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Neotectonic research in applied geomorphological studies

by

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with 28 figures

Summary. The authors illustrate several methods of geomorphological and morpho-neotectonic analysis focused on different practical applications. The first case concerns the research that should be carried out immediately following a destructive seismic event (*geomorphological studies in the event of earthquakes*). A second case is related to the planning of major civil engineering works such as power plants and dams, or to geothermal research (*morpho-neotectonic studies for major projects*).

Geomorphological studies in the event of earthquakes must essentially have two principal objectives, which may be pursued concurrently: one that is strictly scientific and the other concerned with the solution of practical problems. The first is aimed at the identification and location of morphological manifestations caused by earthquakes and of hydrogeological modifications. The second, however, must be orientated towards the immediate resolution of practical problems for the population affected by the earthquake (for example, selection of suitable areas for tent and camper cities, and identification of impending hazards).

Regarding morpho-neotectonic investigations for major projects, the authors propose that studies be carried out according to whether one is working in mountainous areas or in alluvial plains. In both situations, studies are to be developed through four phases of research with differing degrees of interpretative detail:

Phase A: Bibliographical research and regional remote sensing;
Phase B: Detailed aerial photograph interpretation;
Phase C: Field surveys;
Phase D: Final synthesis.

The final product of this research is a document derived from a comparison of the data obtained in Phases A, B, and C, in which active tectonic elements and those held to be active in the time interval under consideration are represented, as well as areas undergoing uplift, subsidence or tilting, and lineaments that may be linked in some way to active tectonic elements. Each phase of the investigation is illustrated with examples of data sheets and maps.

Résumé. Les auteurs illustrent quelques méthodes d'analyses géomorphologiques et morphonéotectoniques ayant pour but différentes situations d'applications pratiques. Un premier cas concerne des recherches à effectuer dans les jours immédiatement successifs à un évènement sismique destructif (*études géomorphologiques à l'occasion de tremblements de terre*); un deuxième cas est lié au projet d'importants travaux civils d'ingénieurs (pour exemple, centrales électriques et digues) ou aux recherches de géothermie (*études morpho-néotectoniques pour d'importants projets*).

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En particulier les études géomorphologiques à l'occasion de tremblements de terre doivent avoir essentiellement deux objectifs principaux contemporainement réalisables: l'un typiquement scientifique et l'autre de consultation technique. Le premier consiste en localisation et rassemblement de manifestations morphologiques dûes aux tremblements de terre et en nouvelles de modifications hydrogéologiques; la consultation technique doit par contre s'occuper de résoudre les problèmes d'utilité immédiate pour les populations touchées par le tremblement de terre (pour exemple, choix de zones adaptées à l'installation de tentes et de roulottes, et individualisation d'éboulements menaçants des villages).

Pour les études morpho-néotectoniques au sujet des projets importants les auteurs proposent les recherches à effectuer selon que l'on se trouve dans des secteurs montagneux ou bien sur des plaines alluviales. Dans les deux cas les études devront être développées à travers quatre phases de recherches de différent degré de détail interprétatif:

Phase A: recherche bibliographique et télédétection régionale;
Phase B: photointerprétation détaillée;
Phase C: levés sur le terrain;
Phase D: synthèse finale.

Le produit final de ces recherches est un document, qui dérive d'un comparaison de données prises de la phase A, B, et C où figurent des éléments tectoniques «actifs» et «considérés actifs» dans l'intervalle de temps considéré, des aires en soulèvement et/ou en affaissement, basculements, les éléments qui peuvent en quelque sorte être liés à des éléments tectoniques actifs, etc. Chaque phase de la recherche est illustrée par des dossiers et des documents cartographiques.

Introduction

Geomorphology is gradually becoming more important in neotectonic studies. Such studies include both the consequences of destructive movements, mostly in connection with seismic events, and the locating of past tectonic movements on the basis of particular geomorphological evidence. Studies of this type are part of that branch of earth science known as "morpho-neotectonics". This is included in the more general field of morphotectonics, which in turn, is a part of structural geomorphology (fig. 1). Morpho-neotectonics is concerned with the relations between landforms and neotectonics, that is, recent and current tectonic movements (PANIZZA & PIACENTE 1976; DEMEK & EMBLETON 1978) or Neogene tectonic movements (OLLIER 1985). Modifications of the Earth's surface brought about by neotectonics are either of the direct type, such as earthquake cracks and landslide phenomena, or of the indirect type, such as scarps, asymmetrical valleys and river bends (PANIZZA & PIACENTE 1978; PANIZZA 1983).

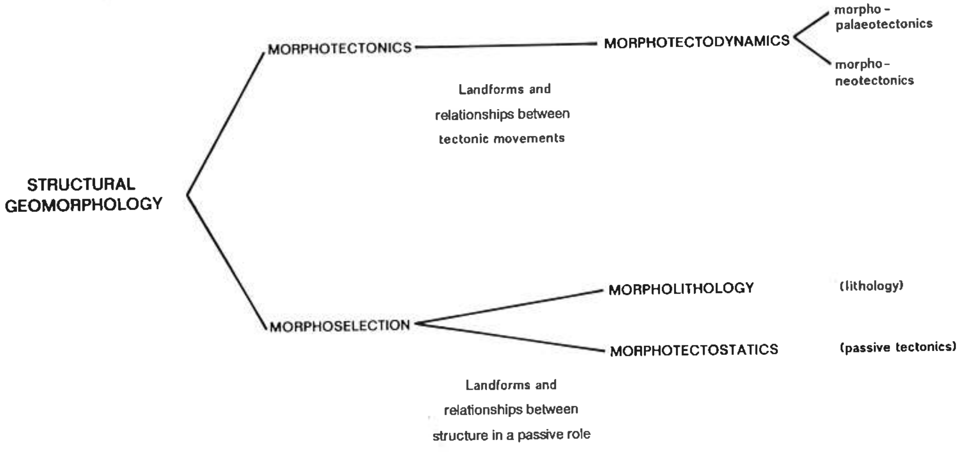


Fig. 1. Relationships in structural geomorphology.

In the case of earthquakes, which represent the most obvious manifestations of present-day tectonic movements, the direct geomorphological consequences, which often cause considerable damage to persons and objects, prove to be surprisingly great. Morphological investigations, whether scientific or applied (and which we shall term *Geomorphological studies in the event of earthquakes*), should be carried out immediately after a seismic event in order to limit the resulting damage.

It is also clear that the study of geomorphological effects, both direct and indirect, may lead us back to the neotectonic movements that produced them and enable us to estimate the chance of recurrence in the future (CARRARO 1976). Some examples of this have been illustrated by PANIZZA et al. (1978), PANIZZA (1983, 1984). Thorough studies of this type (which we shall term *Morpho-neotectonic studies for major projects*) are indispensable to the planning of major civil engineering works such as large building complexes, dams and power-plants, and to research of a geothermal nature.

In the following notes, study methodologies are described and examples provided for the two types of problem listed. This coincides with the objectives set out by the I.G.U. Morphotectonics Working Group (Chairman: M. PANIZZA). In addition, this paper is included in the studies being conducted as part of the *Progetto di Ricerca Morfoneotettonica* which is funded by the Italian Ministry of Education. Particular attention has been given to study methodologies for major projects. The studies considered here have been partially outlined by PANIZZA & CASTALDINI (1985).

Geomorphological studies in the event of earthquakes

Geomorphological and geological problems linked to destructive seismic events have been illustrated by GOVI & SORZANA (1977) and by CAVALLIN et al. (1977) for the earthquake in Friuli (northeast Italy) in May 1976. They have been summarized by COTECCHIA (1981) for the earthquake in Irpinia, Basilicata (southern Italy) in November 1980 (fig. 2). The geomorphological investigations to be carried out in the event of earthquakes with a high destructive potential have been outlined by PANIZZA et al. (1981). This outline will be amplified in the following. In essence, these geomorphological investigations have two principal objectives: one that is strictly scientific, the other concerning the solution of practical problems. Both objectives should be pursued after the seismic event, over the entire area involved in the earthquake.

