM 21672); Fluminimaggiore area, lower Ludlow; x1;
6. terminal view to show siphuncle position and radial arrangement of intermediate callus (IPUM 21674); Fluminimaggiore area, lower Ludlow; x5.
Fig. 7 - *Aptychopsis prima* Barrande, 1872 (IPUM 21661); “Sentiero Flumini” locality, lower Wenlock; x5.



1

2



3

5

4

7

6

Arionoceras submoniliforme (Meneghini, 1857)
Columenoceras agassizi (Barrande, 1866)
Columenoceras cf. *columen* (Barrande, 1867)
Columenoceras? *degener* (Barrande, 1870)
Columenoceras grande (Meneghini, 1857)
Columenoceras? *intermixtum* (Barrande, 1867)
Cryptocycloceras? cf. *deludens* (Barrande, 1870)
Geisonoceras? cf. *socium* (Barrande, 1859)
Geisonoceras sp. *sensu* Gnoli, 1990
Harrisoceras vibrayei (Barrande, 1859)
Murchisoniceras? *calamoides* (Barrande, 1867)
Temperoceras temperans (Barrande, 1867) = *Temperoceras ludense* (Sowerby in Murchison, 1839) *fide* Holland, 2000.

Fam. Sphooceratidae Flower, 1962
Subfam. Sphooceratinae Flower, 1962 amend. Gnoli & Kiselev, 1994
Sphooceras truncatum (Barrande, 1860)

Subfam. Disjunctoceratinae Gnoli & Kiselev, 1994
Disjunctoceras disjunctum (Barrande, 1868)

Fam. Lechritrochoceratidae Flower, 1950
Kosovoceras sandbergeri (Barrande, 1865)

Fam. Phragmoceratidae Hyatt, 1900
Phragmoceras broderipi subleve (Barrande, 1865)
Phragmoceras cf. *labiosum* (Barrande, 1865)
Protophragmoceras minus (Barrande, 1865)

Order Actinocerida Teichert, 1933
Fam. Ormoceratidae Saemann, 1853
Metarmenoceras? *meneghinii* Serpagli & Gnoli, 1977
Sactoceras richteri (Barrande, 1866)

Order Oncocerida Flower in Flower & Kummel, 1950
Fam. Oncoceratidae Hyatt, 1884
Oocerina abdita (Barrande, 1877)
Oonoceras plebeium (Barrande, 1866)
Oonoceras acinaces elongatum (Barrande, 1866)

Fam. Acleistoceratidae Flower in Flower & Kummel, 1950
Galtoceras? *sardous* Serpagli & Gnoli, 1977

Order and Family uncertain
Aptychopsis prima Barrande, 1872 (see remarks below)

For two decades *Aptychopsis*, has been considered, even if with some doubts, to be an opercular nautiloid device (Holland et al., 1978; Turek, 1978; Stridsberg, 1984; Holland, 1996). Its final interpretation, however, is far from accepted. *Aptychopsis prima* was recorded and identified years ago, though never published, by one of us (MG) from two levels in the Wenlock of Fluminimaggiore area. Such a fossil is listed here as part of the Sardinian Silurian cephalopod assemblage for the first time (Pl. 3, fig. 7).

OTHER CONSIDERATIONS

The material collected in the last 40 years allowed not only to better define the composition of the nautiloid cephalopod fauna, but also to interpret its palaeoenvironmental and palaeogeographical significance as well as to test the biostratigraphical implication of respective nautiloid assemblages.

In general, the Late Wenlock-Pridoli cephalopod fauna represents the "*Orthoceras*" Limestone Community (Ferretti et al., 1999), a high to medium diversity community in which nautiloids are associated with bivalves, conodonts, graptolites, crinoidal fragments, crustaceans (ostracodes and phyllocarids), gastropods, and rare brachiopods (Gnoli et al., 1988, 1990). Bathymetric studies on about thirty species of nautiloids from the upper Silurian "Orthoceras limestone" of southwestern Sardinia has implied a water depth of <350m, based on those septa that have imploded as they exceeded their calculated hydrostatic limits (Histon & Gnoli, 1994, 1999).

Gnoli & Serpagli (1991) identified three successive assemblages of nautiloid cephalopods from the Fluminimaggiore Formation and tested their biostratigraphical significance by means of conodonts recovered from the same samples. The *Pseudocycloceras transiens*-*Columenoceras grande* Assemblage characterizes Wenlock sediments. It represents a quite widespread fauna, also known from Central Bohemia, Podolia, Poland and Northern Urals (Gnoli & Serpagli, 1991). The *Merocycloceras declive*-*Cryptocycloceras*? *deludens* Assemblage occurs in Ludlow strata, and its representatives are also reported from Central Bohemia, Armorican Massif, the Carnic Alps, Podolia and Poland. The *Kopaninoceras*? *thyrsus*-*Orthocycloceras*? *fluminese* Assemblage spans from the Pridoli to the earliest Lochkovian and is known also from Central Bohemia, Armorican Massif, the Urals, the Russian Platform, Podolia and Poland.

The strong faunal link between Sardinia and the Barrandian of Central Bohemia during the Silurian times, already stressed by many of the previous works, was later confirmed by Holland et al. (1994). Worldwide distribution of cephalopod limestone biofacies distribution was used by Gnoli (2003) to assess the reconstruction of the North Gondwana margin during the Silurian-Early Devonian. A Q-mode cluster analysis on a matrix of faunal similarities, estimated by means of the Jacard coefficient, revealed the greatest faunal similarity between southwestern Sardinia and the Prague Basin (0.89), followed by similarity between the Carnic Alps and the two areas just mentioned (0.70).

REFERENCES

BARRANDE J. (1860). Troncature normale ou périodique de la coquille. *Bulletin de la Société Géologique de France*, Série II,, 17: 573-600.

BARRANDE J. (1865-74). Système Silurien du centre de la Bohême, Ière partie: Recherches Paléontologiques, vol. II, Classe de Mollusques, Ordre des Céphalopodes, 1865: ser. 6, pl. 1-107; 1866: ser. 7, pls. 108-244; 1867: ser. 1, 712pp.; 1868: ser. 8, pls. 245-350; 1870: ser. 2, 266pp., ser.9, pls. 351-460; 1874: ser. 3, 804pp.; 1877: ser. 4, 742pp., ser. 5, 743pp., supplément 1, 297pp., supplément 2, pls. 461-544. Prague, Paris.

CANAVARI M. (1899). La fauna dei calcari nerastri con Cardiola ed Orthoceras di Xea S. Antonio in Sardegna (I. Ostracoda). *Paleontographia Italica*, 5: 187-210.

CHEN J., LIU G. & CHEN T. (1981). Silurian nautiloid faunas of central and southwestern China. *Memoirs of the Nanjing Institute of Geology and Palaeontology*, 13: 1-104.

COMASCHI CARIA I. (1949). I fossili della Sardegna. Istituto per gli Studi Sardi, 410pp., Cagliari.

COMASCHI CARIA I. (1974). Animali e piante fossili della Sardegna. 73pp. Editrice Sarda Fossataro, Cagliari.

DZIK J. (1984). Phylogeny of the Nautiloidea. *Palaeontologia Polonica*, 45: 3-203.

FERRETTI A., GNOLI M. & VAI G.B. (1999). Silurian to Lower Devonian Communities of Sardinia, 271-281. *In* Boucot A.J. &. Lawson J.D. (Eds.), Paleocommunities: A Case Study from the Silurian and Lower Devonian, Cambridge Univ. Press.

Gnoli M. (1987). Revision and autecological remarks of the species *Columenoceras grande* (Meneghini, 1857) (Nautiloidea, Orthocerida). *Bollettino della Società Paleontologica Italiana*, 26 (3): 245-250.

Gnoli M. (1990). New evidence for faunal links between Sardinia and Bohemia in Silurian time on the basis of nautiloids. *Bollettino della Società Paleontologica Italiana*, 29 (3): 289-307.

Gnoli M. (1994). Remarks on minor elements of the Upper Silurian cephalopod fauna of SW Sardinia. *Atti della Società dei Naturalisti e Matematici di Modena*, 124, (1993): 19-26.

Gnoli M. (1996). Occurrence of Bohemian-type Phragmoceratid (Nautiloidea) from the Silurian of Southwestern Sardinia. *Accademia Nazionale di Scienze Lettere e Arti di Modena*, Collana di Studi, 15: 355-360.

Gnoli M. (1998). Some remarks and emendation of the family Arionoceratidae Dzik 1984 (Cephalopoda, Nautiloidea). *Palaeontologia Electronica*, Vol. 1 (2), 1-5. http://palaeo-electronica.org/1998_2/gnoli/text.pdf

Gnoli M. (2003). Northern Gondwanan Siluro-Devonian Palaeogeography assessed by Cephalopods. *Palaeontologia Electronica*, 5 (2): 19 pp. http://palaeo-electronica.org/2002_2/gondwana/gondwana.pdf

Gnoli M. & Kiselev G.N. (1994). Revision of the family Sphooceratidae Flower, 1962. *Bollettino della Società Paleontologica Italiana*, 33 (3): 415-420.

Gnoli M., Kriz J., Leone F., Olivieri R., Serpagli E. & Storch P. (1990). Lithostratigraphic units and biostratigraphy of the Silurian and early Devonian of Southwest Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 11-23.

Gnoli M., Leone F., Olivieri R. & Serpagli E. (1988). The Mason Porcus Section as reference section for Uppermost Silurian-Lower Devonian in SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 27 (3): 323-334.

Gnoli M. & Serpagli E. (1977). Silurian cephalopods of the Meneghini collection (1857) with the reproduction of the original plate. *Bollettino della Società Paleontologica Italiana*, 16 (2):137-142.

Gnoli M. & Serpagli E. (1991). Nautiloid assemblages from middle-late Silurian of Southwestern Sardinia: a proposal. *Bollettino della Società Paleontologica Italiana*, 30 (2): 187-195.

Gnoli M. & Serventi P. (2006). A further Oncocerid nautiloid from the Upper Silurian of South West Sardinia. *GeoAlp*, 3: 3-8.

Histon K. & Gnoli M. (1994). Bathymetry of the Silurian Nautiloid fauna from the “Orthoceratite Limestone”, SW Sardinia. *In* Schönlaub H.P. & Kreutzer L.H. (Eds.), IUGS Subcommission on Silurian Stratigraphy. Field Meeting Eastern + Southern Alps. *Berichte der Geologischen Bundesanstalt*, 30: 131-132.

Histon K. & Gnoli M. (1999). Nautiloid Paleobathymetry from the Silurian “*Orthoceras* Limestone” Facies of SW Sardinia, Italy. *In* Oloriz F. & Rodriguez-Tovar F.J. (Eds.), Advanced researches on Living and Fossil Cephalopods, Kluwer Academic/Plenum Publisher, New York: 281-293.

Holland C.H. (1996). More aptychopsid plates (nautiloid cephalopod opercula) from the Irish Silurian. *Irish Journal of Earth Science*, 15: 91-92.

Holland C.H. (2000). *Harrisoceras* and *Temperoceras* closely related cephalopod genera from the British Silurian. *Bollettino della Società Paleontologica Italiana*, 39 (1): 117-122.

Holland C.H., Gnoli M. & Histon K. (1994) Concentration of Palaeozoic nautiloid cephalopods. *Bollettino della Società Paleontologica Italiana*, 33 (1): 83-99.

Holland C.H., Stridsberg S. & Bergström J. (1978). Confirmation of the reconstruction of *Aptychopsis*. *Lethaia*, 11: 144.

Kiselev G.N. & Gnoli M. (1992). About revision of the genus *Michelinoceras* Foerste, 1932. *Vestnik St. Peterburgskogo Universiteta*, Seriya 7, Geologiya, Geografiya, 1992: 74-75.

Leone F., Hamman W., Laske R., Serpagli E. & Villas E. (1991). Lithostratigraphic units and biostratigraphy of the post sardic Ordovician sequence in south west Sardinia. *Bollettino della Società Paleontologica Italiana*, 30: 201-235.

Meneghini G. (1857). Paléontologie de l’Ile de Sardaigne. *In* La Marmora, A., Voyage en Sardaigne. 584pp., Imprimerie Royal, Turin, Paris.

Moore R.C. (Ed.) (1964). Treatise on Invertebrate Paleontology, Part K Mollusca 3, 519pp. Geological Society of America and the University of Kansas Press.

Novarese V. (1922). Contributo alla geologia dell’Iglesiente: la serie paleozoica. *Bollettino Reale Ufficio Geologico d’Italia*, 49 (10): 49-74.

Novarese V. & Taricco M. (1923). Cenni sommari sul Paleozoico dell’Iglesiente. *Bollettino della Società Geologica Italiana*, 4: 316-325.

Ristedt H. (1968). Zur Revision der Orthoceratidae: *Akademie der Wissenschaften und Literatur in Mainz, Abhandlungen der mathematisch-naturwissenschaftlichen Klasse*, 1968: 211-287.

Serpagli E. & Gnoli M. (1977). Upper Silurian cephalopods from southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 16 (2): 153-195.

Stridsberg S. (1984). *Aptychopsis* plates- jaw elements or protective operculum. *Lethaia*, 17: 93-98.

Turek V. (1978). Biological and stratigraphical significance of the Silurian nautiloid *Aptychopsis*. *Lethaia*, 11: 127-138.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 119-130

The upper Silurian Bivalvia dominated palaeocommunities succession of southwestern Sardinia – correlation with Perunica and the peri-Gondwanan regions of Europe

JIRI KRIZ

J. Kriz - Division of Regional Geology of Sedimentary Formations, Czech Geological Survey, P. O. Box 85, Praha 011 (Czech Republic); jiri.kriz@geology.cz

ABSTRACT - The upper Silurian Bivalvia dominated palaeocommunities succession of southwestern Sardinia is correlated with Perunica (Prague Basin, Bohemia) and the other peri-Gondwanan regions (the Montagne Noire and Massif Armoricain, France and the Carnic Alps, Austria and Italy). Bivalvia are in all regions closely related and show that recurrent cephalopod limestone biofacies developed in Perunica and peri-Gondwana in the upper Sheinwoodian, lower Homerian (Wenlock), the lower Gorstian and lower Ludfordian (Ludlow) with the homologous and analogous Bivalvia dominated benthic communites. In the upper Ludfordian (Ludlow), lowermost and uppermost Pridoli the cephalopod limestone facies developed only in the Prague Basin on some of the tectonically uplifted basin subsegments. In other peri-Gondwanan regions the Pridoli is characterized mostly by the diversity restricted communities and subcommunities formed by the same or closely related Bivalvia species, characteristic for the Pridoli of Perunica.

KEY WORDS - Silurian, Sardinia, Perunica, peri-Gondwanan Europe, Bivalvia palaeocommunities.

INTRODUCTION

The project “Upper Silurian and lowermost Devonian Bivalvia of Bohemian type from South-Western Sardinia” started in 1981 during the Subcommission on Silurian Stratigraphy field meeting at Gotland. I asked Enrico Serpagli and Maurizio Gnoli about the possibility to collect and to study the Silurian and lowermost Devonian bivalves in Sardinia described by Meneghini (1857) and listed by Gnoli et al. (1980). After a little scepticism about the possibility to find some more bivalves there Enrico Serpagli invited me to visit Sardinia in 1982.

First visit of southwestern Sardinia was very successful and for that collecting “expeditions” followed in 1986 and 1989. During these three collecting trips I made in cooperation with E. Serpagli, M. Gnoli, P. Rompianesi from the Institute of Palaeontology, Modena, S. Barca, F. Leone, G.L. Pillola from the University of Cagliari, V. Havlicek and P. Storch from the Czech Geological Survey, and S. Massole and G. Figus, the friends of “Gruppo Grotte di Fluminimaggiore” extensive collection of more than 750 identifiable bivalves, which is now deposited in the Museum of Palaeontology of the University of Modena and Reggio Emilia, and which made possible to publish in the cooperation with E. Serpagli the monograph on the upper Silurian and lowermost Devonian Bivalvia of Bohemian type from southwestern Sardinia in 1993. In this paper, 69 species of Bivalvia of Bohemian type and 7 new species and 3 new subspecies were described. Collection was realized at 8 localities from 65 mostly loose blocks of various sizes found on vineyeards and pastures. A fruitful cooperation was financially supported by the University of Modena and the Czech Geological Survey, by grants of the Italian “Ministero dell’Università e della Ricerca Scientifica” and “Consiglio Nazionale delle Ricerche” (CNR).

One of the most important conditions of success to reconstruct the Sardinian original sections strongly tectonized during the Variscan Orogeny was the technique of collecting fossils block by block and to study the associations of bivalves and other fauna separately as if they were collected in individual layers. We used this method for the first time together with F. Paris when studying the Silurian and lowermost Devonian in the vicinity of la Meignanne in the Massif Armoricain in France (Kriz & Paris, 1982). Since the original quarry in la Meignanne was abandoned and filled by water, it was possible to study just a single dark argillitic and limestone blocks in the vineyard walls, built especially from the light Devonian limestones. Based on the analysis of the assemblages from the three different blocks and based on the old museum collections, one ostracode dominated *Entomozoe (Richteria) migrans* Assemblage from the Ludlow, and three Bivalvia dominated *Cheiopteria bridgei*, *Snoopyia insolita*, and *Antipleura bohemica* assemblages were recognized from the upper Pridoli.

The assemblages described from la Meignanne (Kriz & Paris, 1982) showed very close relationship with the assemblages from the Bohemian Prague Basin and it was obvious that for the further studies of Bivalvia from Perunica (Havlicek et al., 1994) and the peri-Gondwanan regions would be necessary first to describe and analyse the Bivalvia dominated palaeocommunities from the Prague Basin where they are well developed and stratigraphically determined thanks to co-occurrence with graptolites and thus the possibility to correlate them with the classic graptolite zonation described in the Prague Basin (Jaeger *in* Kriz et al., 1986; Storch, 1994, 1995a, b).

The work was realized and the study of the Bivalvia dominated palaeocommunities of Bohemia type from the Silurian and Lower Devonian carbonate facies was submitted as the manuscript before 1989 (see references in Kriz, 1991) to the monograph “Silurian and Lower Devonian paleocommunities”, edited by A.J. Boucot and J.D. Lawson as the final publication of I.G.C.P. Project no. 53 Ecostratigraphy published in 1999. The manuscript published eleven years later (Kriz, 1999*a*) made possible to reconstruct and correlate the palaeocommunities recognized in Sardinia with the palaeocommunities already described from Bohemia and from the other parts of the European peri-Gondwana and Perunica.

RELATIONSHIP BETWEEN THE UPPER SILURIAN BIVALVIA DOMINATED PALAEOCOMMUNITIES OF SARDINIA AND OTHER PERI-GONDWANAN EUROPE AND PERUNICA

The upper Silurian Bivalvia dominated palaeocommunities succession is best known in the Prague Basin in Bohemia, Perunica (Kriz, 1991,1999*a*, 1999*b*, 1999*c*). They form the *Cardiola*, *Cheiopteria*, *Snoopyia* and *Patrocardia* community groups (Kriz, 1999*a*).

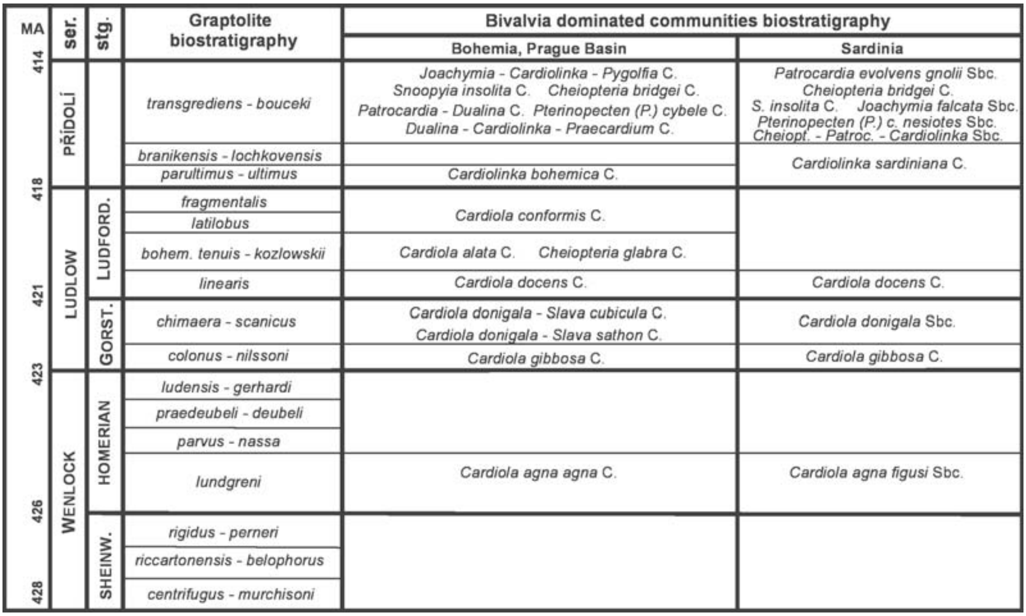
CARDIOLA *COMMUNITY GROUP*

The most characteristic Silurian *Cardiola* Community Group, composed mostly by Nephiomorphia Kriz, 2007, originated in the cephalopod limestone biofacies, which developed within the shallow-water, shell-rich carbonate “Prague Basin Facies” (Kriz et al., 2003) at the sea bottom below normal wave base, and temporarily ventilated by surface currents (Ferretti & Kriz, 1995). All of the communities of the *Cardiola* Community Group are homologous and analogous (Boucot & Kriz, 1999) and all of them contain the evolutionarily related species of the characteristic Silurian families Antipleuridae Neumayr, 1891, Butovicellidae Kriz, 1965, Cardiolidae Hoernes, 1884, Lunulacardiidae Fischer, 1887, Praecardiidae Hoernes, 1884, Slavidae Kriz, 1982, Spanilidae Kriz, 2007 and Stolidotidae, Starobogatov, 2007.

The earliest community of the *Cardiola* Community Group - *Carnalpia nivosa* Community (Kriz, 1999*a*) is known from the Carnic Alps, Austria and Italy (*Cyrtograptus rigidus* Biozone, upper Sheinwoodian, Wenlock). It was described from the biodetrital limestone forming the lenses in the dark graptolitic shale at the Cellon Section, Austria. The community is dominated by the cardiolids *Carnalpia* Kriz, 1974, *Cardiolopsis* Stache in Heritsch, 1929 and *Cardiola* Broderip in Murchison, 1939. Less common are bivalves of the genera *Slavinka* Kriz, 1982, *Patrocardia* Fischer, 1887, and *Maminka* Barrande, 1881. More than 58% are epibyssate, 22% semi-infaunal and 6% reclining forms. Juvenile stages of bivalves and gastropods are common and mostly juvenile cephalopod fragmocones form majority of the firm substrate at the sea bottom. Disarticulated trilobites (aulacopleurids, cheirurids, encrinurids, odontopleurids, and proetids) are rare.

First widely distributed *Cardiola agna agna* Community (Kriz, 1999*a*) of the *Cardiola* Community Group originated most probably in the Prague Basin, Bohemia (*Cyrtograptus lundgreni* Biozone, upper Wenlock) and became quickly distributed together with its *Cardiola agna figusi* Subcommunity (Kriz & Serpagli, 1993) and the *Slava pelerina – Isiola zila* Subcommunity (Kriz, 1999*c*) in the peri-Gondwanan region (Carnic Alps, Austria, Montagne Noire, France, and Sardinia, Italy).