The scientific study consists of the identification and collection of the largest possible number of morphological manifestations of the earthquake, such as fault scarps, fissures, landslides, ground subsidence, land swelling, mud volcanoes, etc. The scientific study may also include the collection of data on drainage system modifications, such as appearances or disappearances of springs, changes of a physical and/or chemical nature in the groundwater system and variations of water levels in wells. It is of fundamental importance that all such manifestations be located, identified and examined with urgency, before they can

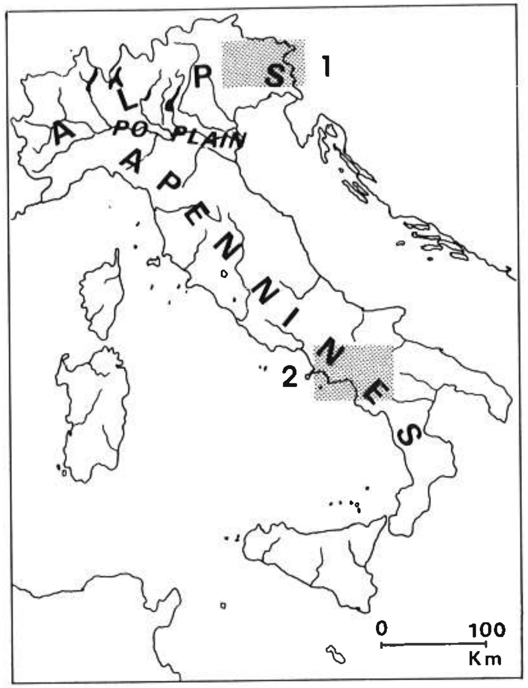


Fig. 2.
1: Area involved in the earthquake in May, 1976 – Friuli;
2: Area involved in the earthquake in November, 1980 – Irpinia-Basilicata.

be altered or even erased, especially if they are of small dimensions or produced in incoherent or loose terrain (for example, the surface fault described in BOLLETTINARI & PANIZZA 1981). Obliteration may take place through the intervention of man, atmospheric agents and subsequent seismic or gravitational movements.

The scientific part of the study should be synthesised in the form of a large-scale map, where all the data collected will be indicated, so as to offer a general picture of the earthquake's morphotectonic consequences. Examples of such maps are given by PANIZZA (1983). This document will constitute an indispensable foundation for the planning and subdivision of subsequent scientific operations in which other authorities will also be involved. These scientific operations will also be useful for the general seismotectonic study of the areas affected by the earthquake and for technical consultation.

The applied part of the study must focus on problems of immediate importance to the people affected and provide support for the public organizations in charge of coordination and assistance such as military services and fire departments. It should thus aid in the selection of suitable areas for the location of tent cities, barracks and areas for trailers. Such areas should not be steeply sloping or unstable, should not be situated at the foot of landslide slopes, and should not be subject to flooding. The sites must also be located at points where they will not hold up traffic for rescue operations and where adequate sanitary facilities may be easily set up. Other areas must be designated for specific back-up facilities, such as food and clothing storehouses, and field hospitals. Still others must be designated for the dumping of debris from destroyed buildings and waste materials.

Another task is that of identifying areas with landslides and debris-threatened dwellings or other potential obstructions to roads.

In the cases of the earthquakes in Friuli (1976) and in Irpinia, Basilicata (1980), study and comparison of aerial photographs taken prior to and after the earthquake proved to be particularly important in determining the effects produced by seismic tremors on slopes. In both cases, the areas were characterised by persistent seismic activity with repeated and relatively strong shocks even a few days later, which were capable of modifying the previous situation and creating an intermixture of cause and effect. In fact, it was clear that the earthquake shocks had set earlier, unstabilised landslides into motion, caused collapse on slopes that had already been subject to mass movement in the past, and mobilised talus slopes in conditions of unstable equilibrium. Reference will also be made to studies of a technical nature for the initial repair and regulating work to be done on the water system and any other ground-level or underground mains.

This phase of intervention will also culminate in the production of a map which should be compiled alongside the one described previously. This map will offer a picture of the disturbed places that have been examined. In this way, it will serve as a basis for the technicians who will be working in the subsequent zoning and reconstruction stage in the disturbed area (see, for example, C.N.R., 1983).

An example of a map of disturbances prior to and related to an earthquake is shown in fig. 3. The typology and aims, both immediate and long-term, of the study proposed thus far, are summarised briefly in the outline shown in fig. 4.

Morpho-neotectonic studies for major projects

As has been mentioned, the phrase "Morpho-neotectonic studies for major projects" refers to those investigations to be carried out prior to the planning of major civil engineering works. The term also encompasses studies that are conducted to evaluate an area's geothermal potential in cases where the area is tectonically active. In this latter case, tectonic elements such as faults and fractures may be connected with recent intrusive plutonic rocks.

The methods described below have been developed on the basis of research conducted in Italy as part of the project entitled *Progetto Finalizzato Geodinamica – Sottoprogetto Neotettonica*. The project is funded by the Consiglio Nazionale delle Ricerche (see, for example, C.N.R. 1978, 1979, 1980, 1982). The methods have also been derived from applied studies carried out by the authors in Italy, Indonesia and South America.

First, investigative criteria should be differentiated according to whether the area in question corresponds to a mountainous or plain sector (Ist. Geol. Univ. Modena, 1978; CASTALDINI 1984). In mountainous sectors undergoing active erosion, it is generally possible to identify outcrops of disjunct and folded structures. On the other hand, in alluvial plains undergoing active sedimentation, loose deposits may cover the tectonic structures. These different geological situations require different methods of study. They are discussed separately here, but it might be necessary to apply both methods in the case where one site presents both situations or when one is investigating an extensive area.

The neotectonic period to be considered will vary according to the aims of the study. In this contribution, the Quaternary has been adopted.

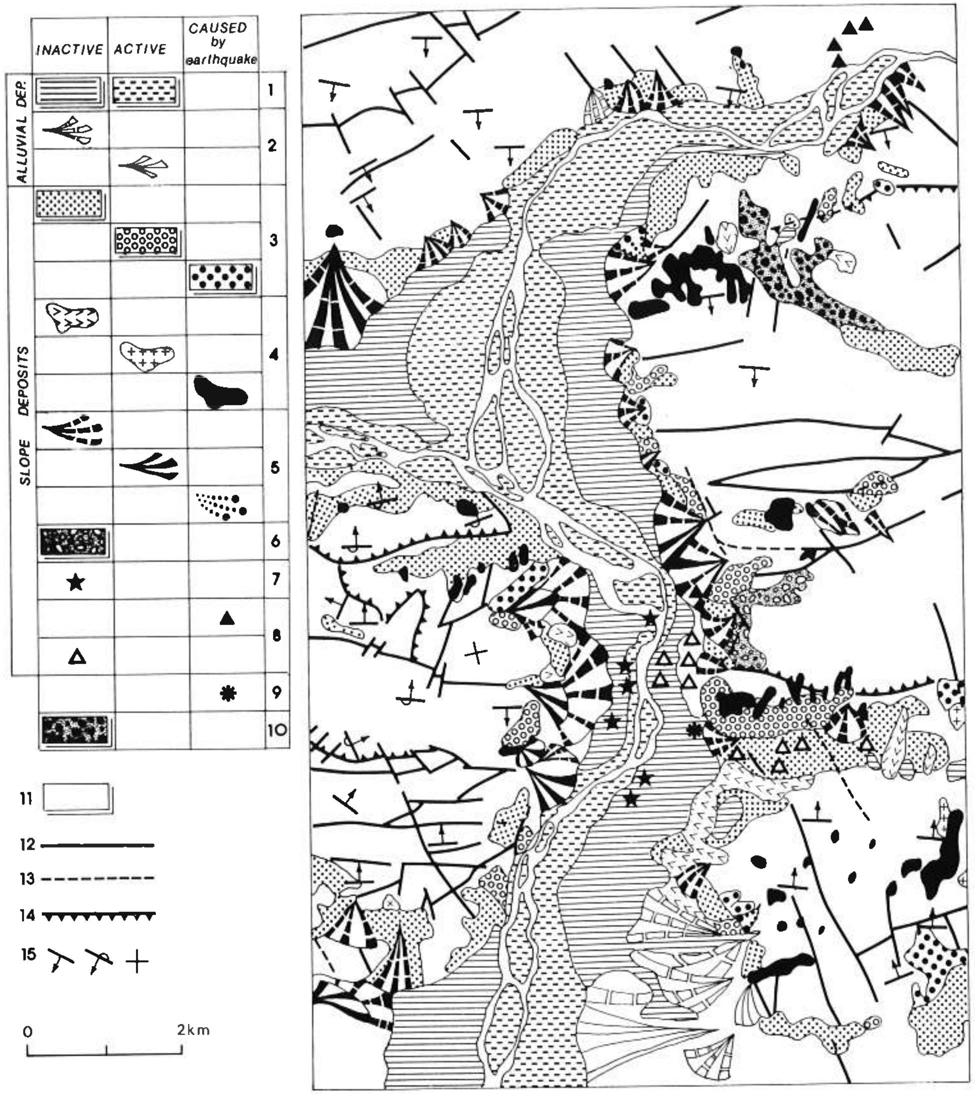


Fig. 3. Simplified detail from the geological map of the Friuli area primarily involved in the 1976 earthquake (from MARTINIS (1977) with modifications). 1) gravel; 2) fan; 3) talus; 4) landslide debris; 5) talus cone; 6) strongly-cemented breccia; 7) landslide blocks; 8) boulders due to rockfall; 9) earthquake-induced ground crack; 10) till; 11) bedrock; 12) fault; 13) supposed fault; 14) overthrust; 15) strike and dip of beds.

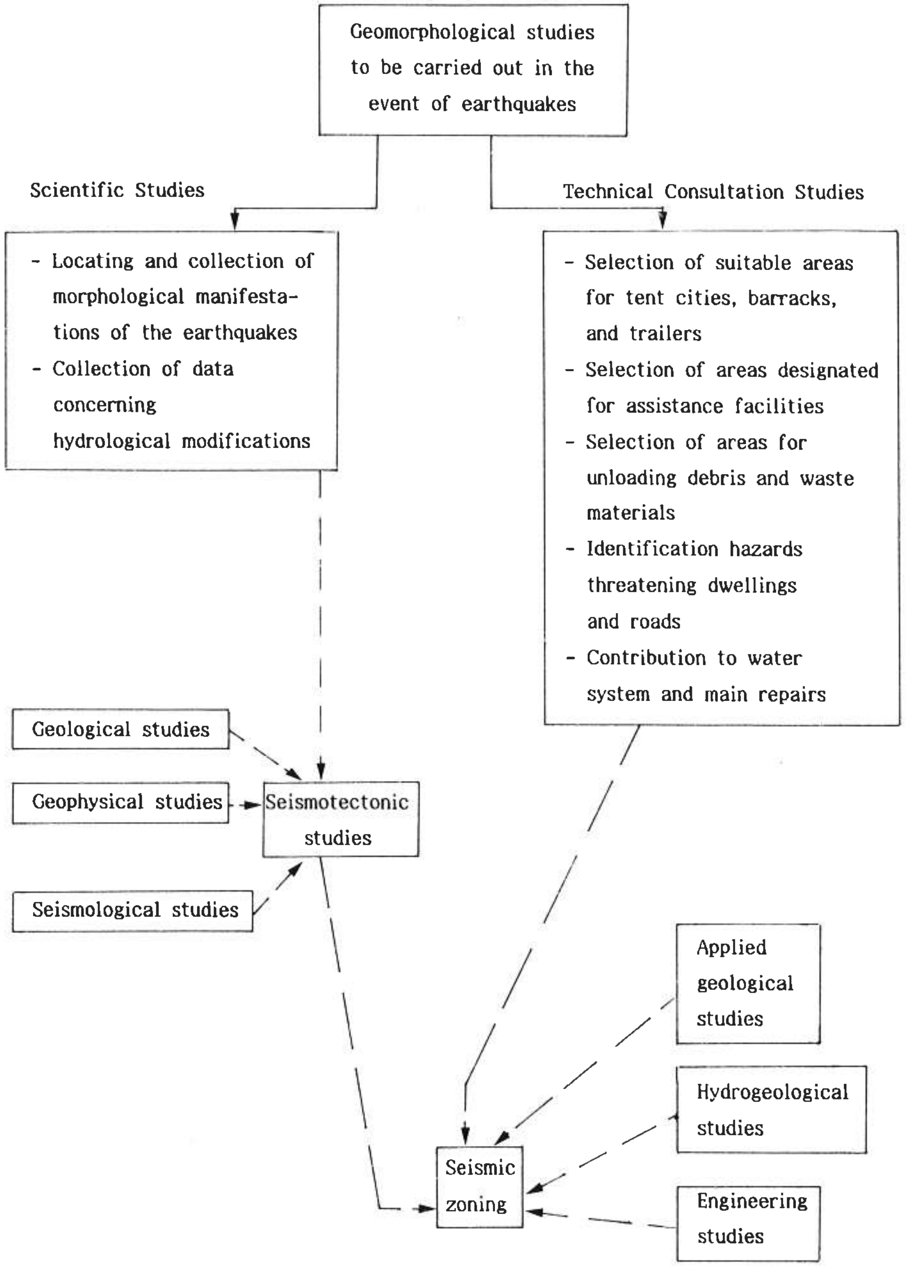


Fig. 4. Outline summary of the geomorphological studies to be carried out in the event of earthquakes.

Studies in mountainous areas

These studies have been divided into four phases of research with differing degrees of interpretative detail:

Phase A: Bibliographical research and regional remote sensing;
Phase B: Detailed aerial photograph interpretation;
Phase C: Field surveys;
Phase D: Final synthesis.

It should be noted that, because of their confidential nature, figs. 6, 8, 10, 13, 15 and 16 are shown without topographical references.

Phase A: Bibliographical research and regional remote sensing

a) *Bibliographical research.* – Bibliographical research is undertaken primarily in order to track down information on the distribution of Plio-Quaternary deposits as well as information on the distribution of tectonic elements and any tectonic activity. It should be carried out concurrently with regional remote sensing. The first stage is to locate all possible quotations dealing with neotectonic movements and the distribution of Plio-Quaternary terrains. Every indication or even mere supposition that may be connected with the tectonics of the area should be noted. Only at a later stage should one proceed to arrange the various, ill-assorted data more logically by tracing the evolution of the interpretative thought of the various authors chronologically.

The individual neotectonic elements should be numbered and individually described on data sheets, as part of the second stage of the bibliographical research. All authors who cited the elements should be specified on these sheets in chronological order. The tectonic, geological and chronological characteristics of the elements are to be listed, together with indications as to what checking operations will be performed in the field (fig. 5). As far as tectonic activity is concerned, important observations may also be obtained from publications dealing with the most recent seismic events in the area.

The bibliographical research should be consolidated in the form of a map of the Plio-Quaternary terrain and tectonic elements (fig. 6). This could consist of a small-scale document (1 : 100 000 to 1 : 250 000). Transposition of the bibliographical tectonic elements (obviously of a length that is compatible with the cartographic scale adopted), from the original works to the topographical map does not always prove to be an easy matter. In fact, the elements indicated by various authors do not always coincide in length, direction and location. Furthermore, they may be given on maps containing few topographical references. In the most difficult cases, it is preferable to choose the alignment as indicated on maps of a neotectonic nature. In the case of a group of faults, one could represent the line corresponding to the better-preserved morphological elements which is more likely to accord with recent tectonics.

Bibliographical Data Sheet for Neotectonic Element No.:

Bibliography:

Description:

Chronological summary:

Field checks:

Fig. 5. Example of data sheet for the neotectonic elements found in the bibliographical research.