In Sardinia the *Cardiola agna figusi* Subcommunity (Fig. 1) was discovered at the locality Xea Sant'Antonio, near Fluminimaggiore (Kriz & Serpagli, 1993). It occurs in the



MA	ser.	stg.	Graptolite biostratigraphy	Bivalvia dominated communities biostratigraphy	
				Bohemia, Prague Basin	Sardinia
414	PŘÍDOLÍ		*transgrediens - bouceki*	*Joachymia - Cardiolinka - Pygolfia* C. *Snoopyia insolita* C. *Cheiopteria bridgei* C. *Patrocardia - Dualina* C. *Pterinopecten (P.) cybele* C. *Dualina - Cardiolinka - Praecardium* C.	*Patrocardia evolvens gnolii* Sbc. *Cheiopteria bridgei* C. *S. insolita* C. *Joachymia falcata* Sbc. *Pterinopecten (P.) c. nesiotes* Sbc. *Cheiopt. - Patroc. - Cardiolinka* Sbc.
			branikensis - lochkovensis		*Cardiolinka sardiniana* C.
			parultimus - ultimus	*Cardiolinka bohemica* C.	
418	LUDLOW	LUDFORD.	*fragmentalis*	*Cardiola conformis* C.	
			latilobus		
			bohem. tenuis - kozlowskii	*Cardiola alata* C. *Cheiopteria glabra* C.	
			linearis	*Cardiola docens* C.	*Cardiola docens* C.
421		GORST.	*chimaera - scanicus*	*Cardiola donigala - Slava cubicula* C. *Cardiola donigala - Slava sathon* C.	*Cardiola donigala* Sbc.
			colonus - nilssoni	*Cardiola gibbosa* C.	*Cardiola gibbosa* C.
423	WENLOCK	HOMERIAN	*ludensis - gerhardi*		
			praedeubeli - deubeli		
			parvus - nassa		
			lundgreni	*Cardiola agna agna* C.	*Cardiola agna figusi* Sbc.
426		SHEINW.	*rigidus - perneri*		
			riccartonensis - belophorus		
428			*centrifugus - murchisoni*		

Fig. 1 - The upper Silurian Bivalvia dominated palaeocommunities succession of the Prague Basin, Bohemia and correlation with the Bivalvia dominated palaeocommunities succession of southwestern Sardinia (modified after Kriz, 1999b).

dark micrite to biomicritic limestone forming lenses in the dark shales. The subcommunity is dominated by the cardiolids *Cardiola* and *Isiola* Kriz, 1976 accompanied by different species of *Slava* Barrande, 1881, *Stolidotus* Hede, 1915, *Maminka* and *Patrocardia*. More than 59% are epibyssate and 18% were infaunal forms. Fragmented fragmocones of cephalopods are subordinate to bivalves and form majority of the firm substrate at the sea bottom. Disarticulated smooth, articulated brachiopods are very common, together with very common *Monograptus flemingi* (Salter, 1852). The *Cardiola agna figusi* Subcommunity was also recognized in one block from the Xea Sant'Antonio locality together with abundant *Colonograptus colonus* (Barrande, 1850) indicating the lowermost Ludlow.

Kriz (1996) recognized the *Cardiola agna figusi* Sucommunity in the Montagne Noire, France. *Cardiola agna figusi* Kriz, 1993 is also dominant, but the composition of the community is modified. Also here the firm substrate formed by cephalopod fragmocones is suitable for more than 51% of epibyssate bivalves, but micritic sediment was also suitable for infaunal and semi-infaunal bivalves (more than 34%).

Slava pelerina – Isiola zila Subcommunity (Kriz, 1999*c*) was recognized in the Carnic Alps at the Rauchkofel Boden Section. The subcommunity is homologous and analogous with the *Cardiola agna agna* Community described from the Prague Basin. It is characterized by very low diversity indicating restricted living conditions, probably higher energy in comparison with the Sardinia *Cardiola agna figusi* Subcommunity. The dominant bivalves are infaunal *Slava pelerina* Kriz, 1985 and *Isiola zila* Kriz, 1999c. The species of the genera *Slava, Isiola, Cardiola* and *Maminka* were recognized. Majority of bivalves were infaunal.

Cardiola gibbosa Community (Fig. 1) is the lower Ludlow community described from the Prague Basin, Bohemia (Kriz, 1999*a*) and in Sardinia, Italy (Kriz & Serpagli, 1993). In Sardinia the community was discovered at the locality Xea Sant'Antonio, near Fluminimaggiore. It occurs in the dark micritic lenticular limestone, which originally formed a horizon in the calcareous shales. The community is dominated by *Cardiola gibbosa* Barrande, 1881, accompanied by species of *Butovicella*, *Maminka*, *Manulicula* Kriz, 1967, *Procarinaria* Perner, 1911, a.o. More than 68% are epibyssate and the rest are reclining, semi-infaunal, and infaunal forms. Fragmented fragmocones of cephalopods are abundant, forming the firm substrate at the sea bottom. A lower diversity of the *Cardiola gibbosa* Community in Sardinia indicates less favourable condition on a micritic bottom than in Bohemia.

The *Cardiola gibbosa* Community represents most probably the ancestral community for the *Cardiola donigala* Subcommunity described from the locality Sant'Antonio Donigala in Sardinia (Kriz & Serpagli, 1993). This community is characteristic for the upper Gorstian, Ludlow. Kriz (1999a) described the *Slava cubicula – Cardiola docens* Community in the cephalopod limestones of the higher Gorstian in the Prague Basin. In the same year Kriz (1999b) studied this community at the type locality, where the new excavation was realized. He recognized that the supposed species *Cardiola docens* Barrande, 1881 there is in reality *Cardiola donigala* Kriz, 1993 described from Sardinia and represents an ancestral form to *Cardiola docens*. The Bohemian community was renamed for the *Cardiola donigala –Slava cubicula* Community. It is mainly composed of epibyssate forms (more than 74%) the rest is mostly the infaunal forms. More recently was in the Prague Basin recognized in the lower Gorstian the *Cardiola donigala-Slava sathon* Community (Manda & Kriz, 2007). Since the age of the Gorstian *Cardiola donigala* Subcommunity in Sardinia is not exactly known and the very low diversity community was recognized only in one block of rocks from the type locality, well documented *Cardiola* *donigala – Slava cubicula* Community from the Prague Basin, Bohemia (Kriz, 1999b) is considered as the typical.

In Sardinia the *Cardiola donigala* Subcommunity (Fig. 1) occurs in the dark micritic lenticular limestone, which originally formed a horizon in the calcareous shales. The subcommunity is dominated by *Cardiola donigala*, accompanied by the species of *Cardiola, Slavinka* Kriz, 1982, *Maminka,* and *Patrocardia*. All of the bivalves are considered epibyssate. Fragmented fragmocones of cephalopods are common. A lower density and diversity indicate less favourable condition on a micritic bottom.

The *Cardiola donigala* Subcommunity was also discovered in the Montagne Noire in France (Kriz, 1996) but the dominant species is known only from old collections and is preserved together with common cephalopods and pristiograptids.

The *Cardiola donigala* Subcommunity is ancestral to the *Cardiola docens* Community described by Kriz (1999a) from the uppermost Gorstian and lower Ludfordian of the Prague Basin in Bohemia (Fig. 1). In Sardinia, Italy (Kriz & Serpagli, 1993) the *Cardiola docens* Community was discovered at the localities Galemmu near Fluminimaggiore, in Sant'Antonio Donigala and Funtanamare. In Sardinia the community is dominated by *Cardiola docens* and occurs in the grey to dark micritic and biomicritic or unsorted biodetrital limestones, which form larger lenticular horizons within the sequence of the calcareous shales. Current oriented nektobenthic orthocone cephalopod fragmocones are very common in the limestones. Epibyssate bivalves are dominant (82%).

The *Cardiola signata* Subcommunity described from the uppermost Gorstian, Tajmyr, Russia (Kriz & Bogolepova, 1995) and the *Cardiola consanguis* Subcommunity from the upper Gorstian, Rauchkofel Boden Section, Carnic Alps (Kriz, 1999c) represent the low diversity Gorstian subcommunities of the *Cardiola docens* Community.

The *Cardiola docens* Community in Bohemia is also characterized by epibyssate bivalves (95 - 99%) and occurs in the cephalopod limestone biofacies. Kriz (1996) described the *Cardiola docens* Community from the Montagne Noire, France (85% of epibyssate bivalves) and in 1999c from the Carnic Alps, Austria (100% of epibyssate bivalves). The *Cardiola docens* Community is distributed also in Morocco (Anti-Atlas), Russia (Caucassus), and Spain (Kriz, 1999c).

The higher Ludfordian (*Neocucullograptus kozlowskii* Biozone) *Cardiola alata* Community from the Prague Basin, Bohemia (Kriz, 1998) and its *Cardiola alata – Cardiola pectinata* Subcommunity from the Carnic Alps (Kriz, 1999c) are not known from Sardinia (Fig. 1).

Upper Ludlow and lowermost Pridoli *Cardiola conformis* Community (*Monograptus latilobus* Biozone – *Monograptus ultimus* Biozone) developed in the Prague Basin, Bohemia (Kriz, 1998, 1999a) is not known in Sardinia. *Cardiolinka bohemica* Community characteristic for the lowermost Pridoli occurs in the Prague Basin (Kriz, 1998, 1999a) and in the Carnic Alps (Kriz, 1999*c*) and was also not found in Sardinia (Fig. 1).

CHEIOPTERIA *COMMUNITY GROUP*

The *Cheiopteria* Community Group (Kriz, 1999a) is characterized by very high dominance of the semi-infaunal pterineid *Cheiopteria* Pojeta & Kriz, 1976, occurring in very high-density populations, and occurs in the micritic limestone facies which was a deeper water facies than the contemporary cephalopod limestone biofacies. The earliest known *Cheiopteria glabra* Community described from the Prague Basin (Kriz, 1999a) is contemporary to the *Cardiola alata* Community (Ludfordian) (Fig. 1). It is ancestral to the *Cheiopteria bridgei* Community, first described as assemblage from the upper Pridoli of the Massif Armoricain, France (Kriz & Paris, 1982) and later as the community known from the Turkey and Florida (Pojeta et al., 1976), Massif Armoricain, Prague Basin, Bohemia (Kriz, 1999a), and Sardinia (Kriz & Serpagli, 1993). Kriz (2004) described analogous and homologous latest Frasnian, Upper Devonian *Cheiopteria feisti* Community

---

Plate 1

Dominant and characteristic bivalves from southwestern Sardinia (IPUM: collections of the Museum of Palaeontology of the University of Modena and Reggio Emilia, Italy).

Fig. 1 - *Snoopyia insolita* (Barrande, 1881), Galemmu, block 29, the *Snoopyia insolita* Community, upper Pridoli; IPUM 22923, left view, x9.5.

Fig. 2 - *Cardiolinka sardiniana* Kriz in Kriz & Serpagli, 1993, Argiola, block 29, the *Cardiolinka sardiniana* Community, upper Pridoli; IPUM 23157, left view, x6.0.

Fig. 3 - *Joachymia falcata* (Barrande, 1881), Barbusi, block 1, the *Joachymia falcata* Community, upper Pridoli; IPUM 23181, right view, x6.5.

Fig. 4 - *Cheiopteria bridgei* Pojeta & Kriz, 1976, Argiola, block 32, the *Cheiopteria bridgei* Community, upper Pridoli; IPUM 23165, left view, x6.5.

Fig. 5 - *Pterinopecten (P.) cybele nesiotes* Kriz in Kriz & Serpagli, 1993, Galemmu, block 9, the *Petrinopecten (P.) cybele nesiotes* Community, upper Pridoli; IPUM 22863, left view, x5.3.

Fig. 6 - *Paracardium eremita* Barrande, 1881, Argiola, block 17, the *Cheiopteria bridgei* Community, IPUM 23086, right view, x2.0.

Fig. 7 - *Cardiola cornucopiae* (Goldfuss, 1837), Mason Porcus, block 2, ?*Cheiopteria-Patrocardia-Cardiolinka* Community, upper Pridoli; IPUM 22993, left view, x2.0.

Fig. 8 - *Cardiola docens* Barrande, 1881, Fontanamare, block 1, the *Cardiola docens* Community, Ludlow; IPUM 23072, left view, x2.3.

Fig. 9 - *Mila parvula* Kriz in Kriz & Serpagli, 1993, Argiola, block 21, the *Cardiola docens* Community, Ludlow; IPUM 23119, right view, x3.5.

Fig. 10 - *Butovicella galemmu* Kriz in Kriz & Serpagli, 1993, Galemmu, block 3, the *Cardiola docens* Community, Ludlow; IPUM 22833, left view, x6.1.

Fig. 11 - *Cardiola donigala* Kriz in Kriz & Serpagli, 1993, Sant'Antonio Donigala, block 7, the *Cardiola donigala* Community, Ludlow; IPUM 23050, left view, x2.0.

Fig. 12 - *Butovicella migrans* (Barrande, 1881), Xea Sant'Antonio, block 11, the *Cardiola agna figusi* Community, Wenlock; IPUM 22658, right view, x4.4.

Fig. 13 - *Manulicula manulia* (Barrande, 1879), Argiola, block 25, the *Cardiola gibbosa* Community, Ludlow; IPUM 23124, left view, x5.4.

Figs. 14-15 - *Maminka comata* Barrande, 1881, articulated shell, Argiola, block 24, the *Cardiola gibbosa* Community, Ludlow; IPUM 23120, 14) left view, x2.2, 15) dorsal view, x1.6.

Fig. 16 - *Cardiola gibbosa* Barrande, 1881, Xea Sant'Antonio, block 1, the *Cardiola gibbosa* Community, Ludlow; IPUM 22621, right view, x4.6.

Fig. 17 - *Tenka aspirans* (Barrande, 1881), Galemmu, block 46, the *Cardiola docens* Community, Ludlow; IPUM 22971, left view, x3.2.

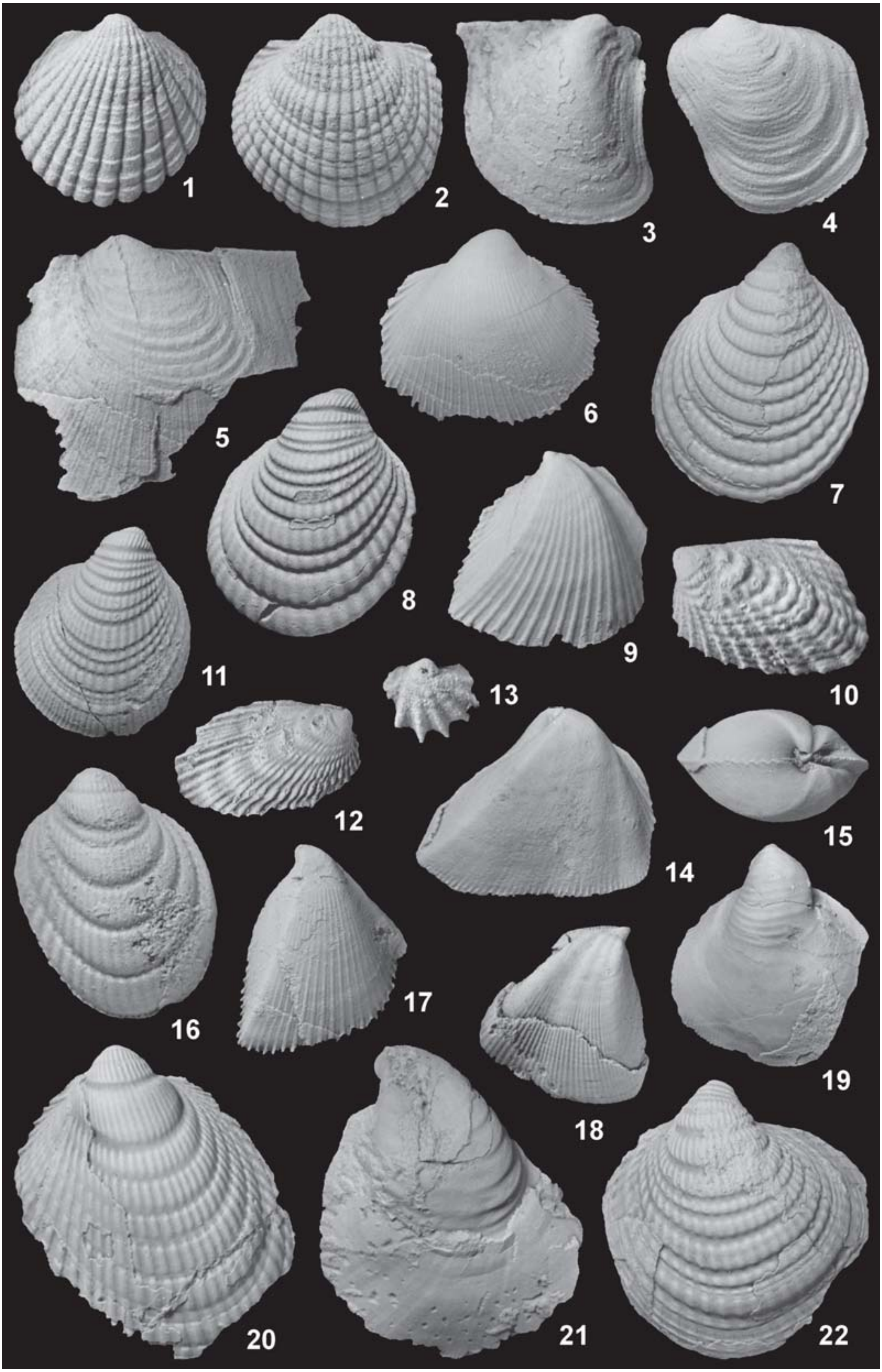
Fig. 18 - *Stolidotus cactus* Kriz, in Kriz & Serpagli, 1993, Xea Sant'Antonio, block 11, the *Cardiola agna figusi* Community, Wenlock; IPUM 22702, right view, x2.4.

Fig. 19 - *Slava cubicula* Kriz, 1985, Galemmu, the *Cardiola docens* Community, Ludlow; private collection, right view, x0.6.

Fig. 20 - *Cardiola agna figusi* Kriz in Kriz & Serpagli, 1993, Xea Sant'Antonio, block 11, the *Cardiola agna figusi* Community, Wenlock; IPUM 22685, right view, x2.7.

Fig. 21 - *Slava fibrosa* (Sowerby in Murchison, 1839), Xea Sant'Antonio, block 11, the *Cardiola agna figusi* Community, Wenlock; IPUM 22693, left view, x1.5.

Fig. 22 - *Isiola lyra* Kriz, 1976, Xea Sant'Antonio, block 11, the *Cardiola agna figusi* Community, Wenlock; IPUM 22659, right view, x1.9.


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

from the Montagne Noire, which is also related to the micritic limestone nodules in dark grey calcareous shales.

In Sardinia, Italy (Kriz & Serpagli, 1993) the *Cheiopteria bridgei* Community (Fig. 1) was discovered at the localities Galemmu and Mason Porcus near Fluminimaggiore, and at the locality Argiola. The community is dominated by *Cheiopteria bridgei* Pojeta & Kriz, 1976 (95% of all individuals) and occurs in the dark micritic to biomicritic lenticular limestones in the calcareous shales of the upper Pridoli, *Monograptus transgrediens* Biozone.

SNOOPYIA *COMMUNITY GROUP*

Communities grouped to the *Snoopyia* Community Group occur in generally uniform environment of the Pridoli characterized by laminated limestones and calcareous shales (Kriz et al., 1986, 2003). The group consists of the communities, which are partly homologous but not analogous with the *Cardiola* Community Group.

From Sardinia the oldest known *Cardiolinka sardiniana* Community (Fig. 1) of this group was described (Kriz & Serpagli, 1993) from the early Pridoli at the locality Argiola. The community was also recognized at the locality Combe d'Yzarne in the Montagne Noire, France (Kriz, 1996), and in the Chelm Borehole, Poland (Korejwo & Teller, 1964). At the Sardinian type locality the community is characterized by relatively high diversity and low population density and by more than 62% of infaunal and semi-infaunal forms in contrast to the upper Ludlow *Cardiola* dominated communities with prevailing epibyssate forms.

The descendant *Dualina-Cardiolinka-Praecardium* Community occurs in the similar laminated limestone facies of middle and upper Pridoli and is characterized by relatively higher diversity. It was described from the Prague Basin (Kriz, 1999a), Chelm borehole in eastern Poland (Korejwo & Teller, 1964), Normandy (Babin & Robardet, 1974) and eastern Serbia (Kriz & Veselinovic, 1975). In Sardinian uppermost Pridoli this community is developed as the *Cheiopteria – Patrocardia – Cardiolinka* Subcommunity (Fig. 1). It is also characterized by prevailing infaunal and semi-infaunal forms (more than 64%) and by similar diversity and lower density at the locality Mason Porcus near Fluminimaggiore.

Other late Prídolian *Snoopyia* Community Group communities and subcommunities mostly occupied less favourable parts of the sea bottom with restricted living conditions (limited current activity, low oxygen, etc.). They are characterized by very low diversity and mostly by very high population densities. The *Snoopyia insolita* Community was described from the upper Pridoli of the Massif Armoricain, locality la Meignanne, France (Kriz & Paris, 1982). It also occurs in Chelm borehole, eastern Poland (Korejwo & Teller, 1964), Prague Basin, Bohemia (Kriz, 1999a), and in the Montagne Noire, France (Kriz, 1996).

In Sardinia the *Snoopyia insolita* Community (Fig. 1) was described (Kriz & Serpagli, 1993) from the upper Pridoli at the localities Galemmu near Fluminimaggiore and at the locality Argiola. It is characterized by more than 77% of dominant infaunal species.

The upper Pridoli *Joachymia falcata* Subcommunity (Fig. 1) discovered in Sardinia at the locality Barbusi (Kriz & Serpagli, 1993) is analogous and homologous with the *Joachymia – Cardiolinka – Pygolfia* Community described from the upper Pridoli of the Prague Basin (Kriz, 1999a). The *Joachymia falcata* Subcommunity is characterized by epibyssate forms (100%) and generally by very low diversity and high density.

Another Sardinian monospecific *Pterinopecten (Pterinopecten) cybele nesiotes* Community (Fig. 1) (Kriz & Serpagli, 1993) is most probably related to the *Pterinopecten (Pterinopecten) cybele cybele* Community described by Kriz (1999a) from the Prague

Basin, Bohemia, from Podolia, Ukraine (Sinicyna, 1968), Normandy, France (Babin & Robardet, 1974), and Chelm borehole, Eastern Poland (Korejwo & Teller, 1964). Both communities are monospecific and dominated by epibyssate species in mass occurrence.

PATROCARDIA *COMMUNITY GROUP*

In the upper Pridoli of Sardinia the *Patrocardia evolvens gnolii* Subcommunity (Fig. 1) was discovered at the Galemmu locality near Fluminimaggiore (Kriz & Serpagli, 1993). This monospecific subcommunity is most probably related to the *Patrocardia – Dualina* Community described from the uppermost Pridoli of the Prague Basin, Bohemia by Kriz (1999a). It is the oldest known community of the *Patrocardia* Community Group and it is characterized by dominance of infaunal bivalves together with epibyssate representatives of the family Lunulacardiidae. The Sardinian monospecific community is due to restricted living conditions represented by the species probably forming clumps of individuals attached directly to the fragments or to each other on the soft bottom.