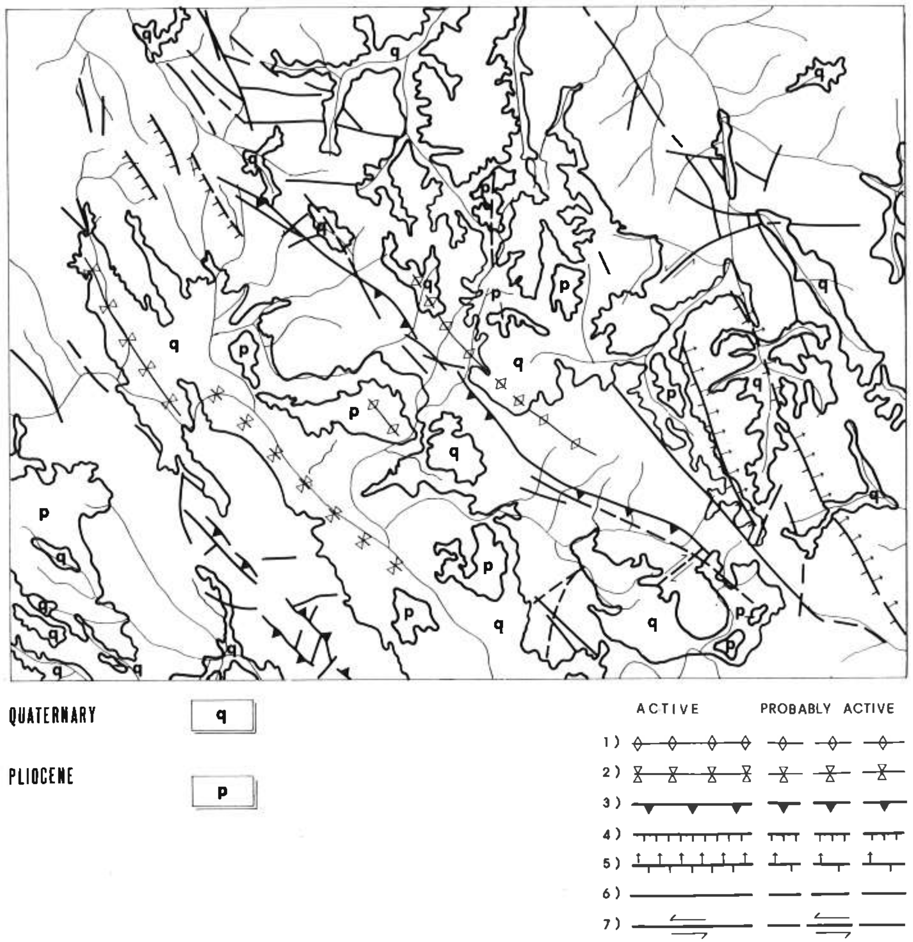


Fig. 6. Map of Plio-Quaternary terrains and tectonic elements. 1) anticlinal axis; 2) synclinal axis; 3) thrust (saw-teeth on overthrown limb); 4) normal fault (hatching on downthrown side); 5) reverse fault (hatching on downthrown side; arrows indicate dip of the fault plane); 6) fault of undefined type; 7) wrench fault.

Another aim of the bibliographical research is to collect other data that may be utilised with reference to the specific objectives of the study. Thus, it is useful, for example, to carry out studies on the seismicity of the area in question, to be transformed into a map of seismic epicentres; studies on vertical movements of the ground, both recent and in-progress, to be synthesised in the form of isolines relating to the whole of the movements; studies on geothermal or volcanic phenomena, and so on.

b) *Regional remote sensing*. – This part of the investigation concerns the identification, selection and morphological description of alignments or photo-lineaments. These terms refer to everything in a satellite image that shows a continous course, but one whose nature remains undetermined (CARRARO et al. 1978; Gruppo Geologia Spaziale Settore Alpino 1978). However, it should be noted that HASSAN (1975) has proposed the use of the terms "lineation, lineament, and linear" to indicate linear elements which are not qualified further but are in decreasing order of size.

The first stage consists of the identification of the total range of photo-lineaments. These are lines that have mainly or nearly rectilinear courses, but they may also have curved or sub-circular courses (CAIRE 1975). In addition, they have been rendered visible or traceable in the satellite image by photographic and/or morphological expression. By photographic expression we mean variations in parameters such as tone, texture, sharpness and brightness of the object. Morphological expression, on the other hand, refers to lineament patterns of a lithological type (that is, points of contact between different lithotypes), of a structural type (strike and dip of the strata, folds, faults, fractures), and of a hydrographic and orographic type (watercourses, valleys, watersheds, scarps).

The following images obtained by satellite may be utilised for the identification of the total range of photo-lineaments: Landsat spectral band 5–7, Landsat images in composite false colour, SLAR images, photomosaics and aeromagnetic images (BOLLETTINARI & MANTOVANI 1986). The ideal is to have images which have been taken at different times. This enables one to obtain documents that are more plentiful in information and sometimes to eliminate defects due to cloudiness, atmospheric pollution, vegetation or solar azimuth (BODECHTEL et al. 1975; CASSINIS & MARCOLONGO 1977; FUNICIELLO et al. 1977).

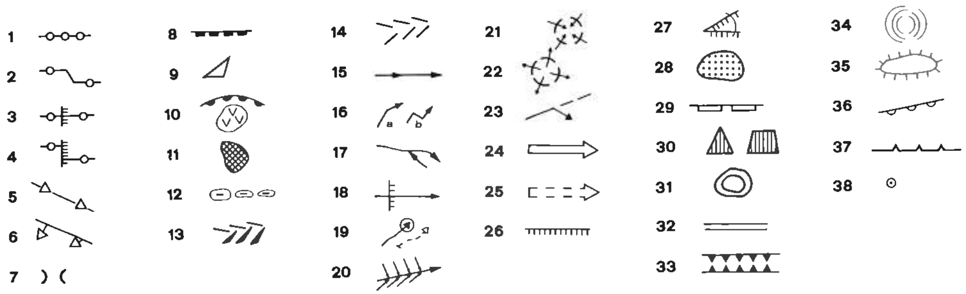


Fig. 7. Legend for morpho-neotectonic features (from PANIZZA & CASTALDINI 1985). 1) linear ridge; 2) planar discontinuity of ridge; 3) altimetric discontinuity of ridge; 4) planar-altimetric discontinuity of ridge; 5) alignment of peaks; 6) non-coincidence between alignment of peaks and watershed; 7) col; 8) scarp; 9) reverse slope; 10) landslide; 11) area with particular recurrent and/or aligned forms of erosion; 12) karst and pseudo-doline forms; 13) valley asymmetry; 14) rectilinear valley; 15) gully; 16) (a) river bend and (b) double river bend; 17) barbed confluence; 18) step or anomaly in the longitudinal profile of a watercourse; 19) (a) blind valley and (b) dry valley; 20) drainage pattern asymmetry; 21) centripetal drainage pattern; 22) radial drainage pattern; 23) river capture; 24) rectilinear drainage; 25) rectilinear palaeodrainage; 26) terrace edge; 27) converging and diverging terraces; 28) aggradation; 29) straight coast; 30) (a) triangular facet and (b) trapezoidal facet; 31) isolated relief; 32) line of undefined nature; 33) distinct tectonic line; 34) circular structure; 35) palaeosurface; 36) anomaly on palaeosurface; 37) fissure; 38) sand and/or mud volcano.

All the photo-lineaments that have emerged during the various phases of interpretation of the different types of image are finally transferred on to one image. This image constitutes the final identification document. It is during this final phase that screening of the photo-lineaments should take place. In the screening process one seeks to sort out those photo-lineaments that are directly related to the purpose of the work at hand. Photo-lineaments to be discarded include those of an anthropogenic nature, such as roads, aqueducts, electrical lines, crop divisions; photo-lineaments found on only one type of image (as in the case of jet aircraft trails, for example) and those of a natural type that are not linked to tectonic forms (such as those of climatic origin). The lineaments thus obtained (CARRARO et al 1978; Gruppo Geologia Spaziale Settore Alpino 1978) must be selected with reference to the geomorphological evidence indicative of Quaternary tectonic activity.

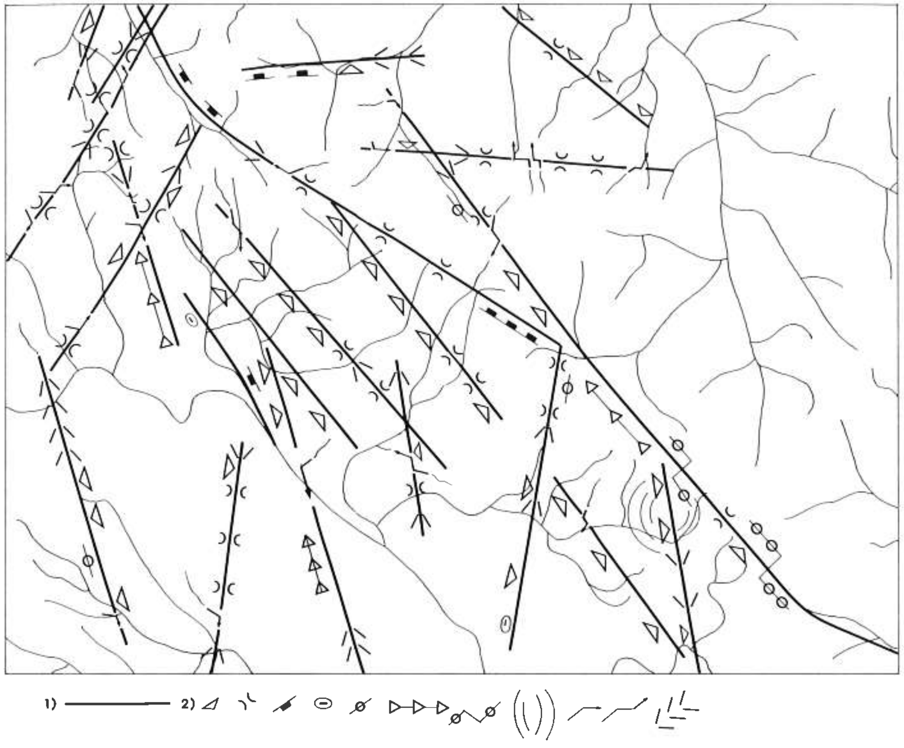
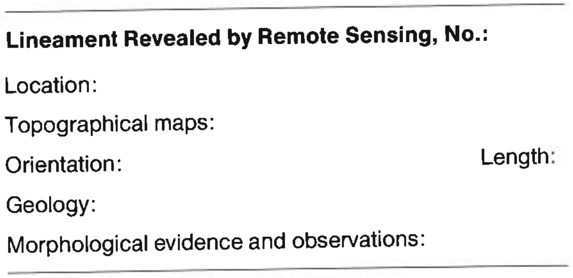


Fig. 8. Map of selected lineaments in the same area of Fig 6. 1) selected lineaments; 2) morpho-neotectonic features; see legend to Fig. 7.

The Legend used for the morpho-neotectonic symbols characterising the lineaments is one appropriate to detailed aerial photograph interpretation (Phase B). This Legend, apart from some additions and modifications, has been taken from C.N.R. (1976) and has already been partially illustrated by PANIZZA et al. (1978), PANIZZA (1983, 1984). It is outlined here (fig. 7) in the integral form appearing in PANIZZA & CASTALDINI (1985).

Following the preceding operation, each lineament is then individually described and reproduced on a map of selected lineaments (fig. 8) on the same scale as that used for the map of Plio-Quaternary terrain and tectonic elements (fig. 6).



Lineament Revealed by Remote Sensing, No.:

Location:

Topographical maps:

Orientation: Length:

Geology:

Morphological evidence and observations:

Fig. 9. Example of data sheet for lineaments obtained through remote sensing.

A data sheet is compiled for each lineament (fig. 9). The position of the lineament should be indicated with reference to the topographical maps on which it is located. The orientation, length, and geology of the terrain crossed by the lineament are also specified. In the case where the lineaments follow a circular course, it is advisable to indicate the maximum radius of the structure itself, rather than its orientation and length. Lastly, all geomorphological signs characterising the lineament are recorded with any observations, especially those concerning relationships between the lineaments themselves.

c) *Synthesis of bibliographical research, regional remote sensing and other data.* – Phase A is concluded by constructing a synthetic map, prepared by comparison of the following maps:

- Map of the Plio-Quaternary terrain and tectonic elements;
- Map of selected lineaments;
- Map of seismic epicentre distribution;
- Other documents depending on the specific objectives of the investigation, such as maps of recent vertical movements, maps of geothermal phenomena and maps of volcanic phenomena.

The preparation of the synthetic map (fig. 10) which should be reproduced on the same scale as the preceding maps, helps to sub-divide the tectonic elements and lineaments into three categories:

1. tectonic elements that are probably active;
2. tectonic elements that are probably inactive;
3. lineaments that may be linked to possible active tectonic elements.

The faults taken from the map of the Plio-Quaternary terrain and tectonic elements, for example, which can be shown to displace the Quaternary or Plio-Pleistocene terrain on the map shown in fig. 6, or the folded structures which seem to have conditioned or limited sedimentation as a consequence of tectonics, are to be inserted in the first category. Other tectonic elements to be inserted in the first category are those that were already held to be active in the literature. Another group consists of the faults that coincide with a lineament on the map of selected lineaments. Such a lineament should show the following characteristics: it must be *qualified* in terms of the distinctness, quantity, quality, and congruence of the geomorphological features, and the fault must be linked to several seismic epicentres.

All the elements on the map of Plio-Quaternary terrain and tectonic elements not included in the first category come under the second category. Transferring them to the Phase A synthetic map is considered unnecessary as they do not involve neotectonic synthesis.

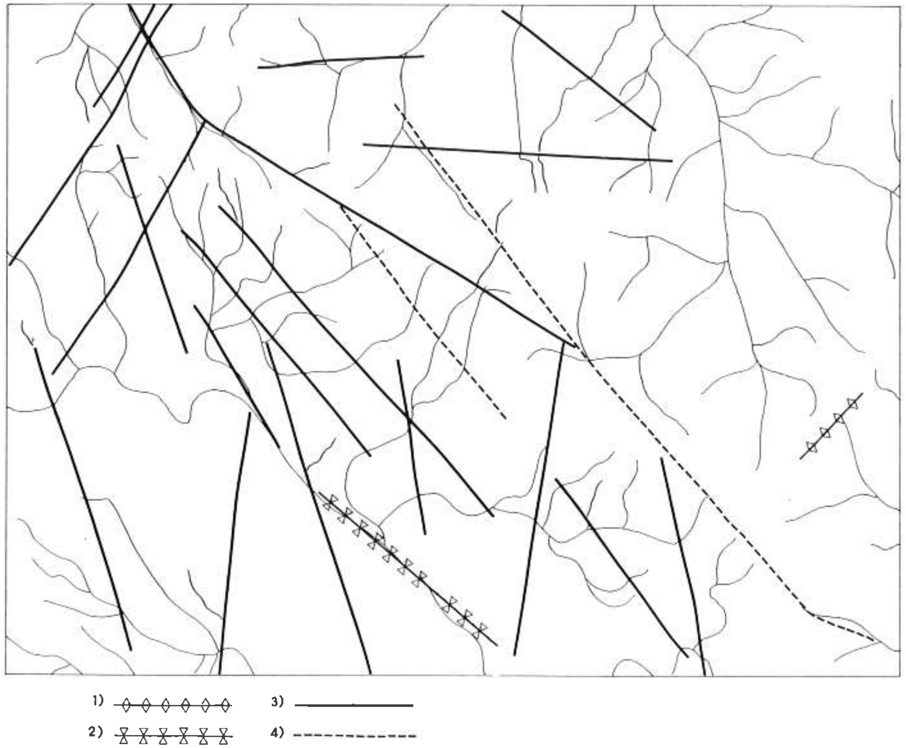


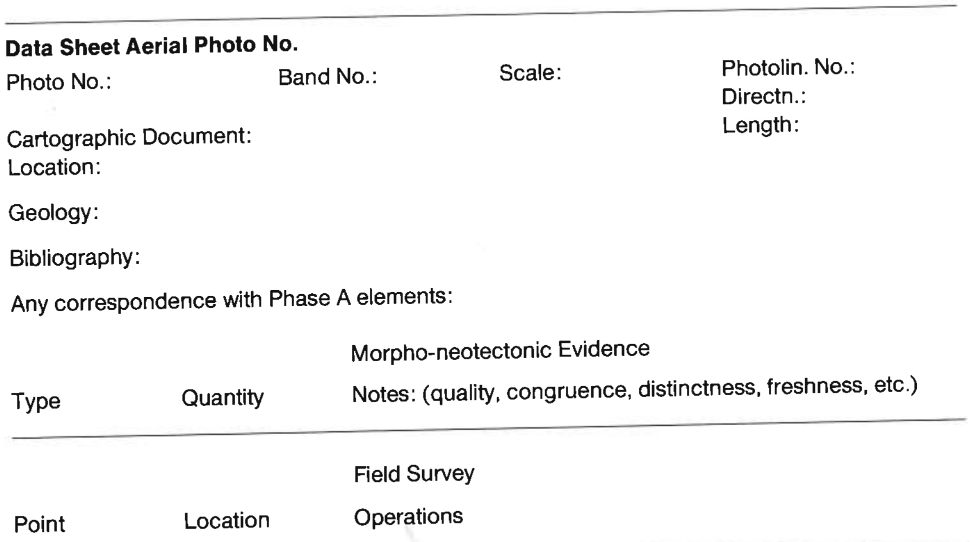
Fig. 10. Phase A synthetic map of the same area of Fig. 6 and 8. 1) probably active anticline; 2) probably active syncline; 3) probably active fault; 4) lineament linked to possible active tectonic element.

Coming under the category of lineaments that may be linked to possible active tectonic elements are those lineaments (on the map of selected lineaments, fig. 8) which, though not coinciding with tectonic elements drawn from the literature, show the following attributes: they must be qualified in terms of the distinctness, quantity, quality and congruence of the morphological features or appear to be cut into Plio-Quaternary terrain. These lineaments may find confirmation of their neotectonic validity in their coincidence with alignments of seismic epicentres. All the lineaments that may be linked to possible active tectonic elements should also be reproduced on the Phase A synthetic map. As far as tectonic elements and lineaments are concerned, the Phase A synthetic map (fig. 10) should contain only the tectonic elements that are probably active and the lineaments that may be linked to possible active tectonic elements.