CONCLUSIONS

Bivalvia dominated communities described from the Silurian of Sardinia (Kriz & Serpagli, 1993) represent useful tool to correlate precisely Sardinian upper Wenlock, Ludlow and Pridoli cephalopod limestone biofacies and micritic facies with other European peri-Gondwana regions in spite of the fact that the graptolites occur in the upper Silurian of southwestern Sardinia only in the upper *Cyrtograptus lundgreni* Biozone (lower Homerian, upper Wenlock) and in the *Neodiversograptus nilssoni* Biozone (lowermost Ludlow).

When compared with the Prague Basin, the Bivalvia dominated communities are in Sardinia characterized by the lower diversity. Some of Bohemian communities are thus developed in Sardinia as the *Cardiola agna figusi, Cardiola donigala, Cheiopteria–Patrocardia–Cardiolinka, Pterinopecten (P.) cybele nesiotes, Joachimia falcata,* and *Patrocardia evolvens gnolii* subcommunities.

The distribution of the Cardiolidae in the European peri-Gondwanan regions (the Montagne Noire, the Carnic Alps and southwestern Sardinia) and Perunica (Prague Basin) demonstrated changes in relationships between these regions (Kriz, 1999*c*).

First carbonate sediments of the Silurian cephalopod limestone biofacies in southwestern Sardinia occurred during the late Wenlock, early Homerian low stand when the close relationships are documented between the Montagne Noire, France and Sardinia by the common occurrence of two Cardiolidae species (*Isiola lyra* and *Cardiola agna figusi*) and other species [*Butovicella migrans* (Barrande, 1881), *Maminka comata* Barrande, 1881, *Procarinaria zephirina* (Barrande, 1881), and *Slava sathon* Kriz, 1985].

The close relationship between Bohemia and Sardinia is well documented by the common occurrence of *Isiola lyra* and other bivalves [*Butovicella migrans, Maminka comata, Stolidotus trimerus* Barrande, 1881, *Stolidotus elongans* (Barrande, 1881), *Slava fibrosa* (Sowerby *in* Murchison, 1839), *S. pelerina* Kriz, 1985, and *S. discrepans* Barrande, 1881]. Close relationships are also between Sardinia and the Carnic Alps evidenced by common occurrence of the species *Slava pelerina, S. fibrosa, S.* cf. *sathon,* and *Maminka comata*. In Sardinia the carbonate sedimentation of the cephalopod limestone biofacies was interrupted in the late Homerian post-*lundgreni* times.

The close relationships continued in the earliest Gorstian (*Neodiversograptus nilssoni* Biozone) between southwestern Sardinia and the Perunican Bohemia and are documented by common occurrence of *Cardiola gibbosa* Barrande, 1881 and other bivalves

[*Butovicella migrans, Maminka comata, Manulicula manulia* (Barrande, 1879), *Modiolopsis senilis* Barrande, 1881, and *Procarinaria zephirina*].

In the late Gorstian (*Saetograptus chimaera* Biozone) the very close relationship between Sardinia and Bohemia document common occurrence of *Cardiola donigala*, *Cardiola consanguis* Barrande, 1881, *Cardiola* cf. *signata* Barrande, 1881, *Cardiola* aff. *docens*, *Slavinka amarygma* Kriz, 1985, and *Maminka comata*.

The close relationship between Sardinia and the Perunican Bohemia continued also in the early Ludfordian when it is documented by common occurrence of *Cardiola docens*, *Cardiola consanguis* Barrande, 1881 and other species (*Butovicella galemmu* Kriz, 1993, *Tenka aspirans* (Barrande, 1881), *Slava sathon, Slava cubicula,* and *Tetinka* aff. *cuneus* Barrande, 1881). Carbonate sedimentation in southwestern Sardinia was during low stand characterized by the cephalopod limestone biofacies.

In the upper Ludfordian (Ludlow) and the lowermost Pridoli the cephalopod limestone facies is characteristic only for the Prague Basin where it developed in some of the basin subsegments (Kriz, 1991) which were tectonically uplifted in the late Ludfordian, earliest and latest Pridoli.

During the late Ludfordian and Pridoli high stand in southwestern Sardinia the carbonate sedimentation with cephalopod limestone biofacies was interrupted. It occurred again during the latest Pridoli when similar carbonates as in other European peri-Gondwanan and Perunican regions sedimented.

In general, the Pridolian Bivalvia dominated communities in southwestern Sardinia have very similar character as in Perunica. The earliest *Cardiolinka sardiniana* Community shows very high diversity and has numerous species common to Bohemia and Sardinia [*Cardiolinka fortis* (Barrande, 1881), *Dualina* aff. *socialis* Barrande, 1881, *Cheiopteria bridgei*, *Butovicella* aff. *medea* Kriz, 1969, *Cardiola* aff. *conformis* Barrande, 1881, *Dualina* aff. *secunda* Barrande, 1881, *Patrocardia* cf. *eximia* Barrande, 1881), *Majda* aff. *bohemica* (Barrande, 1881), *Praecardium* cf. *adolescens* Barrande, 1881, and *Praeostrea* cf. *moror* Kriz, 1966]. In the Pridoli, communities and subcommunities are characterized by generally lower diversity in Sardinia. Similar situation is in the Montagne Noire and the Carnic Alps.

REFERENCES

BABIN C. & ROBARDET M. (1974). Mollusques Bivalves du Silurien supérieur et de l'extreme base du Dévonien en Normandie. *Annales de la Société Géologique du Nord,* 94: 19-45.

BARRANDE J. (1850). Graptolites de Bohême. 74 pp, 4 pl. Prague.

BARRANDE J. (1879). Systême silurien du centre de la Bohême. I. ère partie: Recherches Paléontologiques, V. Brachiopodes. 153 pp.,153 pls. Prague, Paris.

BARRANDE J. (1881). Systême silurien du centre de la Bohême. I. ère partie: Recherches Paléontologiques, Classe des Mollusques, ordre des Acéphalés. VI. 342 pp., 356 pls. Prague, Paris.

BOUCOT A.J. & KRIZ J. (1999). Definition of the terms "homologous" and "analogous" community. *In* Boucot A.J. & Lawson J.D. (Eds.), Palaeocommunities: A case study from the Silurian and Lower Devonian. World and Regional Geology series 11, Cambridge University Press: 32.

FERRETTI A. & KRIZ J. (1995). Cephalopod limestone biofacies in the Silurian of the Prague Basin, Bohemia. *Palaios,* 10(3): 240-253.

FISCHER P. (1880-87). Manuel de conchyliologie et de paléontologie conchyliologique ou histoire naturelle des mollusques vivants et fossiles. F. Savy, Paris, pp. 1-112, 1880; pp. 113-304, 1881; pp. 305-416, 1882; pp. 417-608, 1883; pp. 609-688, 1884; pp. 689-896, 1885; pp. 897-1008, 1886; pp. 1009-1369, 1887.

GNOLI M., PAREA G.C., RUSSO F. & SERPAGLI E. (1980). Paleoecological remarks on the "*Orthoceras* limestone" of Southwestern Sardinia (middle-upper Silurian). *Memoire della Società Geologica Italiana,* 20 (1979): 405-423.

GOLDFUSS G.A. (1837). Petrefacta Germaniae - Abbildungen und Beschreibungen der Petrefacten Deutschlands und der angrenzenden Länder 6. Lieferung = Teil II, 3: 141-224.

Havlicek V., Vanek J. & Fatka O. (1994). Perunica microcontinent in the Ordovician (its position within the Mediterranean Province, series division, benthic and pelagic associations). *Journal of Geological Sciences, Geology,* 46: 25-56.

Hede J.E. (1915). Skånes Colonusskiffer. *Lunds Universitets Årsskrift,* 11: 1-65.

Heritsch F. (1929). Faunen aus dem Silur der Ostalpen. *Abhandlungen der Geologischen Bundesanstalt,* 23: 1-183.

Hoernes R. (1884). Elemente der Palaeontologie. Veit and Company, Leipzig. 594 pp.

Korejwo K. & Teller L. (1964). Upper Silurian non-graptolite fauna from the Chelm borehole (eastern Poland). *Acta Geologica Polonica,* 14 (2): 233-301.

Kriz J. (1965). Genus *Butovicella* gen. n. in the Silurian (Bivalvia). *Vestnik Ustredniho Ustavu Geologickeho,* 40: 207-208.

Kriz J. (1966). *Praeostrea* Barrande, 1881 from the lower Paleozoic of Central Europe (Bivalvia). *Casopis Narodniho Musea, oddil prirodovedny*, 135: 25-32.

Kriz J. (1967). The genus *Manulicula* gen. n. from the Silurian of Bohemia (Bivalvia). *Vestnik Ustredniho Ustavu Geologickeho,* 42: 123-126.

Kriz J. (1969). Genus *Butovicella* Kriz, 1965 in the Silurian of Bohemia (Bivalvia). *Journal of Geological Sciences, Palaeontology,* 10: 105-139.

Kriz J. (1974). New Genera of Cardiolidae (Bivalvia) from the Silurian of the Carnic Alps. *Vestnik Ustredniho Ustavu Geologickeho,* 49: 171-176.

Kriz J. (1976). *Snoopyia* gen. n. and *Isiola* gen. n. (Cardiolidae, Bivalvia) from the Silurian of Bohemia. *Vestnik Ustredniho Ustavu Geologickeho,* 51: 371-373.

Kriz J. (1982). *Slavinka* gen. n. and Slavidae fam. n. (Bivalvia) from the Silurian of Bohemia. *Vestnik Ustredniho Ustavu Geologickeho,* 57: 237-240.

Kriz J. (1991). Silurian of the Prague Basin (Bohemia) - tectonic, eustatic and volcanic control on facies and faunal development. *In* Bassett M.G., Lane P.D. & Edwards D. (Eds.). The Murchison Symposium: proceedings of an international conference on The Silurian System: *Special Papers in Palaeontology,* 44: 179-203.

Kriz J. (1996). Silurian Bivalvia of Bohemian type from the Montagne Noire and Mouthoumet Massif, France. *Palaeontographica A.,* 240: 29-63.

Kriz J. (1998). Recurrent Silurian-lowest Devonian cephalopod limestones of Gondwanan Europe and Perunica. *In* Landing E. & Johnson M.E. (Eds), Silurian cycles: Linkages of dynamic stratigraphy with atmospheric, oceanic, and tectonic changes. *Bulletin New York State Museum*, 491: 183-198.

Kriz J. (1999a). Bivalvia dominated communities of Bohemian type from the Silurian and Lower Devonian carbonate facies. *In* Boucot A.J. & Lawson J.D. (Eds), Palaeocommunities: A case study from the Silurian and Lower Devonian. *World and Regional Geology series 11*, Cambridge University Press, Cambridge. 225-248.

Kriz J. (1999b). Silurian Bivalvia - evolution, palaeocology, palaeogeography, importance for biostratigraphy and correlation. *Abhandlungen der Geologischen Bundesanstalt,* 54: 377-384.

Kriz J. (1999c). Silurian and lowermost Devonian bivalves of Bohemian type from the Carnic Alps. *Abhandlungen der Geologischen Bundesanstalt,* 56 (1): 259-316.

Kriz J. (2004). Latest Frasnian and earliest Famennian (Late Devonian) bivalves from the Montagne Noire (France). *Senckenbergiana lethaea,* 84 (1/2): 85-123.

Kriz J. (2007). Origin, evolution and classification of the new superorder Nepiomorphia (Mollusca, Bivalvia, Lower Palaeozoic). *Palaeontology,* 50 (6): 1341-1365.

Kriz J. & Bogolepova O.K. (1995). *Cardiola signata* Community in cephalopod limestones from Tajmyr (Gorstian, Silurian, Russia). *Geobios,* 28 (5): 573-583.

Kriz J., Degardin J.M., Ferretti A., Hansch W., Gutiérrez Marco J.C., Paris F., Piçarra d-Almeida J.M., Robardet M., Schönlaub H.P. & Serpagli E. (2003). Silurian stratigraphy and paleogeography of north Gondwanan and Perunican Europe. *In* Landing E. & Johnson M.E. (Eds.), Silurian lands and seas - paleogeography outside of Laurentia. *New York State Museum Bulletin,* 493: 105-178.

Kriz J., Jaeger H., Paris F. & Schönlaub H.P. (1986). Pridoli – the fourth subdivision of the Silurian. *Jahrbuch der Geologischen Bundesanstalt, Wien,* 129 (2): 291-360.

Kriz J. & Paris F. (1982). Ludlovian, Prídolian and Lochkovian in la Meignanne (Massif Armoricain): Biostratigraphy and correlations based on Bivalvia and Chitinozoa. *Geobios,* 15 (3): 391-421.

Kriz J. & Serpagli E. (1993). Upper Silurian and lowermost Devonian Bivalvia of Bohemian type from South - Western Sardinia. *Bollettino della Società Paleontologica Italiana,* 32(3): 289-347.

Kriz J. & Veselinovic M. (1975). Ludlovian, Pridolian and Lochkovian bivalves from the Suva Planina Mountains (Eastern Serbia, Yugoslavia). *Vestnik Ustredniho Ustavu Geologickeho,* 50: 365-369.

Manda S. & Kriz J. (2007). New cephalopod limestone horizon in the Ludlow (Gorstian, lower *L. scanicus* Biozone) of the Prague Basin (Bohemia, Perunica). *Bollettino della Società Paleontologica Italiana,* 46 (1): 33-45.

Meneghini G. (1857). Paléontologie de l'Ile Sardaigne. *In* La Marmora A., Voyage en Sardaigne. 584 pp., Imprimerie Royal, Turin.

Murchison R.I. (1839). The Silurian System founded on geological researches in the counties of Salop, Hereford, Radnor, Montgomery, Caermarthen, Brecon, Pembroke, Monmouth, Gloucester, Worcester and Stafford; with descriptions of the coalfields and overlying formations. 768 pp. John Murray, London.

Neumayr M. (1891). Beiträge zu einer morphologischen Eintheilung der Bivalven. *Denkschriften der Kaiserlichen Akademie der Wissenschaften. Mathematisch-Naturwissenschaftliche Classe,* 58: 701-801.

Perner J. (1911). *In* Barrande, J: Systême silurien du centre de la Bohême. I. ère partie: Recherches Paléontologiques, V. Gastéropodes, III. 390 pp., Prague, Paris.

Pojeta J., jr., Kriz J. & Berdan J.M. (1976). Silurian-Devonian pelecypods and Paleozoic stratigraphy of subsurface rocks in Florida and Georgia and related Silurian pelecypods from Bolivia and Turkey. *Geological Survey Professional Papers*, 879: 1-32.

Salter J.W. (1852). Description of some graptolites from the south of Scotland. *Quarterly Journal of the Geological Society of London,* 8: 388-392.

Sinicyna, I.N. (1968). Dvustvorcatye molljuski skalskogo, borshovskogo i chortkovskogo gorizontov Podolii. *Izdatelstvo Leningradskogo Universiteta*,1968: 72-94.

Starobogatov, Ja. I., 1977. Systematic position of conocardiids and the system of the Paleozoic Septibranchia (Bivalvia). *Bjulleten'Moskovskogo Obšèestva Ispytatelei Prirody, Otdel Geologièeskij*, 52(4):125-139. [In Russian].

Storch P. (1994). Graptolite Biostratigraphy of the Lower Silurian (Llandovery and Wenlock) of Bohemia. *Geological Journal,* 29: 137-165.

Storch P. (1995a). Biotic crises and post-crisis recoveries recorded by Silurian planctonic graptolite faunas of the Barrandian area (Czech Republic). *Geolines,* 3: 59-70.

Storch P. (1995b). Upper Silurian (upper Ludlow) graptolites of the *N. inexpectatus* and *N. kozlowskii* biozones from Kosov Quarry near Beroun (Barrandian area, Bohemia). *Vestnik Ustredniho Ustavu Geologickeho*, 70: 65-89.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 131-142

Chitinozoan assemblages and biostratigraphy of the Silurian of Sardinia

Paola Pittau, Miriam Del Rio

P. Pittau - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); pittaup@unica.it
M. Del Rio - Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127 Cagliari (Italy); delriom@unica.it

Abstract - Silurian chitinozoan assemblages and biozones of southeastern Sardinia are well calibrated against graptolite biozones, whereas those deriving from isolated blocks of the Fluminimaggiore Formation of southwestern Sardinia have less precise biochronologic constraints. An attempt to arrange, into a regional frame, the up to now known chitinozoan assemblages according to the stratigraphic significance of index species, is presented in this short paper. One biozone, *Conochitina emmastensis*, is recognized in the Aeronian - Telychian of the Rio Ollastu section. Three chitinozoan biozones: *C. goniensis-C. subcyatha, Sphaerochitina jaegeri, S. serpaglii* are correlated from the *belophorous-rigidus* to the *lundgreni-testis* graptolite biozones. One chitinozoan biozone, *C. pachycephalana*, calibrated against *vulgaris-gerhardi* graptolite biozone and fitting ecostratigraphically within the *Cardiola docens-C. donigala* bivalves community. *Angochitina* cf. *elongata* Biozone ecostratigraphycally encompassing the *Cardiola docens* community; *Urnochitina urna* and *Eisenackitina bohemica* ecostratigraphically correlating respectively with *Cheiopteria-Patrocardia-Cardiolinka, Patrocardia evolvens evolvens-Panenka* bivalves communities and *Pterinopecten-Cybele nesiotes* and *Patrocardia evolvens evolvens-Panenka* communities that encompass Pridoli and Lochkovian.

Key words - Silurian, Sardinia, Chitinozoans, Biostratigraphy.

INTRODUCTION

The Silurian stratigraphy of Sardinia is relatively well known due to the intensive studies carried out by experts in graptolites (for references see Storch & Piras, 2009, this volume) and in conodonts (for references see Corriga et al., 2009, this volume). Besides these two fossil groups, researches have been also focused on Wenlock, Ludlow and Pridoli molluscs, cephalopods, bivalves, gasteropods and on other minor components of the faunal associations that have been of primary significance in defining paleoecology and paleonvironments of the depositional settings; but, have of minor importance in defining the stratigraphic column. Studies on chitinozoan microfaunas, in turn, are relatively recent and commenced in the 1990s.

Chitinozoan assemblages have been studied in the allochtonous Silurian succession of southeastern Sardinia (External Nappe Zone), and in western autochtonous External Zone of the island, as well. Pittau & Del Rio (2000), Pittau et al. (2002a, 2002b, 2003, 2006) studied chitinozoans in several tectonic units, in the Gerrei area, and Sarrabus area; Dufka and Gnoli (1996) described chitinozoans from the autochtonous Silurian of the Fluminese area, in southwestern Sardinia.

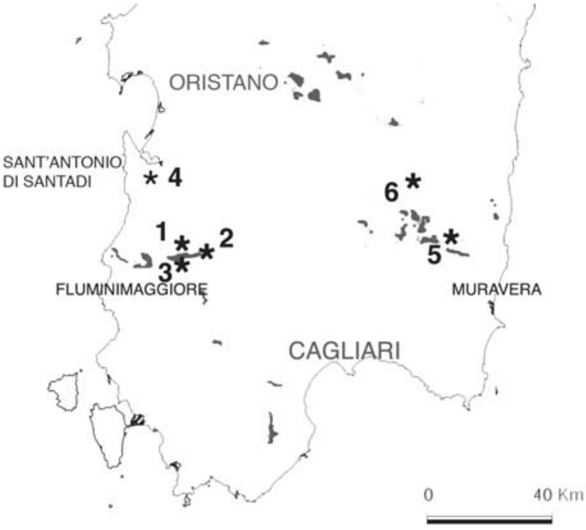


Fig. 1 - Outcrops of the Silurian-Lower Devonian succession in the External Zone and the External Nappe with location map of the sites cited in the text. 1) Fluminimaggiore Path (Sentiero Fluminimaggiore) in Xea San'Antonio locality. 2) Fluminimaggiore, Galemmu locality. 3) Fluminimaggiore, Mason Porcus. 4) Sant'Antonio di Santadi (S. Antonio Donigala). 5) Rio Ollastu. 6) Goni.

The chitinozoan assemblages have been studied in samples coming from sections and also from loose blocks (Fig. 1). Of particular significance are the sections exposed at Riu Ollastu (Pittau et al., 2003), Goni (Pittau et al., 2000) and Mason Porcus near Fluminimaggiore (Dufka & Gnoli, 1996).

Loose limestone blocks, coming from several localities of the External Zone of the basement, contained few or long-ranging graptolites, some samples yielded conodonts, and have been discussed with regard to their bivalve communities by Kriz & Serpagli (1993). Here we refer to displaced blocks, which were positive for chitinozoans, as listed in Dufka & Gnoli (1996).

1) In the Fluminimaggiore area, just outside the village, numerous block samples have been collected:
- at Galemmu (site map 1 of Fig. 1), with positive blocks 2/7, 2/9, 2/15, 2/17, 2/30, 2/46.
- at Xea Sant'Antonio (site map 3 of Fig. 1), otherwise called "Sentiero Fluminimaggiore", with the positive block 1/X.
- Chitinozoan bearing samples, labelled 3/MP5 and 3/MP6, come also from the Mason Porcus section, near Fluminimaggiore, (site map 2 of Fig.1).

2) In the central-west coast, Arburese-Capo Frasca area, near Sant'Antonio di Santadi, one positive block labelled 6/7 originated from the locality called Sant'Antonio Donigala (site map 4 of Fig. 1) .

Chitinozoan assemblages identified from southeastern Sardinia come from the Lower Graptolitic Shales Fm outcropping at Rio Ollastu in the Sarrabus area, near Muravera (site map 5, of Fig.1) and from the historical section of Goni, situated in the Gerrei area, at site map 6, Fig 1. The Lower Graptolitic Shales has been extensively studied for its graptolite faunas (Meneghini, 1857; Gortani, 1922; Schneider, 1972; Jaeger, 1976; 1991; Barca & Jaeger, 1991; Rickards et alii, 1995; Piras et al., 2009) and its chitinozoan biozones and assemblages have been calibrated by graptolite stratigraphic data. The studied intervals of the succession are shown in Fig. 2.

Stratigraphically, the overall chitinozoan assemblages of Sardinia, are representatives of the Early and Late Silurian to Lochkovian and, up to now, have been encountered from a limited number of graptolite zones.

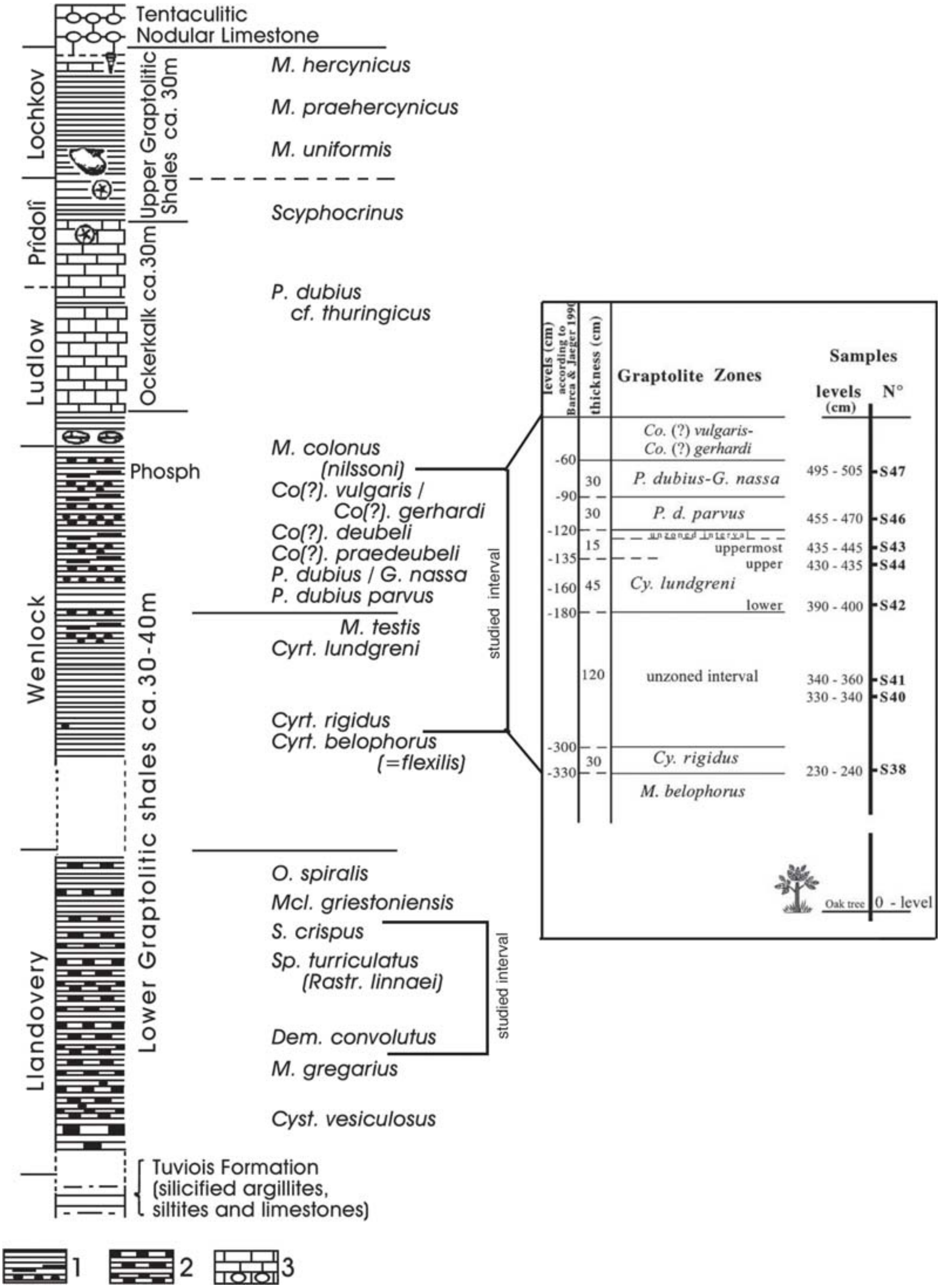


Fig. 2 - Chrono- bio- lithostratigraphic log for the Silurian and the transition to Devonian succession in the south-eastern part of Sardinia (External Nappe Zone). Location of the study samples in the Lower Graptolitic Shales Fm at Rio Ollastu and Goni. Thickness and stratigraphic data are from Jaeger & Barca (1990) and (Pittau et al. 2000; 2003; 2006). 1) alum shales with nodules, lenses and layers of phosphorite; 2) black lydites and graptolitic shales; 3) nodular limestones.

CHITINOZOANS

Chitinozoans are missing in the Rhuddanian and lower Aeronian (lower Llandovery) black shales and lydites. Upper Aeronian and Telychian (upper Llandovery) black graptolitic silty shales of the *Lituigraptus convolutus* to *Streptograptus crispus* graptolite biozones, interchanging with massive lydite beds, have yielded nearly monospecific chitinozoan assemblages. In the upper Sheinwoodian (Wenlock) beds, in *Pristiograptus dubius* to (?)*Cyrtograptus ellesae* biozones, the chitinozoan assemblages are dominated by *Conochitina*. In the Homerian (upper Wenlock), *Cyrtograptus lundgreni* Zone, the assemblages are dominated by *Conochitina*, in the lower part, and *Sphaerochitina* in the upper part (*Cy. testis* Subzone). From the upper Homerian (*Colonograptus ludensis*-*Colonograptus gerhardi* graptolite zone) through to the lower-middle Ludlow limestone's with *Cardiola docens, Cardiola donigala* bivalve communities, *Conochitina* prevails in the assemblages. In the black micritic samples of latest Pridoli (*Oulodus elegans detortus* conodont biozone*)* black micritic samples, *Urnochitina* is a predominant form. In the Lochkovian micritic samples *(Icriodus woschmidti* Zone and *Pterinopecten*-*Cybele nesiotes* and *Patrocardia evolvens* bivalve communities, *Eisenackitina* and *Bulbochitina* predominate.

The complete list of chitinozoan taxa recognized is the following:

Ancyrochitina ancyrea (Eisenack, 1931)
Ancyrochitina sp.
Angochitina cf. *echinata,* (Eisenack, 1931)
Angochitina cf. *elongata* (Eisenack, 1931)
Angochitina sp.
Belonechitina cf *latifrons* (Eisenack, 1964)
Bulbochitina sp. (aff. *B. bulbosa* or aff. *B. suchomastensis*)
Cingulochitina cf. *wronai* Paris & Krìz, 1984
Conochitina aff. *proboscifera,* Eisenack, 1937
Conochitina cf. *pachycephala* Eisenack, 1964
Conochitina cf. *tuba* Eisenack, 1932

Plate 1

Fig. 1 - *Conochitina emmastensis* Nestor, 1994; Rio Ollastu, *crispus* Biozone; L = 240 µm.
Fig. 2 - *Conochitina* sp. a; Goni section, *lundgreni* Biozone; L = 286 µm.
Figs. 3-4 - *Conochitina subcyatha* Nestor, 1982; Goni section, *lundgreni* Biozone;
3. L = 240 µm;
4. L = 320 µm
Figs. 5-8 - *Conochitina goniensis* Pittau 2000. Goni section, *lundgreni* Biozone;
5. L = 226 µm;
6. L = 265 µm;
7. L = 260 µm;
8. L = 175 µm.
Fig. 9 - *Sphaerochitina ichnussae* Pittau, 2000. Goni section, *lundgreni* Biozone; L = 180 µm.
Fig. 10 - *Sphaerochitina serpaglii* Pittau, 2000. Goni section, *lundgreni* Biozone; L = 160 µm.

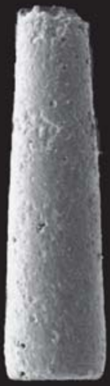

1


2


3


4


5


6


7


8


9


10

Conochitina claviformis Eisenack, 1931
Conochitina emmastensis Nestor 1994
Conochitina goniensis Pittau, 2000
Conochitina pachycephala Eisenack, 1964
Conochitina sp. 4 Nestor, 1994
Conochitina sp. aff. *C elegans* Eisenack, 1931
Conochitina sp.a
Conochitina subcyatha Nestor, 1982
Conochitina sp.
Eisenackitina bohemica (Eisenack, 1934)
Eisenackitina cf. *bohemica* (Eisenack, 1934)
Eisenackitina lagenomorpha (Eisenack, 1931)
Eisenackitina sp. C (? *E. bohemica*)
Eisenackitina? sp. A (aff. *E. lagena*)
Eisenackitina? sp. B (aff. *E. intermedia* or *E. barrandei*)
?*Eisenachitina ampulla* Pittau , 2000
Gotlandochitina ? sp.
Rhabdochitina sp. a
Spaerochitina jaegeri Pittau, 2000
Spaerochitina serpaglii Pittau, 2000
Sphaerochitina ichnussae Pittau, 2000
Tanuchitina sp.a
Urnochitina urna (Eisenack, 1934).

CHITINOZOAN BIOSTRATIGRAPHY

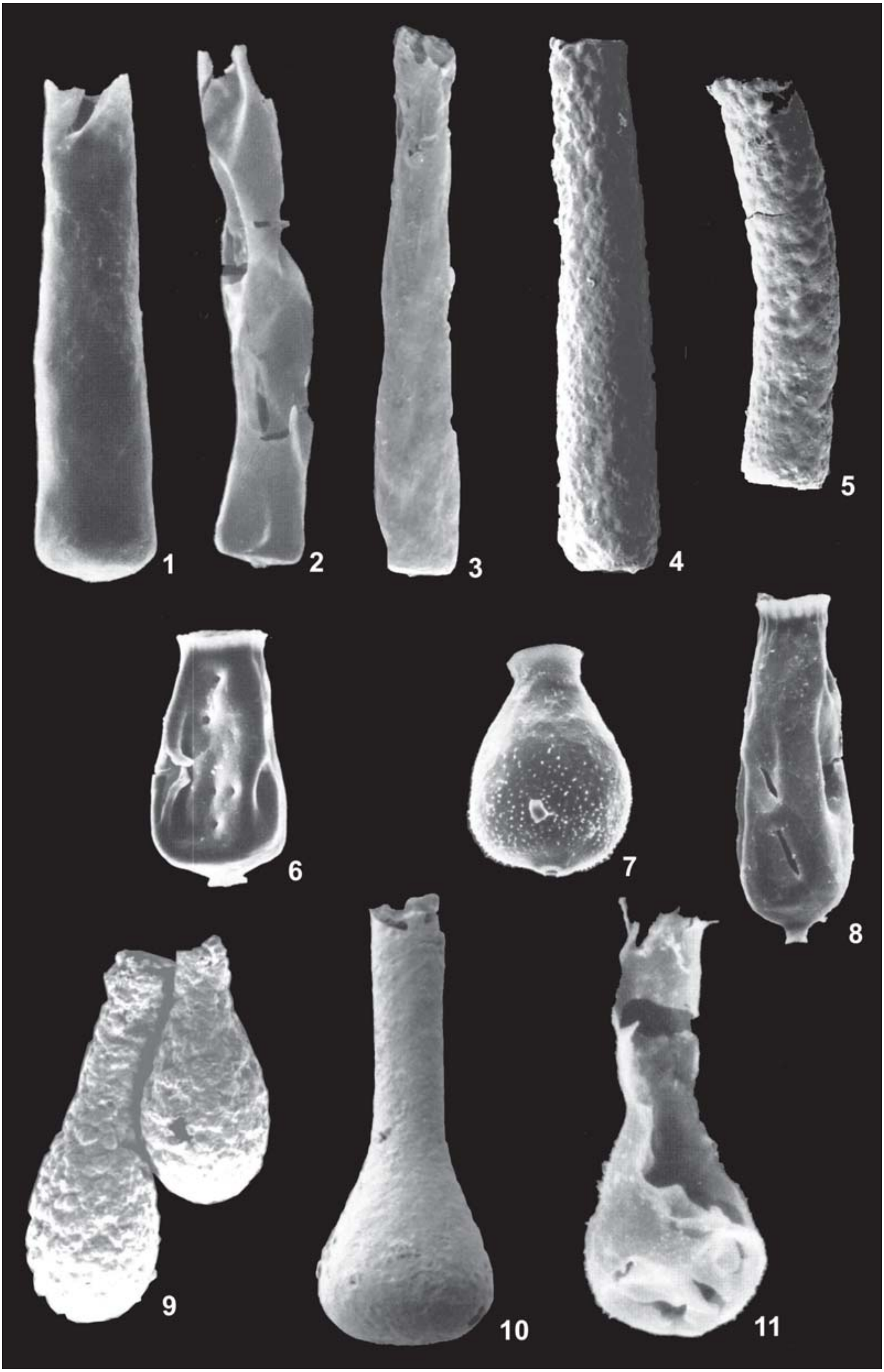
The chitinozoan microfaunas so far encountered from Silurian formations of southeastern and southwestern Sardinia, and biozones already established, are listed below:

Plate 2

Figs. 1-2 - *Conochitina pachycephala* Eisenack, 1964.
1. Galemmu, *Cardiola docens* bivalves community; L = 210 µm;
2. Sant'Antonio Donigala, *Cardiola donigala* bivalves community; L = 270 µm;

Fig. 3 - *Conochitina* sp., Rio Ollastu, *crispus* Biozone; L 390 µm.
Fig. 4 - *Tanuchitina* sp. a.; Goni section, *lundgreni* Biozone; L = 193 µm.
Fig. 5 - *Rhabdochitina* sp.a.; Goni section, *lundgreni* Biozone; L = 210 µm.
Figs. 6, 8 - *Urnochitina urna* (Eisenack, 1934); Fluminimaggiore, *Cheiopteria-Patrocardia-Cardiolinka* bivalves community;
6. L = 126 µm;
8. L = 210 µm.

Fig. 7 - *Eisenackitina bohemica* (Eisenack, 1934); Galemmu, *Cardiola docens* community; L = 142 µm.
Fig. 9 - *Sphaerochitina serpaglii* Pittau, 2000; Goni section, *lundgreni* Biozone; specimen on the left, L = 182 µm; specimen on the right, L = 129 µm.
Fig. 10 - *Sphaerochitina jaegeri* Pittau, 2000; Goni section, *lundgreni* Biozone; L = 180 µm.
Fig. 11 - *Angochitina* cf. *echinata* Eisenacks, 1931; Galemmu, *Cardiola docens* bivalves community; L = 185 µm


1
2
3
4
5
6
7
8
9
10
11

RO Assemblage

Chitinozoan assemblage with *Conochitina emmastensis* Nestor 1994 and *Conochitina claviformis* Eisenack, 1931. Its base is within the *turriculatus* graptolite Biozone and the assemblage ranges into the *crispus* Biozone. It is recorded from the Riu Ollastu section (Pittau et al.,2003). Presumed depositional environment was deep basinal.

IG Biozone (Pittau & Del Rio, 2000)

The distinctive event is the appearance of *Conochitina goniensis* Pittau, 2000 and the co-presence of *Conochitina subcyatha* Nestor, 1982. Numerous large *Conochitininae* occur in the assemblage. In the type-section, at Goni, the IG Biozone is represented by samples S38 and S41 (Fig. 2); it matches with the *Cy. rigidus* graptolite Biozone and the unzoned interval in the succession, between the *Cy. rigidus* and *Cy. lundgreni* biozones. The presumed depositional environment was deep basinal.

IIG Biozone (Pittau & Del Rio, 2000)

Acme biozone of *Conochitina goniensis* Pittau, 2000. Other characteristic species are *Sphaerochitina jaegeri* Pittau, 2000, *Sphaerochitina ichnussae* Pttau, 2000, *Sphaerochitina serpaglii* Pittau, 2000 and *Conochitina subcyatha* Nestor, 1982. In the type-section, at Goni, the IIG Biozone is represented by sample S42 and matches the lower portion of the *Cy. lundgreni* Biozone (Early Homerian). The depositional environment was deep basinal.

IIIG Biozone (Pittau & Del Rio, 2000)

Acme biozone of *Sphaerochitina serpaglii* Pittau 2000 and *S. ichnussae* Pittau, 2000. Its lower limit is the last occurrence (LO) of *Conochitina subcyatha* Nestor, 1982 and the FAD of ?*Eisenackitina ampulla* Pittau, 2000. Biozone IIIG matches the upper portion of the *Cy. lundgreni* graptolite biozone (*M. testis* Subzone). The presumed depositional environment was deep basinal.

IV-G Biozone

Distinctive species is *Conochitina pachycephala* Eisenack, 1964. It is, up to now, the only species present in the chitinozoan assemblage. It occurs after an interval devoid of chitinozoans (Extinction Datum III, Pittau et al., 2006) at the end of the *testis* Biozone. The IV-G biozone matches the *vulgaris-gerhardi* graptolite biozone in the Goni section. The depositional environment is likely basinal, transitional to shelf. This biozone is, very likely, equivalent to the GADa Assemblage of the shelf depositional setting (see below).

GADa Assemblage (based on Dufka & Gnoli, 1996)

Distinctive species is *Conochitina pachycephala* Eisenack, 1964. The chitinozoan assemblage is poor in number of species and represented by *Conochitininae*. Ecostratigraphically, it matches the *Cardiola docens* and *Cardiola donigala* bivalves communities (Kriz & Serpagli, 1993) and likely ranges from upper Sheinwoodian (upper lower Wenlock) to lower(?) Ludlow according to the range of the *Conochitina pachycephala* Biozone of the “global biozonation” (Verniers et al., 1995). This chitinozoan assemblage derives from microfaunas recovered from limestone blocks at Galemmu, in the Fluminimaggiore area, and Sant’Antonio Donigala, in the Arburese area. The depositional environment was a carbonatic and muddy shelf. Biostratigraphically GAD a Assemblage fits the IV-G Biozone of the Lower Graptolitic Shales.

			GRAPTOLITES ZONES	CHITINOZOANS ZONES			
				Basin	Transition	Shelf	Index species
DEV.	LOCH.		uniformis			GAL 2	Eis. bohemica
SILURIAN	PRIDOLI		transgrediens				U. urna
			bouceki				
			branikensis-lochkoviensis				
			parultimus-ultimus				
	LUDLOW	LUDFORDIAN	fragmentalis				A. cf. elongata
			kozlowskii				
			inexpectatus				
			bohemicus				
			linearis-leintwardinensis				
		GORST.	chimaera				
			nilssoni-colonus			GADa	C. pachycephala
	WENLOCK	HOMERIAN	ludensis-gerhardi		IV-G		
			praedeubeli-deubeli				
			parvus-nassa				
			lundgreni-testis	III-G II-G			C. serpaglii C. goniensis
		SHEINWOODIAN	ramosus-ellesae	I-G			C. goniensis C. subcyatha
			belophorus-rigidus				
			riccartonensis				
			murchisoni				
			centrifugus				
	LLANDOVERY	TELYCHIAN	insectus				
			lapworthi				
			spiralis				
			"tullbergi"				
			griestonensis				
			turriculatus-crispus	RO Assemb.			C. emmastensis
			linnei				
		AERONIAN	sedgwickii				
			leptotheca - convolutus				
			triangulatus-pectinatus				
		RHUDDANIAN	cyphus				
			vesiculosus				
			ascensus - acuminatus				

Fig. 3 - Biozonal scheme for western and eastern Sardinia Silurian succession in relation to the graptolites biozonation and depositional facies.

GADb A*SSEMBLAGE* (based on Dufka & Gnoli, 1996)

A small group of species characterize this assemblage: *Angochitina* cf. *elongata* Eisenack, 1931, *A*. cf. *echinata*, few representatives of *Eisenacklitina, Conochitina* and *Belonechitina* (Dufka & Gnoli, 1996). The authors highlighted that *Angochitina* specimens, recovered in Sardinia, are slightly different from the holotypes, nevertheless, this assemblage suite is comparable with the *A. elongata* Biozone of the "global biozonation" (Verniers et al., 1995). GADb assemblage matches with the *Cardiola docens* bivalves community (Kriz & Serpagli, 1993) and, according the maximum stratigraphic range of the *elongata* chitinozoan Biozone, it encompasses Ludlow. This chitinozoan assemblage deposited in a carbonatic and muddy shelf.

MP A*SSEMBLAGE*. (based on Dufka & Gnoli, 1996)

Distinctive species is *Urnochitina urna* (Eisenack, 1934). Accompanying taxa are representatives of *Angochitina, Cingulochitina* and *Eisenackitina*. Ecostratigraphically, this chitinozoan assemblage matches the two bivalve communities studied in the Mason Porcus section, near Fluminimaggiore (Kriz & Serpagli, 1993): those of *Cheiopteria-Patrocardia-Cardiolinka* and *Patrocardia evolvens evolvens- Panenka*. The MP assemblage, according to the stratigraphic range of the distinctive species matches the Pridoli age and the transition to Lochkovian (Silurian Devonian boundary).

GAL2 A*SSEMBLAGE*

The distinctive species *Eisenackitina bohemica* (Eisenack, 1934) unequivocally indicated the Lochkovian age of this assemblage. At Galemmu, where the assemblage has been recovered, the limestone blocks yield also bivalvia communities (*Pterinopecten-Cybele nesiotes* and *Patrocardia evolvens evolvens-Panenka)*. This chitinozoan assemblages developed in a carbonatic and muddy shelf settings.

ECOLOGICAL REMARKS

It is a general rule that distribution of organisms in the natural environments depends on physico-chemical and biological constraints. It is reasonable that also the distribution of chitinozoans is, at a certain extent, affected by facies control. Thus, the assemblages should be studied with respect to the evolution of the ancient sedimentary basins. It is widely accepted that the Silurian Sardinia basins developed in two different depositional settings: in the western basement, sedimentation occurred at the bottom of an epicontinental sea and, if tectonized and polydeformed, the Silurian succession is substantially autochtonous (Carmignani et al., 2001). The eastern basin formed during crustal extension and its localization was a hundred kilometre apart the present position (Carmignani et al., 2001). Sedimentation there, was mainly pelagic. The lower portion of the Lower Graptolitic Shale was characterized by a rhythmic sedimentation of carbonaceous matter-bearing chert, radiolarites, and black silica-argillaceous graptolitic shales with high content of organic matter. The same depositional regime persisted during Aeronian and Telychian, and then passed to possibly isolated basin (upper portion of the Lower Graptolitic Shales) characterized by a more anoxic bottom and a restricted terrigenous input (Barca, pers. com.). Sections of graptolitic shales within the nappe zone are very condensed: 7-8 m of shales representing a duration time of almost 5 million years.

Productivity of chitinozoans is low to very low in the quartzitic facies where the species composition is uniform, consisting of 1-2 species, whilst, a special attention deserves deposits of the so called "condensed facies", in which a number of low-diversity to monospecific chitinozoan associations have been recognized.

Late Wenlock, Ludlow and Pridoli sediments of southwestern Sardinia, belonging to the Fluminimaggiore and Mason Porcus formations, are mostly represented by micritic limestones. In this facies, chitinozoans exhibit low diversity, low abundance or they are completely missing. This could likely be explained by transportation of the floating vesicles from agitated waters into more quiet settings. Moreover, scarcity of chitinozoans in the biomicritic limestone could be also implied from a higher rate of sedimentation in the Iglesiente-Sulcis-Arburese (Dufka & Gnoli, 1996).

Understanding the palaeoecology of the chitinozoans means to provide a precise interpretation of the changing composition of the assemblages and, unlikely, this subject is not conclusive and, further, dependance on facies is expressed in a different way by different chitinozoan taxa. The representatives of the genera *Ancyrochitina* and *Angochitina*, with a prominent and complicated ornamentation of the vesicle, are distributed in the Mason Porcus Fm. These genera are characteristic of the transitional or the slope facies (Laufeld, 1974; Miller, 1982; 1996).

Smooth and weakly ornamented simple forms, like those representatives of the genera *Sphaerochitina, Belonechitina, Bulbochitina, Eisenackitina, Urnochitina,* and *Conochitina* are more widespread and sometimes extended into deep basin settings (Nestor, 1994). Abundant *Sphaerochitina* (*S. serpaglii, S. jaegeri, S. ichnussae*) and small and medium sized specimens of *Conochitina* (*C. goniensis),* in fact, characterize chitinozoan assemblages of the Lower Graptolitic Shales of eastern Sardinia. In the same depositional settings the large *Conochitina* species (*C. proboscifera, C. pachycephala*) are rare, likely because they floated close to the bottom (Miller, 1996). Moreover, the chitinozoan distribution across the Silurian limestone and black-shale formations of Sardinia, has shown that chitinozoans disliked bottom waters enriched with silica, hence their rare occurrence in the early Silurian of the Lower Graptolitic Shales.