All the elements must also be described individually on data sheets as shown in figs. 5 and 9. In addition, these elements must be checked in the field (Phase C) just as in the case of the lineaments that will be located during the detailed aerial photograph interpretation phase.

Phase B: Detailed aerial photograph interpretation

Phase B, which consists of the detailed interpretation of aerial photographs, has the same purposes as the regional investigation in Phase A, but offers greater interpretative possibilities. Using medium- to large-scale aerial photographs (from 1 : 60 000 to 1 : 15 000 approximately), it is aimed mainly at the identification of morpho-neotectonic lineaments. These lineaments are recorded on the basis of their geomorphological characteristics (*morpho-neotectonic investigation*). Interpretation should concentrate on the identification of all fracture-induced lineaments in order to serve as a basis for statistical analysis (*statistical analysis of the total range of fractures*). This type of analysis is particularly useful, when combined with research on permeability, in the case of studies for evaluating geothermal potential.



Data Sheet Aerial Photo No.

Photo No.: Band No.: Scale: Photolin. No.:
Directn.:
Length:

Cartographic Document:
Location:

Geology:

Bibliography:

Any correspondence with Phase A elements:

Morpho-neotectonic Evidence

Type Quantity Notes: (quality, congruence, distinctness, freshness, etc.)

Field Survey

Point Location Operations

Fig. 11. Example of data sheet for detailed aerial photograph interpretation (Phase B).

a) *Morpho-neotectonic investigation.* – As mentioned previously, morpho-neotectonic investigation is based upon those geomorphological characterictics that may indicate recent tectonic movement. Such evidence is identified on the aerial photographs and reproduced on both small- and large-scale topographical maps, according to the legend shown in fig. 7. The next procedure consists of the identification, guided by geological data, of landforms due to inactive tectonics or rather, to passive structure. These are then eliminated from the map, leaving only features (lineaments) with hypothetical neotectonic significance. Using aerial photographs, itineraries for field checking are decided and subsequently represented on the topographical maps, together with notes on the specific field-checks that are to be carried out. A preliminary data sheet (fig. 11) should be compiled for each lineament. The lineament's direction, length and location are indicated on the data sheet, together with aerial photographs on which it was identified, the geological terrain involved, relevant bibliographical references, and any possible correspondence with the elements drawn from Phase A. All relevant geomorphological features must be reproduced with observations as to their quantity, quality, congruence, distinctness and freshness. Not all the lineaments obtained through regional remote sensing interpretation (Phase A) in the analysis of the satellite images will necessarily match those revealed through detailed aerial photograph interpretation (Phase B).

b) *Statistical analysis of the total range of fractures.* – Analysis, interpretation and classification of the various fracture systems (azimuth, frequency and density), and subdivision of the area being studied into classes with different densities of fracturing must also be undertaken.

The first stage is to identify the total range of lineaments that may be fracture-associated, through aerial photograph interpretation. All linear elements with topographical expression (such as scarps, valley-floors and watercourses) and with photographic expression (different tones of grey close together), and those which determine the structural geological significance of a fracture that is present or held to be probable in rocky outcrops or in the cover material, are to be marked on the aerial photographs. The whole body or total range of lineaments that may be fracture-associated must subsequently be transferred from the photographs on to small-scale topographical maps (for example, 1 : 100 000).

A second stage is to define homogeneous areas of lineaments that may be fracture-associated, using an automatic and/or photographic procedure. The data should be computer-processed to obtain ray-diagrams that are representative of the orientation and length of lineaments in relation to their density and frequency within each individual, homogeneous area. The information thus obtained represents one of the two starting points for the preparation of a map of fractures (fig. 15). The second starting point consists of structural statistical measurements taken in the field (Phase C), which will be discussed later.

Phase C: Field surveys

Following literature search and aerial photograph interpretation, field surveys should be carried out according to the itineraries determined during the preliminary investigations. Fieldwork has several purposes: to verify the neotectonic hypotheses regarding the lineaments and tectonic elements cited in the literature and if necessary, to specify their geometrical, geological and geomorphological expression; to check the geological and, in some cases, the stratigraphical relationships of the formations; and to make measurements of the fracturing on significant outcrops.

The aim is to prepare two thematic maps, one of classified lineaments (fig. 13) and one of fractures (fig. 15). The next sections amplify the procedures.

a) *Morpho-neotectonic checks.* – These consists of verifying the presence of faults, fractures or other tectonic structures and of recording the freshness, consistency and distinctness of the geomorphological expression of the lineaments. The field records should include explanatory notes, geological sections, plans, photographs, geological maps or other types of maps, depending on the case in hand. A data sheet of the type shown in Fig. 12 should be compiled for all lineaments, reporting in particular the geological characteristics, of both the bedrock and the superficial deposits, as well as their inter-relationships. Geomorphological features should be specified and any other supplementary data recorded. Every lineament must then be classified justifying the classification from a neotectonic point of view. If it corresponds with a fault, the type and direction of movement and, if possible, the amount of neotectonic displacement should also be stated on the data sheet. Any analyses performed in the field or on laboratory samples should also be specified.

The following categories may be distinguished:

1. Active tectonic element: Proven displacement and/or deformation of rocks and/or significant forms.
2. Tectonic element held to be active: on the basis of supporting geomorphological or other evidence, but showing no visible displacement or deformation of rock or other significant forms.
3. Tectonic element held to be inactive: little or no geomorphological evidence for tectonic activity, no visible displacement or deformation of the rock or other significant forms.
4. Inactive tectonic element: proven lack of displacement and/or rock deformation.
5. Qualified lineament: with numerous, qualified, and congruent geomorphological features or other indications, but showing no outcrops capable of confirming displacement or deformation.
6. Unqualified lineament: with unqualified or unrelated geomorphological indications and showing no outcrops capable of confirming displacement or deformation.

Field Checks (If not performed, explain why)

Date:
Point:

Geology
Bedrock:
Strike and dip:
Age:
Superficial deposits (type & genesis):
Bedrock/superf. dep. relationships:

Geomorphology
Evidence:

Sketch No.:
Survey No.:
Point:
Area:
Photograph No.:
Profile No.:
Point:
Section:
Results:

Lineament Classification

Category:
Justification:

If lin. = fault:
Type and direction of movement:
Amount of displacement, if possible:

Geognostic investigations, proposals, and justifications:
Lab. analyses:
Data on micro-mesotectonics, pedology, archeological analyses, etc.:

Chronological evaluation:

Fig. 12. Example of data sheet for lineament field checks (Phase C).

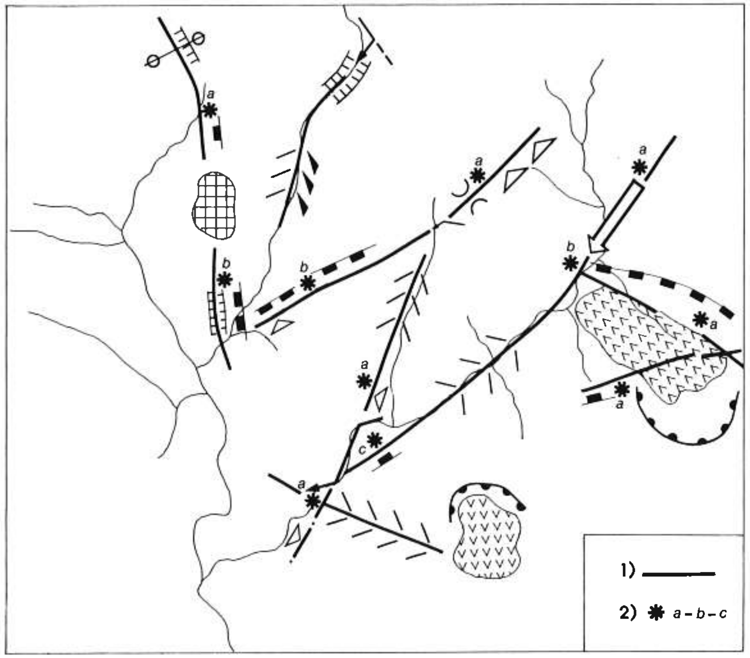


Fig. 13. Map of classified lineaments. 1) classified lineaments; 2) field check-points; see Fig. 7 for morpho-neotectonic symbols.

7. Lineament not corresponding to any tectonic element: though evidently of geomorphological origin, shows proven lack of displacement and rock deformation.