The environmental control on chitinozoan taxa is evident, namely in the case of the Silurian assemblages. The Silurian was a period during which severe biological crises occurred, and several scientists dedicated considerable efforts in attempting to achieve a wider and deeper understanding of the natural environmental processes at the base of mass extinctions, touching some selected planctonic organisms (giant graptolites) more than others, but strongly affecting also shelfal communities (Jeppson & Calner, 2003). As this concerns, distribution of chitinozoan taxa was controlled, at least in part, by the environmental pressure. At the lower boundary and within the *Cyrtograptus lundgreni* Zone, chitinozoan microfauna changes three times (Pittau et al., 2006): from the "*Conochitininae* association" to the "*Goniensis* association", "*Serpaglii-ichnussae* association", and "*Goniensis* relict association" respectively. The chitinozoan changeovers succeeded rapidly and two of three associated positive excursions in Cd, Co and Ni concentrations in the organic structured matter and the whole rock (Pittau et al., 2006). The case study carried out in the classical Goni succession, across the *lundgreni* chron, elucidates dynamic effects and compare extinction events in different biological groups (Pittau et al., 2006; Storch et al., 2009).

ACKNOWLEDGEMENTS

Funding for this work was provided by MIUR-PRIN 2007 (*Analysis of stratigraphic, palaeontological and structural features of the Hercynian basement and the Tertiary cover in Sardinia and Calabria, as a contribution to the geodynamic reconstruction of the central-western Mediterranean basin*).

References

Barca S. & Jaeger H. (1990). New geological and biostratigraphical data on the Silurian in SE Sardinia. Close affinity with Thuringia. *Bollettino della Società Geologica Italiana*, 108 (1989): 565-580.

Carmignani L., Carosi R., Di Pisa A., Gattiglio M., Musumeci G., Oggiano G. & Pertusati P.C., (1994). The Hercynian chain in Sardinia (Italy). *Geodinamica Acta*, 7: 31-47.

Carmignani L., Oggiano G., Barca S., Conti P., Eltrudis A., Funedda A., Pasci S. & Salvadori I. (2001). Note Illustrative della Carta Geologica d'Italia. Carta della Sardegna 1:200.000. Istituto Poligrafico e Zecca dello Stato: 265 pp.

Corriga M.G., Corradini C. & Ferretti A. (2009), Silurian conodonts from Sardinia: an overview. *Rendiconti della Società Paleontologica Italiana*, 3 (1): 77-93.

Dufka P. & Gnoli M. (1996). A report on Silurian and lowermost Devonian chitinozoans from South-western Sardinia. *Bollettino della Società Paleontologica Italiana*, 34:263-269.

Gortani M. (1922). Faune Paleozoiche della Sardegna. II Graptoliti della Sardegna Orientale. *Palaeontographia Italica,* 28: 85-11

Jaeger H. (1976). Das Silur und Unterdevon vom Thüringischen Typ in Sardinien und seine regionalgeologische Bedeutung. *Nova Acta Leopoldina*, 224, 45 (Franz-Kossmat-Symposium): 263-299.

Jaeger H. (1991). Neue Standard-Graptolithenzonenfolge nach der «Großen Krise» an der Wenlock/Ludlow-Grenze (Silur). *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen*, 182: 303-354.

Jeppsson L. & Calner M. (2003). The Silurian Mulde Event and a scenario for secundo-secundo events. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, 93: 135-154.

Kriz J. & Serpagli E. (1994). Upper Silurian and lowermost Devonian Bivalvia of Boemia type from Sardinia South-Western Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (1): 59-76.

Laufeld S. (1974). Silurian Chitinozoa from Gotland. *Fossills and Strata* 5: 1-130.

Meneghini G. (1857). Paléontologie de l'Ile de Sardaigne ou déscription des fossiles recueilles dans cette contrée par le Général Albert de la Marmora pour faire suite à la troisième partie du Voyage en Sardaigne VIII, 586 pp.

Miller M.A. (1982). The use of chitinozoans for recognition of sedimentary environments: concepts and examples. *Journal of Paleontology*,56: 2-19.

Miller M.A. (1996). Chapter 11. Chitinozoa. *In* Jansonius J. & McGrgor D.C. (Eds.), Palynology: principles and applications. *American Association of Stratigraphic Foundation* 1: 307-336.

Nestor V. (1994). Early Silurian chitinozoans of the Estonia and North Latvia. *Academia*, 4: 163 pp.

Piras S., Storch P., Pittau P. & Del Rio M. (2009). The Lower Graptolitic Shales at Rio Minderri and Rio Brabaisu-Rio Ollastu confluence (Rio Ollastu area, Sarrabus, SE Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 181-186.

Pittau P., Cotza F. & Del Rio M. (2002a). Goni spheres: probable agglutinated Silurian foraminifera lining and radiolaria capsular membranes (South-eastern Sardinia, Italy). *In* Cherchi A., Corradini C. & Putzu M.T. (Eds.), Sardinia Field Trip - Palaeontology & Stratigraphy. *Rendiconti della Società Paleontologica Italiana*, 1: 159-168.

Pittau P., Cotza F. & Del Rio M. (2003). Early Silurian siliceous sponge spicule assemblages from Sardinia Hercynian Chain (Italy). *Bollettino della Società Paleontologica Italiana,* 42(3): 225-240.

Pittau P., Cotza F., Cristini S., Del Rio M. & Loi M. (2006). Palaeontologic and biogeochemical characterization of the *C. lundgreni* Event in the black shales of eastern mid-Sardinia. *Lethaia,* 39: 111-127.

Pittau P. & Del Rio M. (2000). Wenlock Chitinozoans of SE Sardinia (Italy). *Bollettino della Società Paleontologica Italiana* 39: 257-291.

Pittau P., Del Rio M. & Barca S. (2002b). The Wenlockian Graptolitic Shale at Goni, SE Sardinia. *In* Cherchi A., Corradini C. & Putzu M.T. (Eds.), Sardinia Field Trip - Palaeontology & Stratigraphy. *Rendiconti della Società Paleontologica Italiana,* 1: 247-253.

Rickards R.B., Holland C.H. & Serpagli E. (1995). Aspects of Silurian and Lower Devonian graptolite faunas and stratigraphy in Southern Sardinia. *Bollettino della Società Paleontologica Italiana* 34: 67-80.

Schneider H.J. (1972). Schichtgebundene NE-Metal- und F-Ba-Lagerstätten im Sarrabus-Gerrei-Gebiet, SE-Sardinien. I. Bericht zur Lagerstättenkunde und Geologie. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte,* 1972-H9: 529-541.

Storch P. & Piras S. (2009). Silurian graptolites of Sardinia: assemblages and biostratigraphy. *Rendiconti della Società Paleontologica Italiana,* 3 (1): 77-93.

Storch P., Piras S., Pittau P. & Del Rio M. (2009). The historical section of Goni (Lower Graptolitic Shales, SE Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 197-204.

Verniers J., Nestor V., Paris F., Dufka P., Sutherland S. & Van Grootel G. (1995). A global Chitinozoa biozonation for the Silurian. *Geological Magazine*, 132: 651-666.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 143-155

The state of research on Sardinian Silurian Crustacea

MAURIZIO GNOLI, VINCENT PERRIER, PAOLO SERVENTI

M. Gnoli - Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia, largo S. Eufemia 19, I-41100 Modena (Italy); maurizio.gnoli@unimore.it
V. Perrier - Université de Lyon 1, UMR CNRS 5125 PEPS, 2 rue R. Dubois, F-69622 Villeurbanne cedex (France); vincent.perrier@univ-lyon1.fr
P. Serventi - Dipartimento del Museo di Paleobiologia e dell'Orto Botanico, Università di Modena e Reggio Emilia, Via Università, 4, I-41100, Modena (Italy); paolo.serventi@unimore.it,

ABSTRACT - Among crustaceans, Ostracoda – mainly Myodocopida – and Phyllocarida are documented from the Silurian of Sardinia. A review of the knowledge on these fossil groups in the Silurian of Sardinia is presented and supplemented by some remarks on myodocope autecology and palaeobiogeography.

KEY WORDS - Silurian, Sardinia, Ostracoda, Phyllocarida.

OSTRACODA

The first evidence for bivalved ostracod crustaceans in the Silurian of Sardinia stems from the work of Mario Canavari (1899) who described 20 taxa that he assigned to the genera *Aparchites*, *Entomis*, *Kloedenia*, *Cypridina* and *Bolbozoe*. Thanks to the careful checking of many rock samples from over 100 localities, collected by colleagues from Modena in the last thirty years, several palaeocopid (*Aparchites*, *Beyrichia*, *Kloedenia)* and myodocope (*Bolbozoe*, '*Cypridinid*', *Entomozoe*, *Pseudoentomozoe, Richteria*) ostracod taxa have now been recorded from Sardinia (see Ferretti et al., 1999). The most recent studies dealing with this Silurian ostracod fauna are those of Perrier (2007) and Perrier et al. (2007), which concentrate on the functional morphology and autecology of the Silurian myodocopes from especially France and the Czech Republic. The Silurian myodocope fauna of Europe (e.g., Sardinia, France, Czech Republic; Fig. 1a) is now relatively well known, but the palaeocopes have not been so intensively studied. Moreover, due to recent discoveries of Silurian ostracods with soft anatomy preserved (Siveter et al., 2003; 2007 and unpublished information), it appears that many forms that were described as palaeocopes on the basis of their carapace morphology may in fact turn out to be myodocopes. This paper will concentrate on the first ostracods that appear to have colonised pelagic niches, in the late Silurian: namely the myodocopes, the group that also comprises the present day pelagic ostracod fauna.

MYODOCOPES OF SARDINIA

Since the 1980's Silurian myodocopes have been recognized as an important component of the Palaeozoic marine ecosystem, alongside palaeocope, podocope and leperditicopid ostracods. Major groups of myodocopes are differentiated on details of valve morphology,

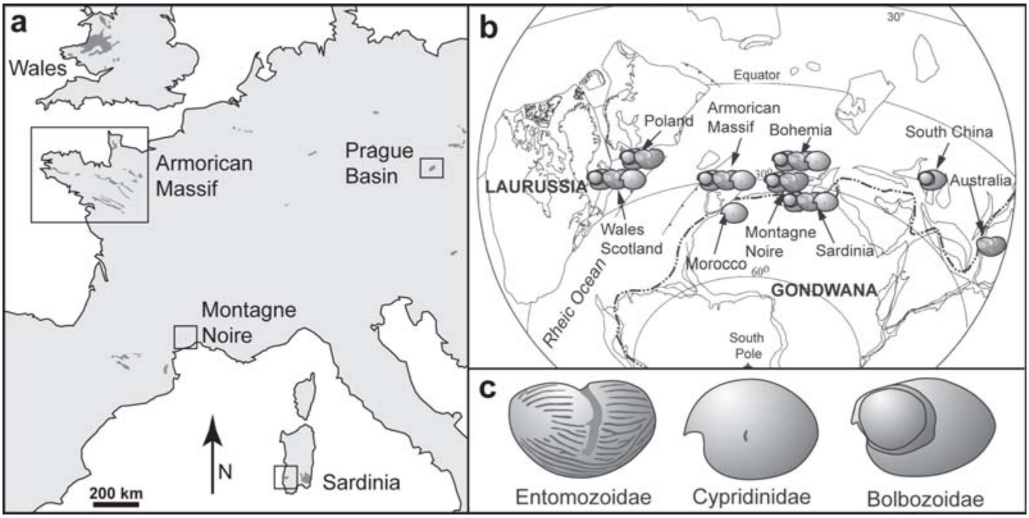


Fig. 1 - a) Occurrence of Silurian myodocopes in western Europe. Squares indicate regions with specimens figured in the present paper. b) Mid-Silurian (420 Ma) distribution of bolbozoid, cypridinid and entomozoid myodocopes (palaeogeography after Cocks & Torsvik, 2002). c) Generalized morphological reconstruction of a Silurian entomozoid, cypridinid and bolbozoid myodocope.

the soft parts being known from only two species (Siveter et al., 2003; 2007). Entomozoid, cypridinid and bolbozoid myodocopes (Fig.1c) are known from Sardinia.

Entomozoidae

The entomozoids are recognisable by their characteristic so-called finger-print ornament (Pl. 1, Figs 1-8; see Gooday, 1983; Olempska, 1992). Their valve margins are generally convex, except for the dorsal margin, which is straight and may be slightly concave over the site of the adductorial sulcus (Pl. 1, Figs 1-4, 10-11), which has a small muscle pit (Pl. 1, Fig. 10). As with the bolbozoids, entomozoid valves are morphologically quite different from other fossil and Recent myodocopes. We regard the group as belonging to the Order Myodocopida (see Gründel, 1969) partly because of the close resemblance of their valves with *Colymbosathon ecplecticos* (see Perrier, 2007; Siveter, 2008), a Silurian cylindroleberidid myodocopid with soft parts preserved (Siveter et al., 2003).

Sardinian entomozoids. - Canavari (1899) described several entomozoids from the Ludlow Series of Sardinia. Based on examination (VP) of his original material, in the Calci Museum, University of Pisa, Italy, Perrier et al. (2007) considered that *Entomis migrans* (Pl. 1, Fig. 2), *Entomis lamarmorai* (Pl. 1, Fig. 3), *Entomis* n. f.? (Canavari, 1899, Pl. 25, Fig. 6) and possibly *Entomis meneghinii* (Canavari, 1899, Pl. 25, Figs 8-11) are conspecific with *Richteria migrans* (Barrande, 1872). Canavari (1899) distinguished his *Entomis migrans* and *Entomis lamarmorai* on the basis of ribbing patterns (compare Pl. 1, Figs 2 and 3). Chaubet (1937) interpreted similar variation in French material from Montagne Noire as polymorphism within a single species, *Entomis migrans*. There is a good though not complete degree of overlap in valve size range and also valve shape (outline) between the French and Czech material (Perrier et al., 2007). The variation in ribbing observed in Sardinian entomozoid material is similar to that of

E. migrans from France and Bohemia. Minor differences in ornament could be the result of a variety of factors including sampling across a range of "populations".

Richteria migrans gives its name to a Silurian fossil community from Sardinia ('*Entomis*' *migrans* of Ferretti et al., 1999, p. 275). *Bolbozoe bohemica* and other myodocope species referred to as "*E.*" *lamarmorai*, "*E.*" *ichnusae* and "*E.*" *meneghinii* (of Canavari, 1899) were included in the community. It occurs in the Ludlow Series and represents a shallow water pelagic assemblage (distribution: benthic assemblage (BA**)** 3 to 4). It should be noted that another *R. migrans* community is recorded in the Middle Ludlow of Czech Republic ('*Entomis*' *migrans* of Kriz 1999, p. 251).

The only other ribbed entomozoid from Sardinia, namely *Entomis* (?) *pteroides* Canavari, 1899, was assigned by Pribyl (1951) to the genus *Pseudoentomozoe*. The non-ribbed taxa that Canavari (1899, Pl. 25, Figs 12-18, Pl. 26, Figs 1-5) described as *Entomis ichnusae*, *Entomis zoppii*, *Entomis subreniformis* n. f., *Entomis* (?) *amygdaloides* n. f., *Entomis* (?) *parvula* n. f. and *Entomis* (?) f. ind. belong outside *Richteria* (see Perrier, 2007; Perrier et al., 2007); opinion on their systematic position awaits new material and further study.

CYPRIDINIDAE

The valve morphology of the Silurian so-called cypridinids is like that of Recent Cypridinidae (Siveter et al., 1987; 1991; Vannier & Abe, 1992; Perrier, 2007; Perrier et al., in prep). Their lateral outline is ovoid (Pl. 1, Figs 12-19) and they have a well-developed rostrum (Pl. 1, Figs 16-17, 20-21) and a simple crescent-shape muscle scar (Pl. 1, Figs 16, 22). Though such valves are generally regarded as cypridinids, their internal anatomy is unknown and therefore this assignment remains to be confirmed.

Silurian cypridinids have received only scant attention. Barrande (1872) did not mention such forms, even though they frequently co-occur with bolbozoids at several localities in the Prague Basin. An early description of a supposed Silurian cypridinid is that of *Cypridina tosterupi* Moberg (1895) from the '*Posidonomya* skiffer' of Sweden. This species was clearly considered by Moberg as a myodocope and was tentatively placed within *Cypridina* Milne-Edward, 1840 (see Kornicker & Sohn, 2000, p. 19-20). Several myodocope species from France and Wales awaiting detailed study were provisionally termed 'Cypridinid' or 'cypridinid-like' (Siveter et al., 1987). Kornicker and Sohn (2000) placed these forms in the Tribe Cypridinini.

Sardinian cypridinids. Canavari (1899) noted that what he described as *Cypridina tyrrhencia*, from the Silurian '*Cardiola* limestones' of southern Sardinia, resembles certain Recent and Carboniferous Cypridinidae. Based on new observations of the original material of *Cypridina tyrrhencia* Canavari, 1899 (Pl. 26, figs 10-12; herein Pl. 1, Figs 12-13) Perrier (2007) and Perrier et al. (in prep.) regard this species as similar to other Silurian cypridinids from France and Wales but within a new genus. This exclusively Silurian genus (Pl. 1, Figs 12-22) is characterized by a tiny crescent-shaped muscle scar that has no counterpart in any post-Silurian to Recent cypridinid (see Kornicker, 1975; 1981). The overall lateral outline of this new genus is simple and similar to numerous post-Silurian myodocopes (e.g., see Wilkinson et al., 2004; Weitschat, 1983).

BOLBOZOIDAE

The bolbozoids are characterized by a hemispheric protuberance (bulb) situated anterodorsally on both valves (see Siveter et al., 1987; 1991; Vannier & Abe, 1992; Perrier 2007; Perrier et al., in prep.; Pl. 2, Figs 8-11, 20-21 herein). Adjacent to the bulb is an adductorial sulcus (Pl. 2, Figs 4-7, 16-17) with a muscle scar (Pl. 2, Figs 4, 15, 25) and a more or less well-developed rostrum anteriorly (Pl. 2, Figs 6, 12-14, 16, 18-24). Apart from *Bolbozoe anomala* all other bolbozoid species have ornamented carapaces (see Perrier 2007; Pl. 2 Figs 22-23 herein). The bolbozoids have a distinctive morphology and are difficult to assign within an extant group of myodocopes.

Sardinian bolbozoids. The four bolbozoid species that Canavari (1899) described from the Silurian of Sardinia show similarity with two species originally recorded (Barrande, 1872) from the Prague Basin. *B. capellinii* Canavari, 1899 (Pl. 26, fig. 19, lost specimen), *B. italica* Canavari, 1899 (Pl. 26, figs 16-18; herein Pl. 2, Figs 1-2) and *B. lanceolata*

Plate 1

Silurian entomozoids (1-11) and cypridinids (12-22) from Europe.

Figs 1-11 - *Richteria migrans* (Barrande, 1872).

1. plastic cast made from a latex mould, incomplete right valve (NM-L 22944), Lectotype, lateral view, courtesy H. Groos-Uffenorde; Praha-Podolí, Bohemia; Scale bar = 500 µm.
2. carapace (I 71) left lateral view; Xea San Antonio, Sardinia; Scale bar = 500 µm.
3. carapace (I 73), left lateral view, previously described as *E. Lamarmorai* by Canavari (1900, pl.25, fig. 3); Xea San Antonio, Sardinia; Scale bar = 500 µm.

4-7. complete carapace (FSL 705032a), right lateral, posterior, ventral and dorsal views; La Combe d'Yzarne, France; Scale bar = 500 µm.

8. right valve (FSL 705026a), flattened specimen; Lounin, Bohemia; Scale bar = 1 mm.
9. left valve (FSL 705009a), detail of triangular smooth area, anterolateral view; Velky Vrch, Bohemia; Scale bar = 100 µm.
10. right valve (FSL 705001a), detail of adductorial sulcus and muscle scar, lateral view; Scale bar = 100 µm.
11. dorsal view of the carapace (FSL 705032a), details of central part of dorsal margin; La Combe d'Yzarne, France; Scale bar = 100 µm.

Figs 12-22 - "Cypridinid" gen. and sp. nov.

12-13. previously described as *Cypridina tyrrhenica* by Canavari (1900, pl.26, fig. 12-13), (12) right valve (I 92), (13) right valve, complete carapace (I 91); Xea San Antonio, Sardinia; Scale bar = 1 mm.

14-15. left valve (LPB 18926), (14) lateral view, (15) oblique ventral view; Les Chevrolières, Armorican Massif; Scale bar = 1 mm.

16. left valve (FSL 710652); St Jean sur Erve, Armorican Massif; Scale bar = 500 µm.
17. right valve (FSL 710520); Les Buardières, Armorican Massif; Scale bar = 500 µm.
18. right valve (FSL 710653); St Jean sur Erve, Armorican Massif; Scale bar = 500 µm.

19-20. internal view of the left valve (FSL 710592), (19) general view, Scale bar = 250 µm; (20) detail of the rostrum; Scale bar = 100 µm; Les Chevrolières, Armorican Massif.

21. right valve (FSL 710520), detail of the rostrum; Les Buardières, Armorican Massif; Scale bar = 200 µm.
22. left valve (FSL 710652), detail of the muscle scar; St Jean sur Erve, Armorican Massif; Scale bar = 100 µm.

Arrow points to anterior in each case.

Collection numbers : FSL (collections of the Université Claude Bernard Lyon 1, France); I (Museo de Storia Natural e del Territorio, Calci, Italy); LPB (University of Brest, France); MNHN (Museum d'Histoire Naturelle de Nantes, France); NM-L (Národní Museum, Prague, Czech Republic); UMC-IP-VP (University of Montpellier, France).

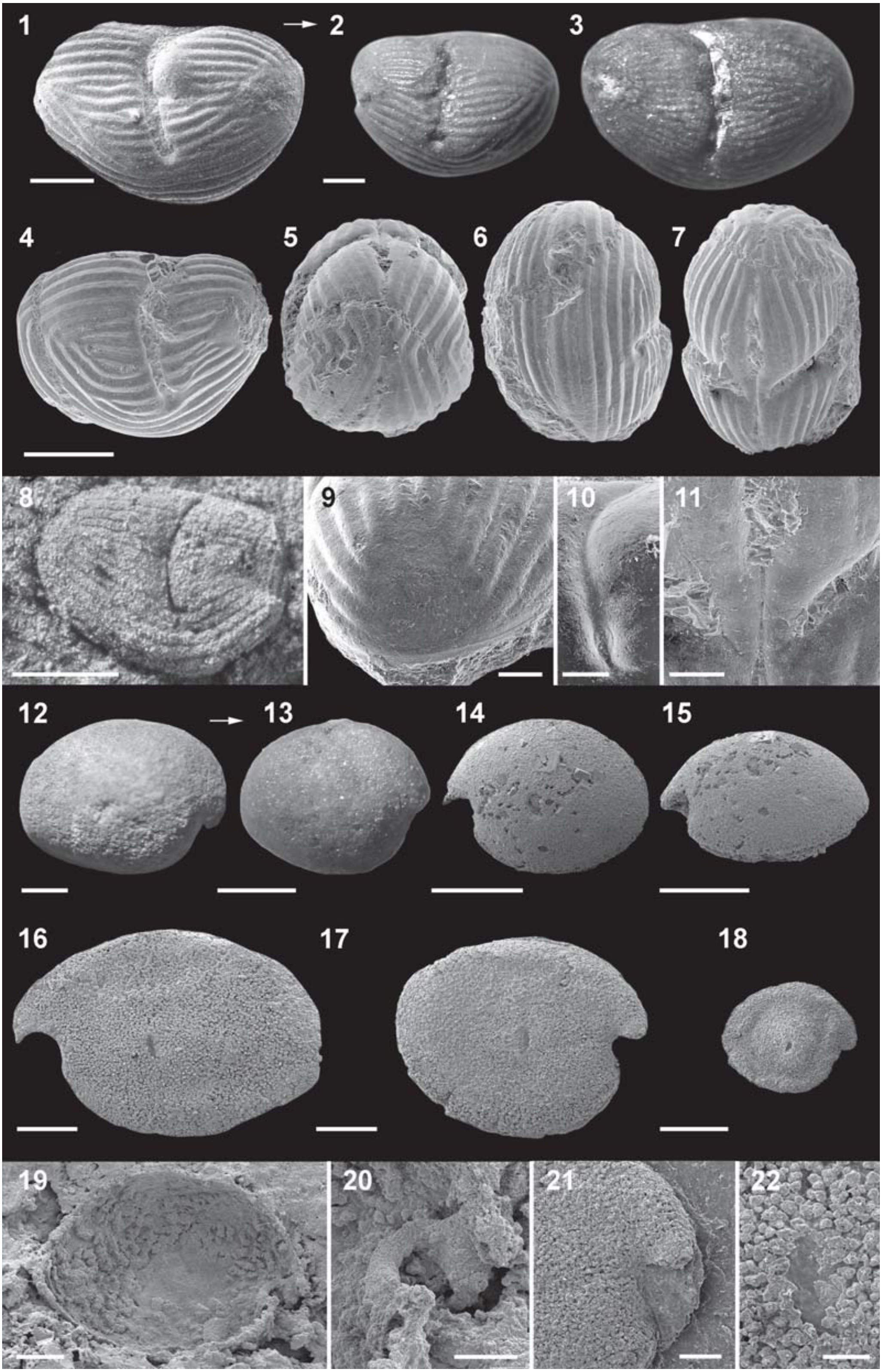

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

Plate 2

Silurian bolbozoids from Europe

Figs 1-15 - *Bolbozoe anomala*.

1-2. previously described as *B. italica* by Canavari (1900, pl. 26, figs 18, 16), (1) left valve (I 98), Scale bar = 2 mm; (2) left valve (I 97a), Scale bar = 500 µm; Xea San Antonio, Sardinia.
3. previously described as *B. lanceolata* by Canavari (1899, pl.26, fig. 20), incomplete right valve (I 99); Xea San Antonio, Sardinia; Scale bar = 2 mm.
4. Lectotype, right valve (NM-L 23572); Lochkov, Bohemia; Scale bar = 2 mm.
5. Paralectotype, left valve (NM-L 13993); Lochkov, Bohemia; Scale bar = 2 mm.
6. right valve (MNHN 154); Chemiré-en-Charnie, Armorican Massif; Scale bar = 500 µm.
7. left valve (FSL 710569); Les Buardières, Armorican Massif; Scale bar = 500 µm.
8-11. complete specimen (FSL 710593), (8) lateral view of left valve, (9) frontal view, (10) oblique frontal view, (11) slightly oblique dorsal view; Les Chevrolières, Armorican Massif; Scale bar = 500 µm.
12. detail of the rostrum internal view (FSL 710592); Les Chevrolières, Armorican Massif; Scale bar = 500 µm.
13-14. detail of the rostrum (FSL 710536), (13) anteroventral view, (14) lateral view; Chemiré-en-Charnie, Armorican Massif; Scale bar = 250 µm.
15. left valve (FSL 710597); detail of the muscle scars; Les Chevrolières, Armorican Massif; Scale bar = 200 µm.

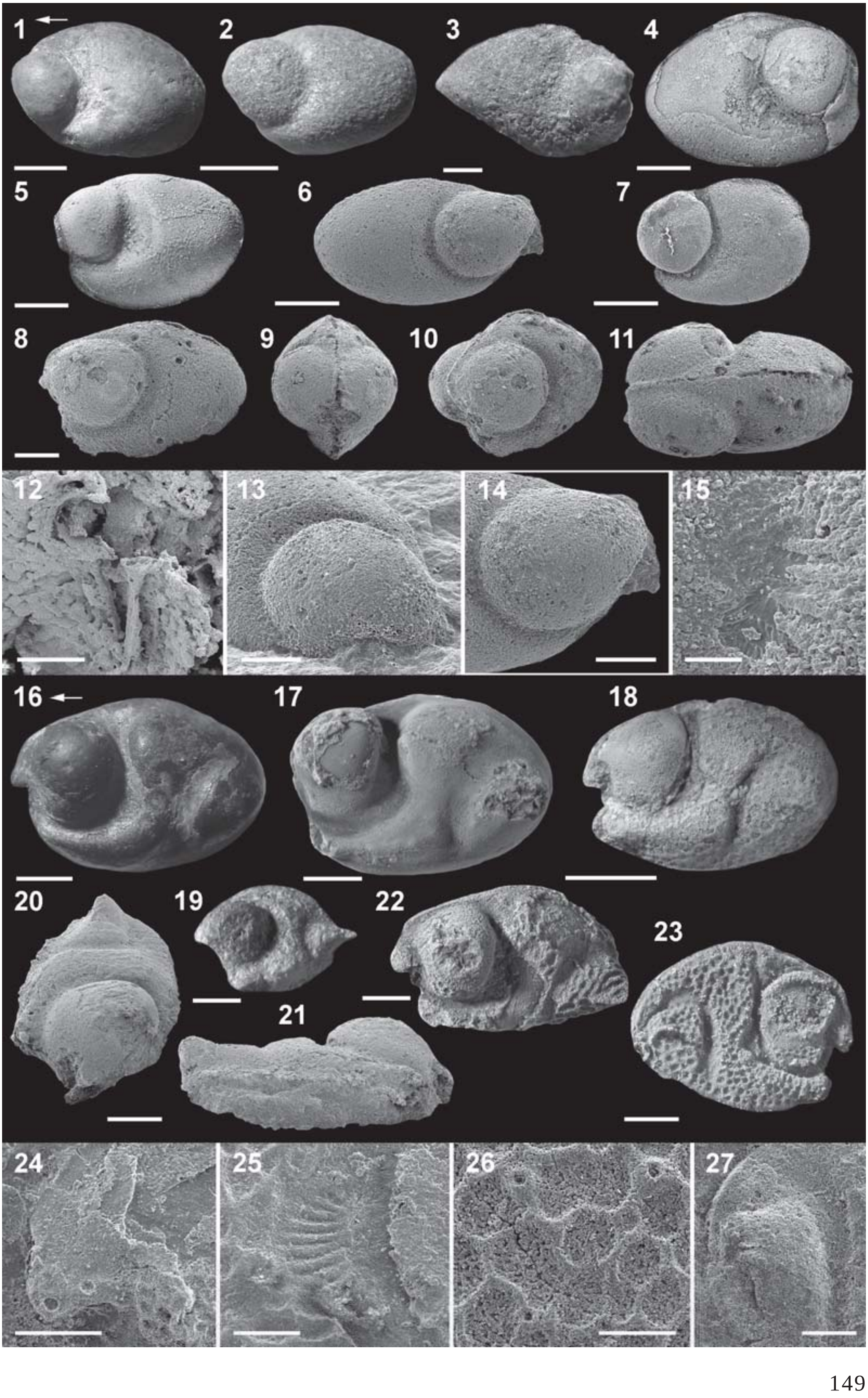
Figs 16-17, 19-21- *Parabolbozoe* sp. indet.

16. left valve, lateral view (I 96), previously described as *B. bohemica* by Canavari (1900, pl. 26, figs 15); Xea San Antonio, Sardinia; Scale bar = 2 mm.
17. left valve, lateral view (UMC-IP-VP 1), previously described as *B. bohemica* by Chaubet (1937, pl. 7, fig.18); La Combe d’Yzarne, Montagne Noire; Scale bar = 2 mm.
19. left valve, lateral view (FSL 710709); Telgruc-sur-Mer, Armorican Massif; Scale bar = 500 µm.
20-21. right valve (FSL 710710), (20) frontal view, (21) ventral view; Telgruc-sur-Mer, Armorican Massif; Scale bar = 500 µm.

Figs 18, 22-27 - *Parabolbozoe bohemica*.

18. Lectotype, left valve (NM-L 23658); Vyskocilka, Bohemia; Scale bar = 1 mm.
22. left valve, lateral view (UMC-IP-VP 6); La Combe d’Yzarne, Montagne Noire; Scale bar = 2 mm.
23. right valve, lateral view (FSL 710401); La Cultais, Armorican Massif; Scale bar = 2 mm.
24. detail of the rostrum (FSL 710759); Lounin, Bohemia; Scale bar = 500 µm
25. detail of the muscle scar (FSL 710428); La Cultais, Armorican Massif; Scale bar = 500 µm.
26. detail of the ornament and pores (FSL 710760); Lounin, Bohemia; Scale bar = 500 µm.
27. detail of the caudal process (FSL 710758); Lounin, Bohemia; Scale bar = 500 µm

Arrow points to anterior in each case. Collection numbers: FSL (collections of the Université Claude Bernard Lyon 1, France); I (Museo di Storia Naturale e del Territorio, Calci, Italy); LPB (University of Brest, France); MNHN (Museum d’Histoire Naturelle de Nantes, France); NM-L (Národní Museum, Prague, Czech Republic); UMC-IP-VP (University of Montpellier, France).


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
20
19
22
23
21
24
25
26
27

Canavari, 1899 (Pl. 16, fig. 20; herein Pl. 2, Figs 3) from the Ludlow of Sardinia may be synonyms of the unisulcate *B. anomala* (Perrier 2007; Perrier et al. in prep.; compare Pl. 2, Figs 1-8). Pribyl (1988) erected the subgenus *Bolbozoe* (*Parabolbozoe*) to embrace bisulcate *Bolbozoe* such as *B. bohemica* Barrande. The completely smooth *B. bohemica* specimen (Pl. 2, Fig. 16) of Canavari (1899) should perhaps be termed *Parabolbozoe* sp. indet. as *P. bohemica* is reticulated (Pl. 2, Figs 18 (Lectotype); Perrier et al., in prep.). Canavari's (1899) opinion that *Bolbozoe polonica* (Gürich, 1896) is a junior synonym of *B. bohemica* is probably correct.

P. bohemica gives its name to a Silurian fossil community from Sardinia (*Bolbozoe bohemica* of Ferretti et al., 1999, p. 272). *R. migrans* and another myodocope species referred to as "*E.*" *meneghinii* (of Canavari, 1899) were included in the community. It occurs in the Ludlow Series and corresponds to a deeper environment (distribution: BA 4 to 5) than the closely related *R. migrans* Community. Another *P. bohemica* pelagic community was described in the middle Ludlow of the Czech Republic (*B. bohemica* of Kriz 1999, p. 250).

DISCUSSION

FUNCTIONAL MORPHOLOGY

Locomotion - The rostral incisure in Recent myodocopes is an important functional feature, allowing protrusion of the frontal (especially the second) pairs of appendages for swimming. A comparable rostral complex occurs in Silurian myodocopes (Pl. 1, Figs 14-21; Pl. 2, Figs 12-14, 20-21, 24), suggesting that if similarly powerful anterior appendages were present, then the bolbozoids and most likely the cypridinids were probably able to swim actively in the water column (Siveter et al., 1991; Vannier & Abe, 1992; Perrier, 2007).

Vision - All Silurian myodocopes have either a prominent mostly unornamented bulb (bolbozoids; Pl. 2) or an unornamented area in the anterodorsal part of their valves (cypridinids and entomozoids; Pl. 2). These features seem to have been directly or indirectly related to vision (Vannier & Abe, 1992; Perrier et al., in prep). This hypothesis is strengthened by the presence and position of a lateral eye in two Silurian fossil myodocope species (Siveter et al., 2003; 2007), where it lies in the same anterodorsal position as the bulb and the unornamented area of other Silurian myodocopes. Recent myodocope species also have their visual apparatus sited anterodorsally (see Land & Nilsson, 1990). It is likely that Silurian myodocopes had lateral compound eyes, comparable to those of Recent and Mesozoic (e.g., *Triadocypris* Weitschat, 1983) myodocopids.

ASSOCIATED FAUNAS

Associates of the myodocopes of the Silurian of Sardinia (Ferretti, 1990) and other coeval outcrops comprise what is essentially a relatively low diversity invertebrate fauna (Siveter et al., 1989; 1991; Vannier & Abe, 1992; Perrier, 2007). Most of the associated groups are pelagic (e.g., cephalopods, graptolites); benthic or nektobenthic forms (e.g., phyllocarids, bivalves) are few. Combined with sedimentary evidence, the faunal association seems to indicate that the bottom water was in general inimical for benthic life.

DEPOSITIONAL ENVIRONMENT

The Silurian myodocopes of Sardinia occur in a complex sedimentary and tectonic setting, within displaced blocks of different ages, and especially in an '*Orthoceras*' limestone (*siluricus* conodont Biozone; Ludlow Series) and a micrite (Pridoli Series) microfacies (Siveter et al., 1991, p. 164-165). Myodocopes were originally obtained from near Flumminimaggiore (Canavari, 1899), by calcining *ex situ* '*Orthoceras*' limestone blocks found in dry-stone walls. Ferretti (1990, Fig. 4) reported that ostracodes can form up to 60 % of the skeletal clasts in some of the limestone blocks. Sardinian myodocopes are generally associated with a recurring orthoconic nautiloid-graptolite-dominated pelagic fauna, with bivalves typically the only sign of a benthic epifauna. The implication - the occurrence of anoxic bottom conditions - is, clearly, important with respect to notions of the habitat of Silurian myodocopes. The facies of the orthoceratid-dominated assemblage in Sardinia has been considered to represent shallow shelf conditions, albeit with anoxic bottom waters (Gnoli et al., 1979), or a deep-water environment (Jaeger, 1976).

PALAEOGEOGRAPHICAL DISTRIBUTION

Some Silurian myodocope species had a wide, possibly cosmopolitan distribution, whereas others seem to have been restricted to particular regions (Siveter et al. 1991; Vannier & Abe 1992; Perrier et al., 2007). Each group of myodocopes (bolbozoids, cypridinids and entomozoids) has at least some species with a relatively widespread palaeogeographic distribution (Fig. 1b). For example *B. anomala*, *P. bohemica* and *R. migrans* have transoceanic distribution, being present on both sides of the large scale Rheic Ocean which was present between the palaeocontinents of Gondwana and Laurussia (Cocks & Torsvik, 2002; see Fig. 1b). This mode of distribution resembles that of Recent pelagic species and endorses the notion that such Silurian forms had a pelagic lifestyle. Species with a more limited geographical distribution perhaps occupied other ecological niches within the water column, or had a different mode of dispersal, or were controlled by different environmental factors.

LIFESTYLE

Several lines of evidence indicate that perhaps the majority of Silurian myodocopes had a pelagic lifestyle (Siveter, 1984; Siveter et al., 1987; 1991; Vannier & Abe 1992; Perrier et al., 2007). Fossil evidence comes from the functional morphology of the carapace, the faunal associates and the depositional environment. Morphological evidence indicates active swimming (rostral complex) and probably well developed visual organs (visual window) in most groups. Some species seem to have had a wide geographical distribution comparable with that of Recent pelagic species. Sedimentological and fossil data (e.g., the nature of faunal associates) indicate that in the case of many Silurian myodocopes bearing localities there was an ocean bottom impoverished in oxygen and unsuitable for benthic life (e.g., black muds). Uncertainties remain concerning their precise habitat and migration pattern within the water column (Perrier, 2007).

PHYLLOCARID MALACOSTRACA

Phyllocarid remains from Sardinia consist of a few three-dimensionally preserved specimens, partly incomplete, from the Fluminimaggiore and Mason Porcus formations of southwestern Sardinia and several phosphatized gnathal lobes that commonly occur in the acid-resistent residues of conodont samples from several localities of southern Sardinia.

The first mention of phyllocarids from Sardinia is due to Taricco (1922, p. 4), who referred on the occurrence of a "phyllocarid bed" within the Ordovician Puddinga sequence at "Roia Srappas" locality, near Fluminimaggiore. However, that fauna was later described as *Tariccoia arrusensis* Hammann, Pillola & Laske, an unusual trilobite-like arthropod (Hammann et al., 1990).

For long time nobody refer on the occurrence of these fossils, until Helmcke (1973) and Jaeger (1976), who reported on their occurrence in the uppermost Silurian-Lower Devonian from southeastern Sardinia. Gnoli & Serpagli (1984) illustrated for the first time phyllocarids from southwestern Sardinia, describing both macro- and microremains. Finally, Gnoli & Serventi (2005) revised that collection and described new material from the same area.

Six taxa have been recognized from the Silurian of Sardinia (Gnoli & Serventi, 2005):
Ceratiocaris (*Bohemicaris*) *bohemica* (Barrande, 1872);
Ceratiocaris? (*Bohemicaris*) sp. ind. cf. *bohemica* (Barrande, 1872);
Ceratiocaris (*Ceriatiocaris*) cf. *cornwallisensis damesi* Chlupac, 1963;
Dithyrocaris cf. *neptuni* Hall, 1863;
Warneticaris cenomanensis (Tromelin, 1874);
Warneticaris sp. ind. cf. *cenomanensis* (Tromelin, 1874).

Ceratiocaris (*Bohemicaris*) *bohemica* is largely the most documented species from the Silurian of Sardinia. Some abdominal somite, caudal parts and telson fragments are

---

Plate 3

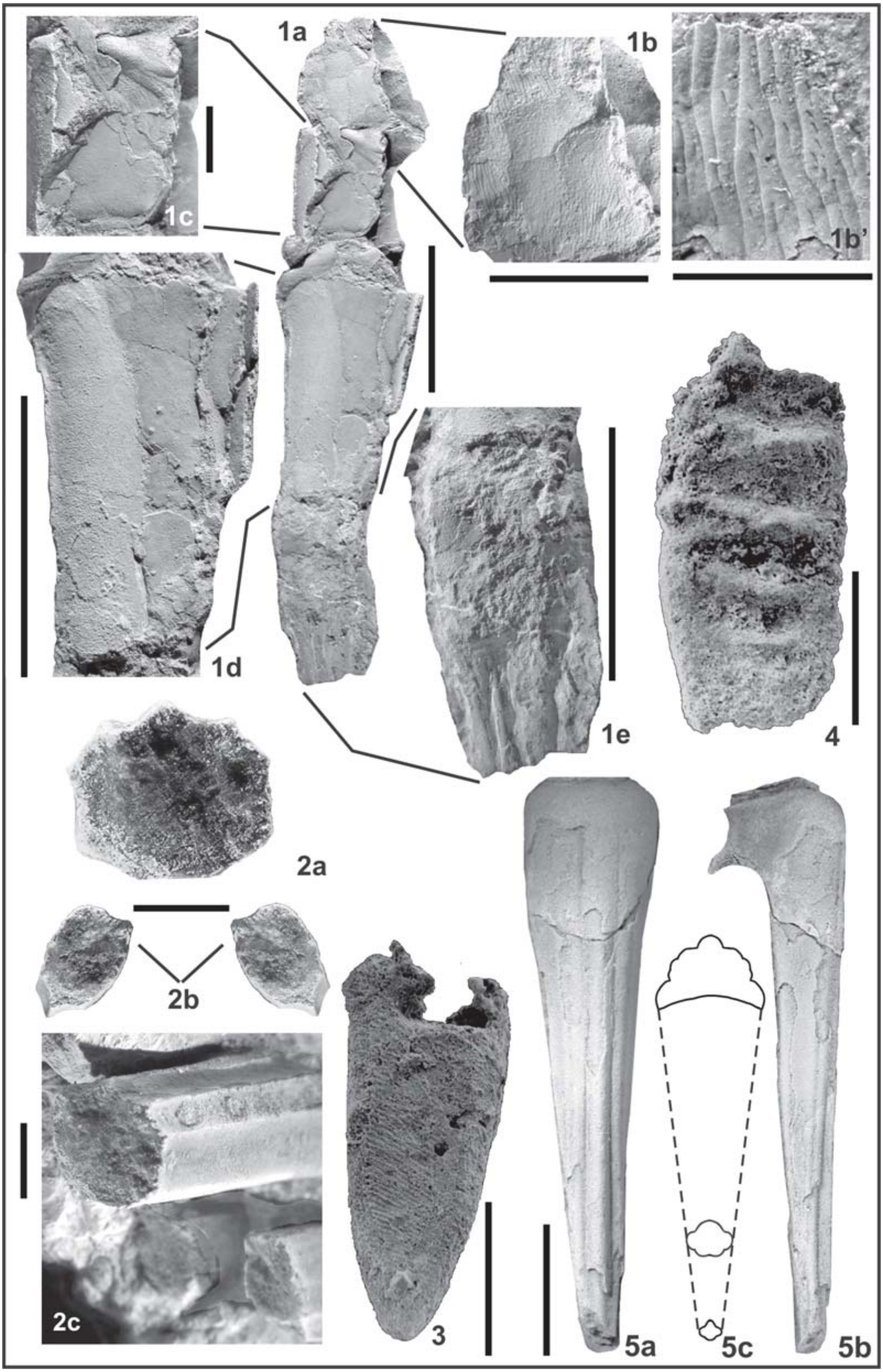
Figs 1-2 - *Ceratiocaris* (*Bohemicaris*) *bohemica* (Barrande, 1872).

1. specimen IPUM 24236; Fluminimaggiore area, Pridoli. a) upper view of the whole specimen, scale bar = 20 mm; b) 5th segment showing sub-parallel wrinkled pattern of ornamentation of the same specimen scale bar = 10 mm; b') particular enlarged to show the very small slit-like structures between the ribs forming ornamentation of the same specimen, scale bar = 5 mm; c) upper view of the 6th abdominal somite of the same specimen, scale bar = 5 mm; d) upper view of the 7th abdominal somite of the same specimen, scale bar = 20 mm; e) poorly preserved caudal part of the same specimen, scale bar = 20 mm..
2. specimen IPUM 24243; scattered block ARG-BK 15, Pridoli. a, b) telson and furcal rami of another specimen (IPUM 24243) showing their polygonal cross-sections (pentagonal the telson, more complex and rounded the furcal rami), scale bar = 15 mm; c) the same specimen in perspective view with the alveoli for bristle insertion, scale bar = 5 mm; note: the left furcal ramus cross-section of fig. 2b is figured reflecting the right one horizontally because this specimen is poorly preserved.

Figs. 3-4 - *Ceratiocaris* gr. *bohemica* (Barrande, 1872).

3. molar part of gnathal lobe of the left mandible (IPUM 19803) occlusal view; sample MP 3, Pridoli, x 50.
4. middle part of gnathal lobe of the right mandible (IPUM 19804) occlusal view; sample MP 4, Pridoli, x 50.

Fig. 5 - *Ceratiocaris* (*Ceratiocaris*?) cf. *cornwallisensis damesi* (IPUM 24237), a) dorsal view of the telson; b) lateral view of the telson showing the ventral recumbent protection to the articulation for the furcal rami movement; c) schematic proximal, distal, and terminal telson cross-sections; level MP 5 Pridoli.