It should be recognised, however, that in many cases a neotectonic age cannot be demonstrated; also, that not every element obtained from the aerial photograph interpretation or literature search will fall neatly into one category alone. In some instances, a lineament may be subdivided into several segments, each with a different neotectonic classification. Finally, the lineaments are transferred to a map of classified lineaments (fig. 13) which will be quite similar to the map shown in fig. 8. The difference between the two consists primarily in the fact that, in light of the larger scale used on the map of classified lineaments, it is possible to appreciate the morphological expression of the tectonic elements and lineaments in greater detail. Moreover this map has also been checked in the field.

b) *Lithological checks.* – Lithological checks are necessary both for the precise tectonic definition of the lineaments and for the dating of any movement.

c) *Structural-statistical analysis.* – Measurement and field checking must be planned to provide the data needed for verification of the macrofracturing pattern. The selection of lithotypes, the basis of the statistical analysis, is linked to the geological and/or structural characteristics of the area, as are the procedures to be adopted for the analysis. In the case of geothermal research, statistical analysis must deal with those lithotypes which are considered to be potential rock reservoirs or impervious cover rocks, related to particular structural conditions. The statistical analysis may be carried out, for example, over a standard area defined as 1 km², including measurements of the geometry of all planes of discontinuity, and their representation on stereographic projections (see, for example, PHILLIPS 1954; SNOW 1970; BARTON 1973). This method allows one to define the structural features of each lithotype analysed.

Measurement Station No.:
Date:

Topographical map No.:
Geological Formation:

Outcrop exposure =
S/D =
Strike/Dip

Principal System

Bedding Plane

Secondary Systems

Frequency

Open System

Closed System

Total Range – Fracture System

Partial Range – Most representative systems

Fracture Plane

Bedding Plane

Average Density =

Direction of flow:
principal =
secondary =
vertical =

Field Notes:

Fig. 14. Example of a microstructural investigation data sheet used for geothermal research.

An example of the parameters that may be utilised in the measuring of the planes, the type of analysis and observations on the masses of rock at every observation point, are shown on the data sheet, fig. 14. The data obtained from the structural-statistical analysis performed in the field, supplemented with those from the statistical analysis of the total range of lineaments that may be fracture-associated, as revealed in the detailed aerial photograph interpretation, are then synthesised on a map of fractures (fig. 15). This is a graphic document representing areas with different densities of lineaments that may be fracture-associated, with related ray-diagrams, block diagrams and measuring-station points.

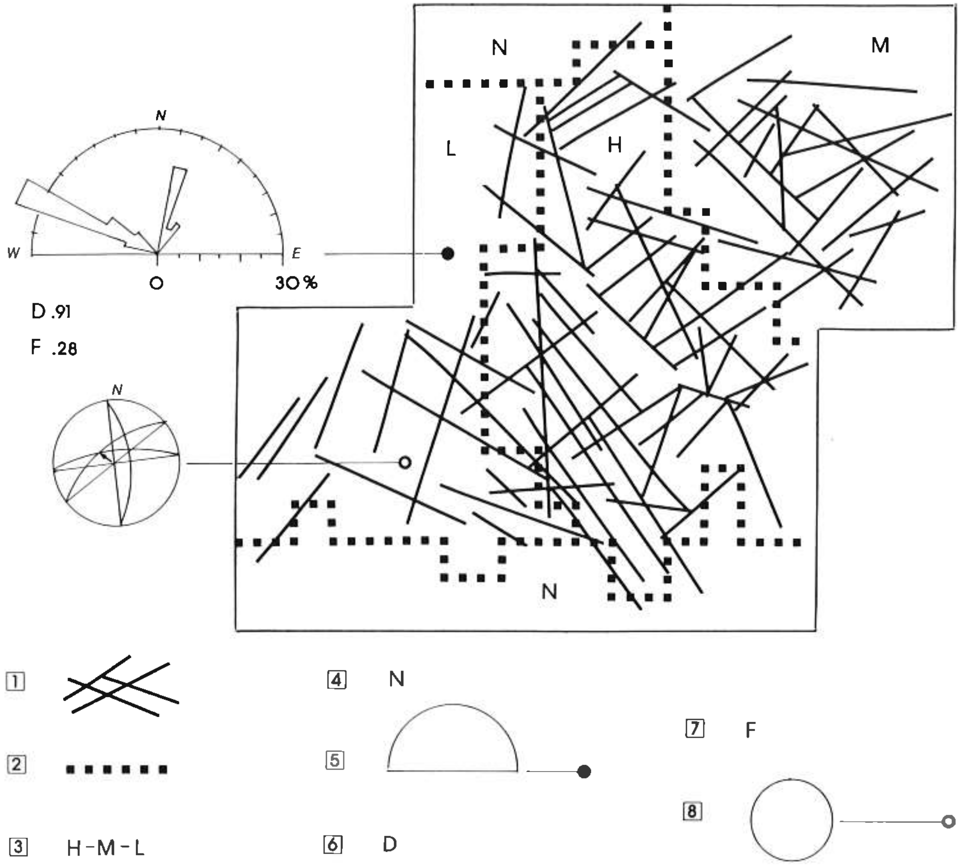


Fig. 15. Example of a map of fractures. 1) fracture-associated lineaments (FAL); 2) boundary separating areas with equal FAL densities; 3) FAL density classes: H=high, M=medium, L=low; 4) area without FAL; 5) ray-diagram; 6) FAL density (km/km²); 7) FAL frequency (number per km²); 8) block diagram and related measurement point.

In the case of neotectonic research, the dynamic and geometrical reconstruction of the successive tectonic events is possible by means of the study of fault planes, grooves, stylolites and fractures. This is a vast field of research, exemplified in the numerous works by ANGELIER, CAREY, and MERCIER which are cited in the bibliography.

Phase D: Final synthesis

Morpho-neotectonic studies for major projects are collated in a final synthetic map (fig. 16), preferably on a small-scale. This is achieved through the three phases of literature review and regional remote sensing, detailed aerial photograph interpretation and field surveys, as well as through interpolation in those instances where it is not possible to carry out fieldwork.

The tectonic elements and lineaments selected from the Phase A synthetic map (fig. 10) and the map of classified lineaments (fig. 13) are those which appear to indicate activity within the limits of the time interval considered.

Orientation data which can offer information on recent or current tectonic stress trends should be extracted from the map of fractures (fig. 15).

To be more specific, the final synthetic map should contain the following data:

- "active tectonic elements" and "tectonic elements held to be active" especially those derived from field investigations, but in some cases interpreted as active on the basis of the bibliographical references;
- "qualified lineaments" which may be linked to possible active tectonic elements, most of which have been checked in the field and the remainder interpreted as in the preceding case.

Indications of areal tectonic movements (uplift, subsidence or tilting), obtained principally from the literature, regional remote sensing and field survey, may also be inserted on the map. As regards neotectonic synthesis, the direction of the most recent principal tectonic stress as deduced from the structural-statistical analysis, may be taken into consideration.

All of the elements represented on the final synthetic map should be given a final serial number and described on data sheets (fig. 17), whether they be tectonic structures or lineaments. The data sheets should summarise all the data from Phases A, B and C, and should contain the following information:

- cartographic references,
- direction and length of the element;
- data derived from aerial photographs and/or literature searches;
- surveys performed in the field;
- classification according to the categories described (with justification).

The various phases, operations and objectives of applied neotectonic studies in mountainous areas are summarised in fig. 18.