1a
1b
1b'
1c
1d
1e
2a
2b
2c
3
4
5a
5b
5c

documented from Ludlow and Pridoli of southwestern Sardinia, whereas gnathal lobes occur from Wenlock to Pridoli from several localities of the southern part of the island. The other taxa are definitely rarer, since their documentation is limited to a few fragments from the Pridoli of Fluminimaggiore area (Gnoli & Serventi, 2005).

References

Barrande, J. (1872). Système Silurien du centre de la Bohème. 1, 647 pp. Prague-Paris.

Canavari M. (1899). Fauna dei calcari nerastri con Cardiola ed *Orthoceras* di Xea San Antonio in Sardegna. *Palaeontographica Italica*, 5: 187-210.

Chaubet M.C. (1937). Contribution à l'étude du Gothlandien du versant méridional de la Montagne Noire. 223 pp. Faculté des sciences de Montpellier, Montpellier.

Cocks L.R.M. & Torsvik T.H. (2002). Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. *Journal of the Geological Society, London*, 159: 631-644.

Ferretti A. (1990). Microbiofacies and constituent analysis of Upper Silurian-Lowermost Devonian limestones from south western Sardinia. *Bollettino della Società Paleontologica Italiana*, 28: 87-100.

Ferretti A., Gnoli M. & Vai G.B. (1999). Silurian to Lower Devonian communities of Sardinia. *In* Boucot A.J. & Lawson J.D. (Eds), Paleocommunities a case study from the Silurian and Lower Devonian. Cambridge University Press, Cambridge: 271-281.

Gnoli M., Parea G.C., Russo F., & Serpagli E. (1979). Palaeoecological remarks on the '*Orthoceras* limestones' of south-western Sardinia (middle-upper Silurian). *Memorie della Società Geologica Italiana,* 20: 405-423.

Gnoli M. & Serpagli E. (1984). Evidence of phyllocarid remains from Silurian-Devonian boundary beds in southwestern Sardinia. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 5: 257-268.

Gnoli M. & Serventi P. (2005). New Evidence of Silurian Phyllocarid remains from SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 44 (3): 255-262.

Gooday A.J. (1983). Entomozoacean Ostracods from the Lower Carboniferous of south western England. *Palaeontology*, 26: 755-788.

Gründel J. (1969). Neue taxonomische Einheiten der Unterklasse Ostracoda (Crustacea). *Neues Jahrbuch für Geologie und Paläontologie*, 6: 353-361.

Hammann W., Laske R. & Pillola G.L. (1990). *Tariccoia arrusensis* n.g. n.s., an unusual trilobite-like arthropod. Rediscovery of the "phyllocarid" beds of Taricco (1922) in the Ordovician "Puddinga" sequence of Sardinia. *Bollettino della Società Paleontologica Italiana*, 29 (2): 153-178.

Jaeger H. (1976). Silur und Unterdevon vom Thüringischen Typ in Sardinien und seine regional geologische Bedeutung. *Nova Acta Leopoldina*, 224: 263-399.

Kornicker L.S. (1975). Antarctic Ostracoda (Myodocopina). *Smithsonian Contributions to Zoology*, 163: 1-720.

Kornicker L.S. (1981). Revision, Distribution, Ecology, and Ontogeny of the Ostracode Subfamily Cyclasteropinae (Myodocopina: Cylindroleberididae). *Smithsonian Contributions to Zoology*, 319: 1-548.

Kornicker L.S. & Sohn I.G. (2000). Myodocopid Ostracoda from the Late Permian of Greece and a basic classification for Paleozoic and Mesozoic Myodocopida. *Smithsonian Contribution to Paleobiology*, 91: 1-33.

Kriz, J. (1999). Bivalvia dominated communities of Bohemian type from the Silurian and Lower Devonian carbonate facies. *In* Boucot A.J. & Lawson J.D. (eds), Paleocommunities a case study from the Silurian and Lower Devonian. Cambridge University Press, Cambridge: 229-252

Land M.F. & Nilsson D.E. (1990). Observations on the compound eyes of the deep-sea ostracod *Macrocypridina castanea*. *Journal of Experimental Biology*, 148: 221-233.

Milne–Edward H. (1840). Ordre des Cyproides ou des Ostracodes. *Histoire Naturelle des Crustacés*, 3: 393–410.

Moberg J.C. (1895). Silurisk posidonomyaskiffer, enegendomlig utbildning af skanes oefversilur. *Sveriges geologiska undersoekning, serie C*, 156: 1–23.

Olempska E. (1992). Shell Structure of the entomozoaceans: allegedly planktonic ostracodes of the Palaeozoic. *Acta Palaeontologica Polonica*, 36: 373-398.

Perrier V. (2007). Biodiversité et écologie des ostracodes myodocopes (Crustacea) du Silurien supérieur d'Europe. 2 Volumes, 534 pp. Unpublished PhD thesis, Faculty of Science Lyon 1, UMR 5125 PEPS.

Perrier V., Vannier J. & Siveter D.J. (2007). The Silurian pelagic myodocope ostracod *Richteria migrans*. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, 98: 1–13.

Pribyl A. (1951). On the Bohemian Ostracoda of the families Entomozoidae and Entomoconchiadae. *Bulletin International, Academie Tchèque des Sciences*, 9: 1-28.

Pribyl A. (1988). Ostracodes from the Silurian of central Bohemia. *Sbornik geologickych Ved Paleontologie*, 29: 49-143.

Siveter D.J. (1984). Habitats and modes of life of Silurian ostracods. *In* Bassett M.G. & Lawson J.D. (eds), The Autecology of Silurian Organisms, Special Papers in Palaeontology, London: 71-85.

Siveter, D.J. 2008. Ostracods in the Palaeozoic? *Senckenbergiana lethaea*, 88: 1-9.

Siveter D.J., Vannier J. & Palmer D. (1987). Silurian Myodocopid Ostracodes: Their depositional Environment and the Origin of their Shell Microstructures. *Palaeontology*, 30: 783-813.

Siveter D.J., Vannier J. & Palmer D. (1991). Silurian Myodocopes: Pioneer pelagic ostracods and the chronology of an ecological shift. *Journal of Micropalaeontology*, 10:157-173.

Siveter D.J., Sutton M.D., Briggs D.E.G. & Siveter D.J. (2003). An Ostracode Crustacean with Soft Parts from the Lower Silurian. *Science*, 302: 1749-1751.

Siveter D.J., Siveter D.J., Sutton M.D. & Briggs D.E.G. (2007). Brood care in a Silurian ostracode. *Proceedings of the Royal Society of London. Series B*, 274: 465-469.

Taricco M. (1922). Sul Paleozoico del Fluminese. *Bollettino del Regio Comitato Geologico d'Italia*, 48 (1920-21): 1-22.

Vannier J. & Abe K. (1992). Recent and early Paleozoic Myodocope Ostracodes: Functional Morphology, Phylogeny, Distribution and Lifestyles. *Palaeontology*, 35: 485-517.

Weitschat W. (1983). On *Triadocypris spitzbergensis*. *In* Stereo-Atlas of Ostracod Shells, Bate R.H., Neale J.W., Sheppard L.M. & Siveter D.J. (eds), The Broadwater Press, Hertfordshire: 127-138.

Wilkinson I.P., Williams M., Siveter D.J., & Wilby P.R. (2004). A Carboniferous necrophagous Myodocopid ostracod from Derbyshire, England. *Revista Espanola de Micropaleontologia*, 36 (1): 187-198.

Rendiconti della Società Paleontologica Italiana, 3 (1), 2009: 157-167

Minor fossil groups in the Silurian of Sardinia

CARLO CORRADINI, MYRIAM DEL RIO, MAURIZIO GNOLI, PAOLA PITTAU

C. Corradini - Dipartimento Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127, Cagliari (Italy); corradin@unica.it
M. Del Rio - Dipartimento Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127, Cagliari (Italy); delriom@unica.it
M. Gnoli - Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia, largo S. Eufemia 19, I-41100 Modena (Italy); maurizio.gnoli@unimore.it
P. Pittau - Dipartimento Scienze della Terra, Università di Cagliari, via Trentino 51, I-09127, Cagliari (Italy); pittaup@unica.it

ABSTRACT - Fossil groups rarely documented from the Silurian of Sardinia as well as Problematica are here briefly described and illustrated. Occurrences of eurypterid remains, silicispongia spiculae and *Scyphocrinites* loboliths are presented. Systematic affinity of *Kolihaia sardiniensis* is discussed, as well as that of peculiar problematic micro-sphaerules.

KEY WORDS - Silurian, Sardinia, Eurypterids, *Kolihaia*, Loboliths, Silicispongia, Problematica.

INTRODUCTION

Fossil remains are abundant and well known from the Silurian of Sardinia since mid-nineteen century. Starting from Meneghini (1857), several authors investigated this variegated fauna, producing a large number of papers. Most of these contributions were focused on the more abundant or spectacular fossil groups, or on those useful for biostratigraphical or palaeoenvironmental purposes. It results that cephalopods, graptolites, conodonts, bivalves and chitinozoans are described and illustrated in numerous papers, whereas reports on other fossil groups are quite rare.

This paper deals with these minor groups, which are rarely found during palaeontological investigations on the Silurian of Sardinia: eurypterids, crinoid loboliths, sponge and other fossils with uncertain affinities. Beside these forms, it is important to note that some taxa, quite common in the Silurian rocks around the world, are almost absent in Sardinia: gastropods are seldom found as internal moulds in the cephalopod limestones, and trilobites are rarely observed, mainly in thin section.

EURYPTERID REMAINS

[*Maurizio Gnoli*]

Eurypterids are aquatic Palaeozoic chelicerates that have been found mostly in Silurian and Lower Devonian deposits of North America and Europe. Outside Avalonia, Armorica, Baltica, Iberia and Laurentia, occurrences of these organisms are very scarce (Tetlie et al., 2007). In North Gondwana, remnants of eurypterids have been reported only from Bohemia (Barrande, 1872), Morocco (Depitout, 1962) and Sardinia (Gnoli, 1992a).

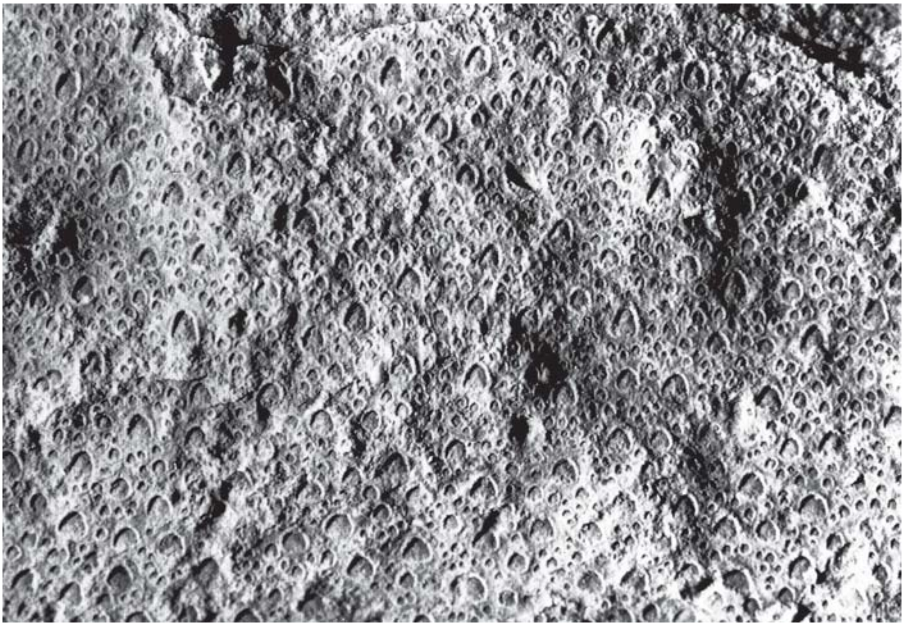


Fig. 1 - Close up of the external side of the eurypterid fragment (IPUM 21731) from Sardinia to show the ornamentation in form of distinct sub-triangular and/or smaller crescent-like scales as well as their arrangement, x6 (refigured after Gnoli, 1992a).

The only evidence of eurypterids in Sardinia is represented by a small fragment from the base of the Homerian (*lundgreni* Zone) in the Fluminimaggiore area (Fig. 1). It consists of a piece of carapace, 3x4 cm wide, having a peculiar outer ornamentation in form of two orders of narrow lunules (0.5 mm long and 0.125-0.625 mm wide), closely spaced on the surface (Gnoli, 1992a). Any generic and specific assignment is impossible for such a small fragment, however the ornamentation is very similar to that described and illustrated by Barrande (1872) in two species from Bohemia (*Pterygotus divers* and *Eurypterus pugio*) and by Depitout (1962) in one specimen, left in open nomenclature, found in Morocco.

LOBOLITHS (CRINOIDEA)

[*Carlo Corradini*]

Loboliths are the result of a peculiar evolution of crinoids belonging to the family Scyphocrinitidae which developed balloon-like holdfasts. This structure, as a gas filled buoy, allowed the crinoid a pelagic mode of life. After the death of the animal, the lobolith got detached, due to biostratinomical physical parameters, and fossilized separately from crowns.

Two different morphologies have been discriminated on the basis of the balloon architecture: the cirrus-loboliths and the plate-loboliths (Haude, 1972). Cirrus-loboliths have walls built of a dense network of rootlets, named “cirri”, and a cavity partitioned into several chambers of various size. Plate-loboliths have the wall pavemented by a double-layer of polygonal ossicles, and the cavity may be subdivided in a few large chambers, each one with a small opening near the distal end of the stem. Constructionalmorphological considerations allow to explain that the plate-loboliths derived from the cirrus-loboliths (Haude, 1972, 1992).

Loboliths are widely distributed in the North Gondwana area (Morocco, Spain, Montagne Noire, Sardinia, Carnic Alps, Bohemia), and are reported also from North America, Baltica, Siberia, China and Kazakhstania. Their stratigraphical range is restricted to a very short interval across the Silurian-Devonian boundary. Therefore Scyphocrinoidea is one of the few crinoid groups with an important biostratigraphical meaning.

In Sardinia, Silurian loboliths (Fig. 2) are documented from some sections in the Ockerkalk limestone of the southeastern part of the island (Helmcke, 1973; Barca & Jaeger, 1990; Barca et al., 1995; Corradini et al., 1998, 2001, 2002; unpubl. data). Several cirrus-loboliths occur in a well defined horizon dated by conodonts to the base of the *detortus* Zone; isolated crinoidal stems are present since the uppermost Ludlow.

Loboliths occur also at the very base of the Devonian both in southeastern and southwestern Sardinia. In the Southeast, poorly preserved specimens have been reported by Barca & Jaeger (1990) and Piras & Paschina (2009) from the Upper Graptolitic Shales of the Villaputzu area, where also isolated calyces are present; in the Southwest, well preserved plate-loboliths occur in a few localities and have been illustrated from the Mason Porcus Section by Gnoli et al. (1988).

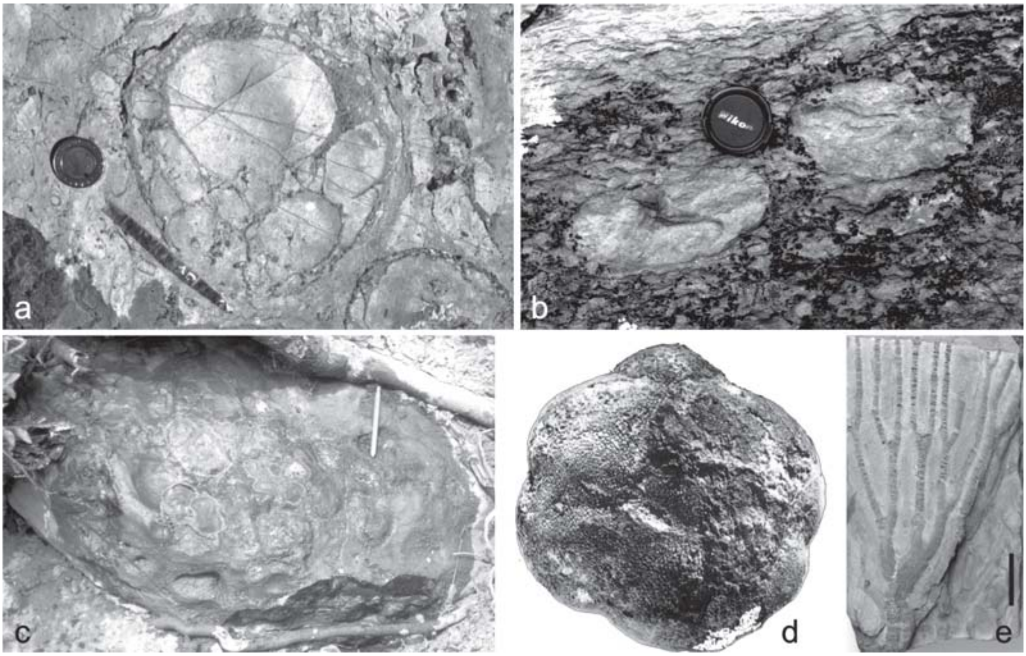


Fig. 2 - a) Slab exposing nicely preserved cirrus loboliths, San Basilio Fenugu section, southeastern Sardinia; *detortus* Zone, latest Pridoli; coin for scale=25 mm. b) Bed with two loboliths, Baccu Scottis section, southeastern Sardinia; *detortus* Zone, latest Pridoli; lens cap for scale=55 mm. c) Block with several plate loboliths, Fluminimaggiore, southwestern Sardinia; *woschmidti* Zone, base of Lochkovian; pencil for scale=17 cm. d) Upper view of an isolated plate-lobolith (after Gnoli et al., 1988, pl. 1, fig. 1b), Mason Porcus section, southwestern Sardinia; *woschmidti* Zone, base of Lochkovian; diameter of the specimen=12 cm. e) Crinoidal calyx, Baccu Scottis, southeastern Sardinia; Lochkovian; scale bar: 20 mm.

KOLIHAIA PRANTL, 1946

[*Maurizio Gnoli*]

Kolihaia eremita was originally described by Prantl (1946) from the Silurian of the Barrandian as a new form of the phylum Annelida (Fam. Serpulidae Burmeister, 1837). Fisher (1962) included the genus *Kolihaia* Prantl, but with uncertain phylum, class and order relationship, in the new family Cornulitidae. In the same family, also the genera *Cornulites* Schlotheim, 1820, *Conchicolites* Nicholson, 1872 and *Cornulitella* Howell, 1952 were included.

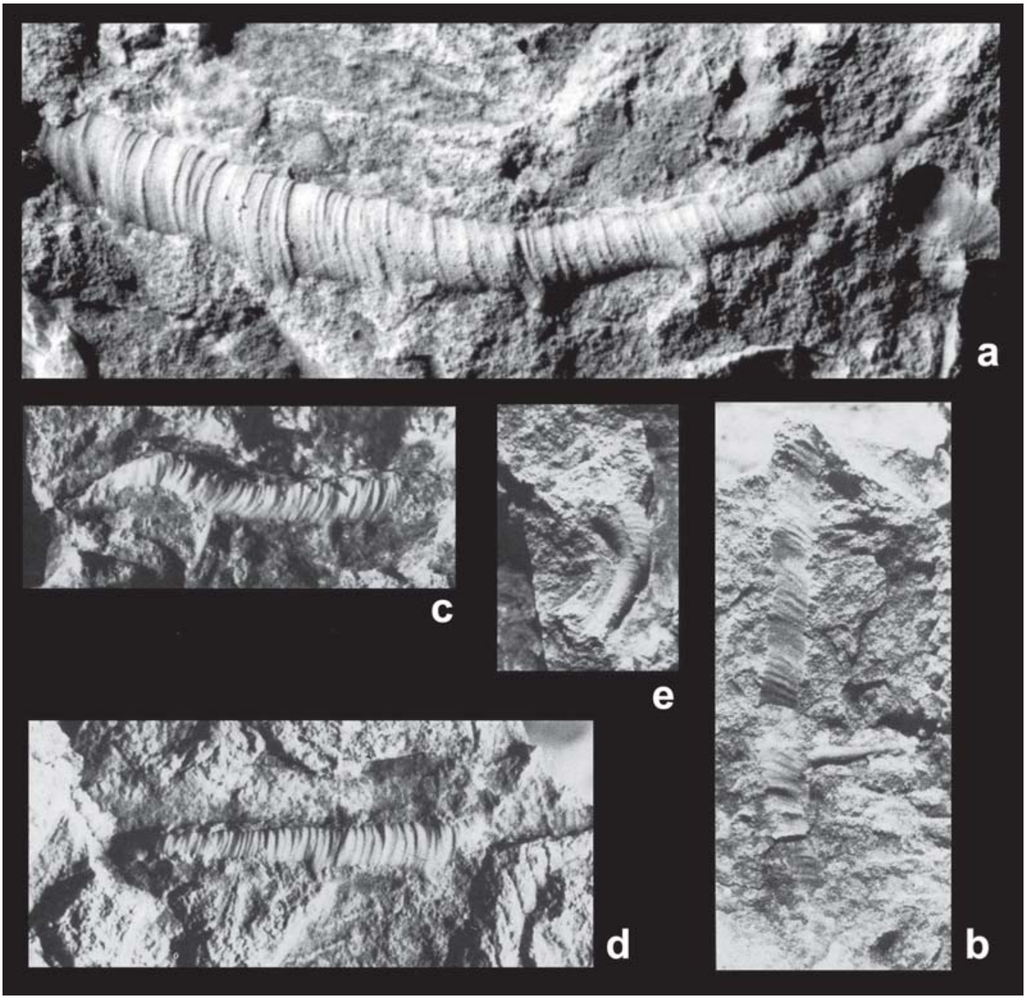


Fig. 3 - *Kolihaia sardiniensis* Gnoli, 1992. Lateral views of different specimens at various magnification: a) holotype IPUM 23551 (x18); b) IPUM 23552 (x12): c) IPUM 23553 (x16); d) IPUM 23554 (x12). e) Enlargement of a single spine: the smooth surface is probably the portion buried in the sediment, whereas the proximal ornamented part shows the same type of the ribbed ornamentation of the main body external wall. IPUM 23555 (x24). All refigured after Gnoli (1992b).

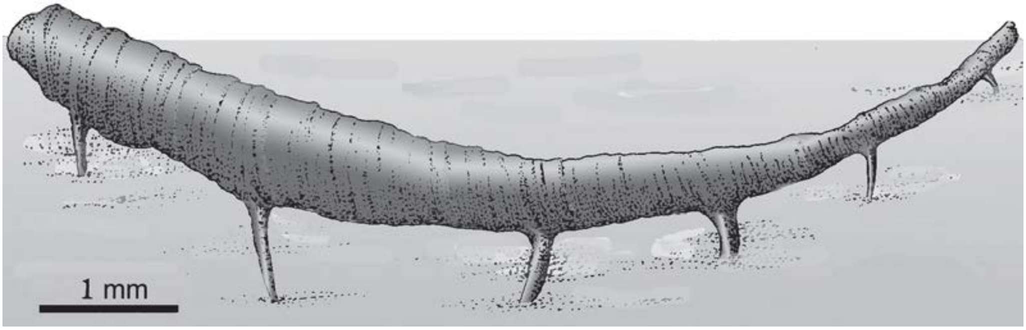


Fig. 4 - Hypothetical reconstruction of the mode of life of *Kolihaia sardiniensis* with its spines partially inserted in the sediment.

Gnoli (1992b) described and figured the new species *Kolihaia sardiniensis* (Fig. 3) from the uppermost Wenlock and lowermost Ludlow respectively of Argiola and Fluminimaggiore (southwestern Sardinia). He interpreted *K. sardiniensis* as a problematic organism belonging to the family Cornulitidae Fisher, 1962 but with uncertain higher taxonomic definition. A possible mode of life was suggested for the organism. The general features and the location of the spines only on one side of the tube, with the exception of the bifurcate last one closest to the distal opening, would indicate a certain bilateral symmetry (Gnoli, 1992b). A benthic, probably epibenthic, way of life was proposed (Fig. 4), with the organism laying on the sea floor with the smooth, distal portions of the spines buried into the soft sediment in contrast with the proximal, ornamented portions of the spines that bear the same type of ornamentation as that occurring on the main tube (Gnoli, 1992b). The presence of a smaller posterior sub-circular and a larger anterior sub-circular aperture is consistent with the animal having been a filter feeder using nutrient particles provided by near bottom currents. Affinities and differences of *K. sardiniensis* with *K. eremita* are remarkable. The former has in fact the spines on almost its body-length and not only closest to distal opening, smaller dimensions and a distal part only gently bent (and not «abruptly» as in the Bohemian species).

The analysis of a rich fauna of more than 1000 well-preserved specimens of *Kolihaia eremita* Prantl from the upper Wenlock of Bohemia, led Kriz et al. (2001) to interpret this organism as an epiplanktic anthozoan, having radiciform processes for attaching to floating or buoyant object, probably algae. The authors left open the possibility to assign this small fossil animal dubitatively to either Rugosa or Tabulata. The presence in *K. sardininesis* of processes regularly distributed along the corallite would indicate, on the contrary, an adaptation to a benthic mode of life (Kriz et al., 2001).

By a micro and ultra structure shell analysis approach, Vinn & Mutvei (2004, 2005) present cornulitids as a possible polyphyletic taxon, with *Cornulites* having strong affinities with lophophorates and tentaculitids. A further recent contribution on Palaeozoic (mainly Wenlock) cornulitids is that of Herringshaw et al. (2007) where an up to date unambiguous terminology of the shell structure, systematics and affinities are reported.

Following Vinn's suggestion (pers. comm., September 2007) to investigate on the shell's micro and ultrastructure of *K. sardiniensi*s, several thin-sections have been carried out at this purpose to check possible vesicles, apical septa and so on, for a better understanding of the taxonomic position of this fossil organism. Unfortunately, the bad preservation of the material has prevented so far to reach any sure answer.

SILICISPONGIA

[*Paola Pittau, Myriam Del Rio*]

The only finding of siliceous sponges from the Silurian of Sardinia is represented by some spiculae collected from the Lower Graptolitic Shales in the Rio Ollastu area (southeastern Sardinia). They belong to several sponge taxa referable to two poriferan classes: Demospongiae and Hexactinellida.

Demospongiae is characterized by siliceous spicules, on monoaxons and tetraxons in which the rays do not meet at right angles, whereas the Hexactinellida group is represented by siliceous spicules, basically hexactines, hexactine-derived spicules, or stauractines, with rays at right angles. Significant is the record of monaxon clavulate and anchorate "root tuft" spicules (*Nabaviella* spp.) (Fig. 5a). These kinds of spicules are generally located in the dermal layer, protruding outwards in the basal part, allowing the sponge to stabilize in a soft substrate. Remarkable are also the specialized follipinule (Fig. 5b-d) and pulvinusactine spicules of *Thoracospongia ichnussiella* Pittau et al., 2003 **(**Fig. 6**)**, which probably formed a part of an armoured dermal layer like that reconstructed by Mehl (1998). This finding indicates that the group of hexactinellid sponges having these peculiar spicules existed at least up to the early Silurian and ranged geographically from Australia to the northern peri-Gondwana.

Inasmuch as these discrete elements are conservative in their skeletal morphology, sponge spicules rarely provide decisive biostratigraphical information. Sometimes, however, sponge spicules may be biostratigraphically useful (Mehl & Mostler, 1993). The sponge spicule assemblages were recovered from the Lower Graptolitic Shales of southeastern Sardinia, in the *L. convolutus, S. turriculatus* and *Str. crispus* zones in black graptolitic silty shales intercalated with massive lydite beds. Centimeter-thick quartz lenses (radiolarites) are commonly embedded in the lydite layers and they contain large numbers of capsular tests of Spumellaria.

The Llandovery strata are believed to have been deposited in a distal platform environment, characterized by limited water circulation and anoxic – dysoxic bottom conditions, as indicated by the sediment type and fossil content (Schneider, 1972; Helmcke, 1973; Jaeger, 1976, 1991; Barca & Jaeger, 1990) which is characterized by epipelagic

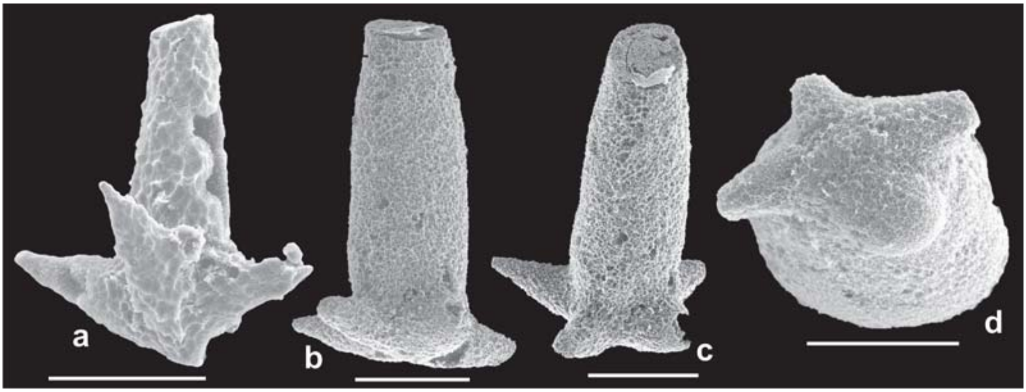


Fig. 5 - Silicispongia spiculae from the Rio Ollastu area. a) Class Hexactinellida: *Nabaviella*? sp. A; sample CP 2769, *Streptograptus crispus* Zone. b-d) Class Hexactinellida: *Thoracospongia ichnussiella* Pittau et al., 2003, follipinules; sample CP 2769, *Streptograptus crispus* Zone. Scale bar=200µm.

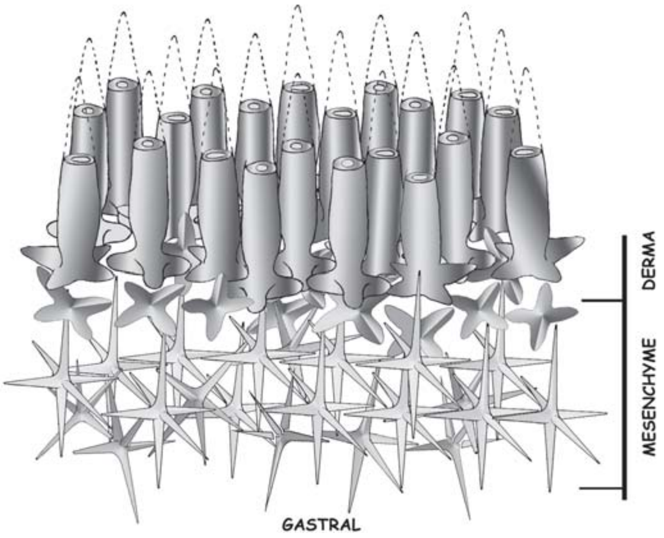


Fig. 6 - Hypothetical reconstruction of *Thoracospongia ichnussiella* Pittau et al., 2003 (after Pittau et al., 2003).

communities: graptolites, chitinozoans, radiolarians. Palaeoecological interpretation rules out that the spicules were deposited at the site they inhabited. An allochthonous or para-authochthonous origin seems more likely, the spicules originating in a high energy and well-oxygenated shelf not far from the black shale depositional basin.

GONI'S SPHERULES: ORGANIC WALLED *PROBLEMATICA* MICROFOSSILS

[*Paola Pittau, Myriam Del Rio*]

Organic walled hemi-spheres and spherules (60 to 180 µm of diameter) are present in some horizons of the Goni section. They are in full relief and show traces of pyritization. Stratigraphically, they are distributed from the *Cyrtograptus rigidus* to the *Cy. lundgreni* zones (middle Wenlock) and, after a disappearence ("eclipse") encompassing several biozones (*P. parvus, P. dubius-G. nassa, C. praedeubeli* and *C. deubeli* zones), they reappear in the *C. vulgaris-C. gerhardi* Zone (Pittau et al., 2006).

MORPHOLOGY

The test wall consists of amorphous organic material; the surface may be smooth or of diverse texture: wrinkled, reticulated, dome-shaped protuberances, spirally rolled raised ridges, undulating basal membranes, may have pores, around 1-1.5 µm in diameter (Pl. 1, Fig. 3), that are frequently rimmed, on the surface; or main(?) apertures, of the order of 10 µm, always flushing with the test surface (Pl. 1, Fig. 1). Surface reticulation may be related to the outlines of the agglutinated mineral used in an outer wall by organisms such as arenaceous foraminifera (Pl. 1, Fig. 1), whilst a "blocky" reticulation (Pl. 1, Figs. 1, 2) is likely effect of a (post?) diagenetic mineralization (pyritization). Dome-shaped protuberances are very frequent in these microfossils, particularly in the spherical ones and in those with a small invaginated region in the test (Pl. 1, Figs. 1, 3, 10).

The assemblages comprise an assortment of morphologies ranging from hemispherical, to spherical ovate and subspherical with invaginated area. Four different morphological types have been discriminated (Pittau et al., 2002): spheres with circular opening and 'reticulate' surface (morphotype A; Pl. 1, fig. 1); hemispheres with basal flange and dome-shaped protuberances (morphotype B; Pl. 1, figs. 2-3); globular test with dome-shaped protuberances and depression areas (morphotype C; Pl. 1, fig. 10) and with globular test, spirally arranged raised ridges and other features (morphotype D; Pl. 1, fig. 6).

Micropalaeontological affinity

The size indicates they were unicellular, but their biological affinity and palaeoecological role is unknown; presumably they are of polyphyletic origin, perhaps related to classes such as Sarcodina and Radiolaria (Pittau et al., 2002).

Globular "reticulate" form (morphotype A) is comparable with organic linings of the agglutinated foraminifer *Saccamina*, in particular with species recorded in the Devonian limestones of Australia (Bell & Winchester-Seeto, 1999).

Specimens similar to morphotypes B, C and D, have been recorded in the Llandovery deep sediments of Wales (Lloydell *et al.*, 1988) and they were tentatively referred to internal moulds of radiolaria. The living radiolarian *Rizoplegma radicatum* (Pl. 1, fig. 8) and some other Spumellaria possess a capsular membrane that during ontogenesis increases in volume forcing club-shaped protuberances through the pores of the shell, which is extracapsular, of similar shape to Goni's spherules. Radiolarian soft bodies, in fact, can be fossilized and this may happen irrespective of the siliceous skeletons (Dumitrica, 1999). In *Cenosphaerocapsula gibbulosa* the presence of «small inflations» or «tubercles» in the spherical shell is a diagnostic feature (Dumitrica, 1999).

The hemispherical forms are comparable with two different fossil types: firstly, test linings of agglutinated foraminifera like *Hemisphaerammina*; secondly, central capsules of radiolaria lying eccentrically with respect to the cortical shell (Dumitrica, 1999). The presence in most of the specimens of a basal flange supports the first hypothesis.

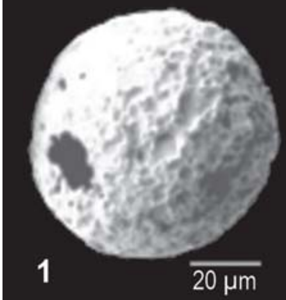
The life style of the main group with spherical test similar to the agglutinated foraminifer *Saccamina* and to the radiolarian *Coenosphaerocapsula* probably was planktonic. A minor

---

Plate 1

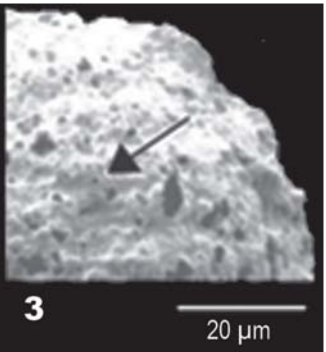
Organic-walled Problematica from Goni.

Fig. 1	- Morphotype A. The specimens are similar to *Saccamina mea* Bell & Winchester-Seeto, 1999.
Figs. 2-3	- Morphotype B. All the illustrated specimens display the basal flange and numerous holes in the surface. 3: detail of fig. 2 showing the equatorial rim and holes in the surface.
Figs. 4-5	- Morphotype C. SEM magnification of the moulds left after dissolving minerals grown during diagenetic or postdiagenetic processes in the dome-shaped protuberances. Minerals smaller than 1 μm.
Fig. 6	- Morphotype D.
Figs. 7, 10	- Morphotype C. Microfossils showing a depression area and the pattern surface broken by dome-shaped protuberances.
Fig. 8	- Capsule of *Rizoplegma radicatum*, living radiolarian with numerous club-shaped protrusion showing a dome shaped outer morphology (after Dumitrica, 1999, fig. 2).
Fig. 9	- Morphotype C.

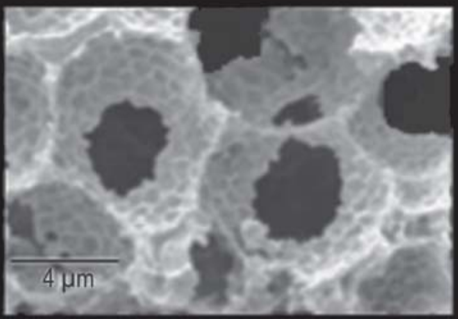


1

2



3

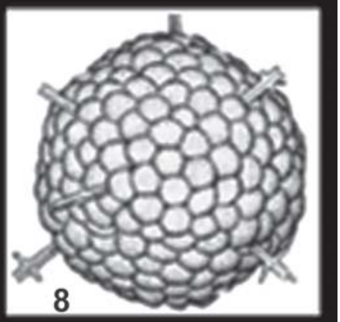


4

5

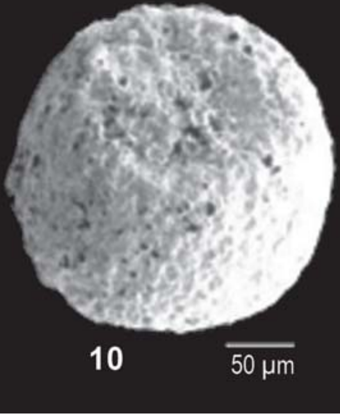
6

7



8

9



10

group composed of flattened, hemispherical forms, resembling the agglutinated foraminifer *Hemisphaerammina* was most likely benthonic. The assessment of their palaeoecological preferences will be helpful for a better understanding of the biotic signal and the interpretation of the palaeoceanographic conditions during the Silurian black-shale deposition.

Acknowledgements

Thanks are due to Dr. Olev Vinn (Tartu University, Estonia) and Dr. Jiri Kriz (Czech Geological Survey in Prague, Czech Republic) for useful suggestions and advises on *Kolihaia*.

Funding for this work was provided by MIUR-PRIN 2007 (*Analysis of stratigraphic, palaeontological and structural features of the Hercynian basement and the Tertiary cover in Sardinia and Calabria, as a contribution to the geodynamic reconstruction of the central-western Mediterranean basin*).

References

Barca S., Corradini C., Ferretti A., Olivieri R. & Serpagli E. (1995). Conodont biostratigraphy of the “Ockerkalk” (Silurian) from southeastern Sardinia. *Rivista Italiana di Paleontologia e Stratigrafia*, 100 (4) (1994): 459-476.

Barca S. & Jaeger H. (1990). New geological and biostratigraphical data on the Silurian in SE Sardinia. Close affinity with Thuringia. *Bollettino della Società Geologica Italiana*, 108 (1989): 565-580.

Barrande J. (1872). Système Silurien du centre de la Bohéme. Première Partie: Recherches Paléontologiques - Supplément au Vol. 1. Trilobites, Crustacés divers et Poissons. Texte Troisième partie. Crustacés divers, non trilobitiques: 434-619. Prague.

Bell K.N. & Winchester-Seeto T.M. (1999). Linings of agglutinated Foraminifera from the Devonian: taxonomic and biostratigraphic implication. *Journal of Micropaleontology*, 18: 27-43.

Corradini C., Ferretti A., Serpagli E. & Barca S. (1998). The Ludlow-Pridoli Section “Genna Ciuerciu” west of Silius. *In* Serpagli E. (Ed.), Sardinia Field-trip Guide-book, ECOS VII. *Giornale di Geologia*, 60, Spec. Issue: 112-118.

Corradini C., Leone F., Loi A. & Serpagli E. (2001). Conodont Stratigraphy of a highly tectonised Siluro-Devonian Section in the San Basilio area (SE Sardinia). *Bollettino della Società Paleontologica Italiana*, 40 (3): 315-323.

Corradini C., Ferretti A. & Serpagli E. (2002). The “Ockerkalk” limestone in the Genna Ciuerciu Section (SE Sardinia, Italy). *Rendiconti della Società Paleontologica Italiana*, 1: 255-260.

Depitout A. (1962). Etude de Gigantostracés siluriennes du Sahara Central. *Publications du Centre de Recherche Saharien, Paris*, Ser. Geol., 2: 1-141.

Dumitrica P. (1999). On the presence of central capsular membranes of Radiolaria in fossil state. *Revista Española de Micropaleontologia*, 31 (2): 155-183.

Fisher D.W. (1962). Small conoidal shells of uncertain affinities. *In* Moore R.C. (Ed.), Treatise on Invertebrate Paleontology, Part W, Miscellanea. 130-143. The University of Kansas and The Geological Society of America, Inc., New York and Lawrence, Kansas.

Gnoli M. (1992a). Occurrence of Eurypterids (Arthropoda) in the Silurian of Southwestern Sardinia. *Bollettino della Società Paleontologica Italiana*, 31(1): 147-149.

Gnoli M. (1992b). The problematic organism *Kolihaia sardiniensis* n. sp. of the latest Wenlock-earliest Ludlow of SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 31(3): 383-385.

Gnoli M., Leone F., Olivieri R. & Serpagli E. (1988). The Mason Porcus Section as reference section for Uppermost Silurian-Lowermost Devonian in SW Sardinia. *Bollettino della Società Paleontologica Italiana*, 27 (3): 323-334.

Haude R. (1972). Bau und Funktion der Scyphocrinites-Lobolithen. *Lethaia*, 5: 95-125.

Haude R. (1992). Scyphocrinoiden, die Bojen-seelilien in hohem Silur-tiefen Devon: *Palaeontographica A*, 222: 141-187.

Helmcke D. (1973). Schichtengebundene NE-metall- und F-Ba-Lagerstätten im Sarrabus-Gerrei-Gebiet, SE Sardinien. II Bericht: zur Stratigraphie des Silur und Unterdevon der Lagerstättenprovinz Sarrabus-Gerrei. Ne*ues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1973-H9: 529-544.

Herrinshaw L.G., Thomas A.T. & Smith M.P. (2007). Systematics, shell structure and affinities of the Problematicum Cornulites. *Zoological Journal of the Linnean Society*, 150: 981-699.

Jaeger H. (1976). Das Silur und Unterdevon vom Thüringischen Typ in Sardinien und seine regionalgeologische Bedeutung. *Nova Acta Leopoldina*, 224, 45 (Franz-Kossmat-Symposium): 263-299.

Jaeger H. (1991). Neue Standard-Graptolithenzonenfolge nach der «Großen Krise» an der Wenlock/Ludlow-Grenze (Silur). *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen*, 182: 303-354.

Kriz J., Fryda J. & Galle A. (2001). The epiplanktic anthozoan, *Kolihaia eremita* Prantl, 1946 (Cnidaria), from the Silurian of the Prague Basin (Bohemia). *Journal of the Czech Geological Society*, 46(3-4): 239-245.

Loydell D.K., McMillan I. & Barron H.F. (1988). Muellerisphaerids from the Llandovery of Western mid-Walles. *Journal of Micropaleontology*, 7 (2): 243-246.

Mehl D. (1998). Porifera and Chancelloriidae from the Middle Cambrian of the Georgina Basin, Australia. *Palaeontology*, 41: 1153-1182.

Mehl D. & Mostler V.H. (1993). Neue Spicula aus dem Karbon und Perm: Konsequenzen für im Spät-Paläozoikum und frühen Mesozoicum. *Geologish-Paläontologishe Mitteilung Innsbruck*, 19: 1-28

Meneghini G. (1857). Paléontologie de l'Ile de Sardaigne. *In* La Marmora A., Voyage en Sardaigne. 584pp. Imprimaire Royal, Turin-Paris.

Piras S. & Paschina F. (2009). The Lower Devonian Upper Graptolitic Shales in the Sa Ruinosa Section (SE Sardinia). *Rendiconti della Società Paleontologica Italiana*, 3 (2): 191-194.

Pittau P., Cotza F.& Del Rio M. (2002). Goni spheres: probable agglutinated Silurian foraminifera lining and radiolaria capsular membranes (South-eastern Sardinia, Italy). *In* Cherchi A., Corradini C. & Putzu M.T. (eds.), Sardinia Field Trip - Palaeontology & Stratigraphy. *Rendiconti della Società Paleontologica Italiana*, 1: 159-168.

Pittau P., Cotza F. & Del Rio M. (2003). Early Silurian siliceous sponge spicule assemblages from Sardinia Hercynian Chain (Italy). *Bollettino della Società Paleontologica Italiana* 42, 3: 225-240.

Pittau P., Cotza F., Cristini S., Del Rio M. & Loi M. (2006) Palaeontologic and biogeochemical characterization of the *C. lundgreni* Event in the black shales of eastern mid-Sardinia. *Lethaia*, 39: 11-127.

Prantl F. (1946). *Kolihaia eremita* n. gen. n. sp. (Annel. Tubicola) ze Stredoceskeho siluru (*Kolihaia eremita* new gen. new sp. a new Tubicolar Annelide from the Silurian of Bohemia). *Vestnik Kralovske Ceske Spolecnosti Nauk, Trida Matemat.- Prirodoved.*, 24: 1-12.

Schneider H.J. (1972). Schichtgebundene NE-Metal- und F-Ba-Lagerstätten im Sarrabus-Gerrei-Gebiet, SE-Sardinien. I. Bericht zur Lagerstättenkunde und Geologie. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte*, 1972: 529-541.

Tetlie O.E., Selden P.A. & Ren D. (2007). A new Silurian Eurypterid (Arthropoda: Chelicerata) from China. *Palaeontology*, 50: 619-625.

Vinn O. & Mutvei H. (2004). Cornulitids, problematic Ordovician calcitic tubicolous fossils. *In* Hints O. & Ainsaar L. (Eds.), WOGOGOB-2004, Conference Materials, p. 102. Tartu University Press, Tartu.

Vinn O. & Mutvei H. (2005). Observations on the morphology, and affinities of cornulitids from the Ordovician of Anticosti Iisland and the Silurian of Gotland. *Journal of Paleontology*, 79(4): 725-736.

Table of Contents