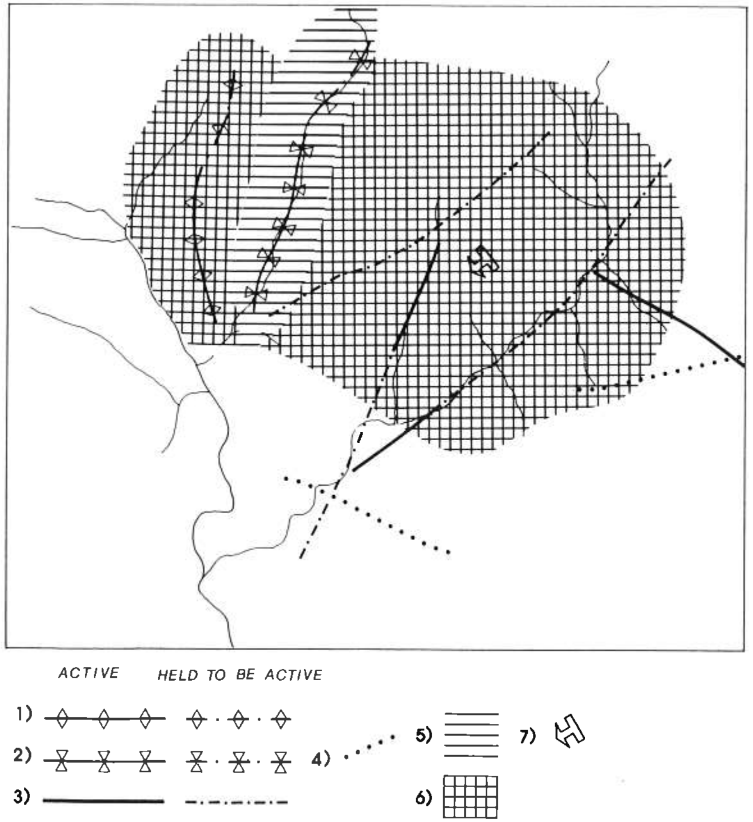
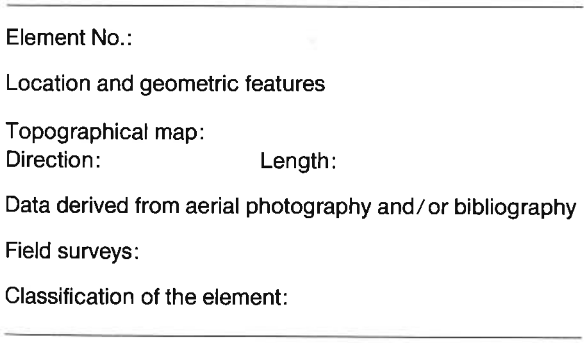


Fig. 16. Final synthetic map. 1) anticline; 2) syncline; 3) fault; 4) qualified lineament; 5) area undergoing subsidence; 6) area undergoing uplift; 7) tilting.



Element No.:

Location and geometric features

Topographical map:
Direction: **Length:**

Data derived from aerial photography and/or bibliography

Field surveys:

Classification of the element:

Fig. 17. Example of a summary sheet for elements represented on the final synthetic map.

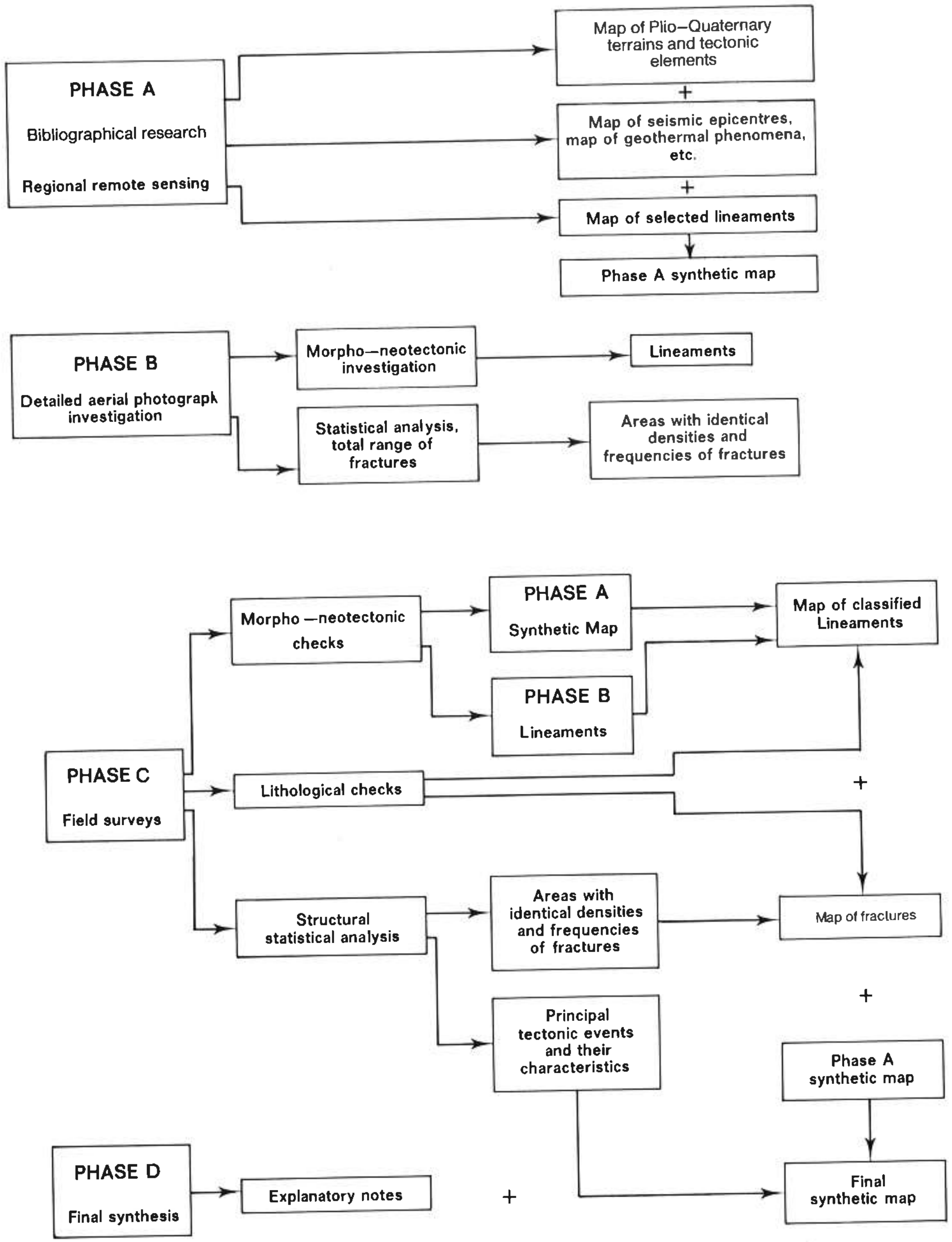


Fig. 18. Summary diagram of morpho-neotectonic studies for major projects in mountainous areas.

Studies in alluvial plains

Neotectonic analysis demands a different approach in the case of alluvial plains where the bedrock is covered with unconsolidated recent sediment, and where it is seldom possible to verify directly the displacement or deformation of deposits or significant forms. From the morphological point of view, landforms in an alluvial plain are essentially linked to fluvial sedimentation and erosion processes. Therefore, the main objective is to locate neotectonic movements from study of the evolution of the area's drainage system. The programme of investigation may follow approximately the same four phases of research described for mountainous areas. The examples that follow are taken from the Po Plain, the alluvial plain situated between the Alps and the Apennines (fig. 2).

Phase A: Bibliographical research and regional remote sensing

Bibliographical research. – Bibliographical research should concentrate on locating information on the distribution of superficial deposits, their ages and the buried bedrock structures that may have conditioned their deposition and influenced the evolution of the plain in general. Compilation of the data sheet shown in fig. 5 remains valid, as does the drawing-up of a final small-scale map (1 : 100 000 to 1 : 250 000) of Quaternary deposits and tectonic elements. Where possible, a detailed subdivision of the Quaternary deposits should be shown on the map (for example, Lower, Middle or Upper Pleistocene and Holocene). An example of such a map is not provided here as it will not differ substantially from that appearing in fig. 6, apart from the age factor and the related chronological details concerning outcropping sediments.

The literature search should also attempt to locate information on the seismicity of the area, as well as on recent or contemporary movements obtained from geodetic measurements.

Regional remote sensing. – The procedures previously outlined for the regional remote sensing phase also apply here. However, the morphological expression of the lineaments will be more clearly represented by anomalies in the drainage network.

Representation of the terrain characteristics through spectral reflectance (fig. 19) is another document that may be drawn up as part of this phase. In order to prepare such a map, the authors conducted an analysis of winter 7-band Landsat images, taken in one sector of the Po Plain using electronic optical equipment which allows for a sub-division of the photographic density into eight levels. The system's output consists of a video image on which areas of equal photographic density are given the same colour.

The hypothesis assumed is that the spectral signal reflects the amount of soil water, considering the season in which the images were taken. Given the geological characteristics of the plain, these characteristics, in turn, are indicative of morphological lineaments and are thus significant in regard to neotectonics.

Fig. 19 was prepared from photographs obtained from the video images and represents, in a rough and generalized manner, the zonation of the part of the plain that was analysed, as related to those density classes that appeared most significant, that is, the lowest and highest densities. The classes are shown in decreasing order of density (increasing order of spectral reflectance), beginning from class 1 which indicates maximum

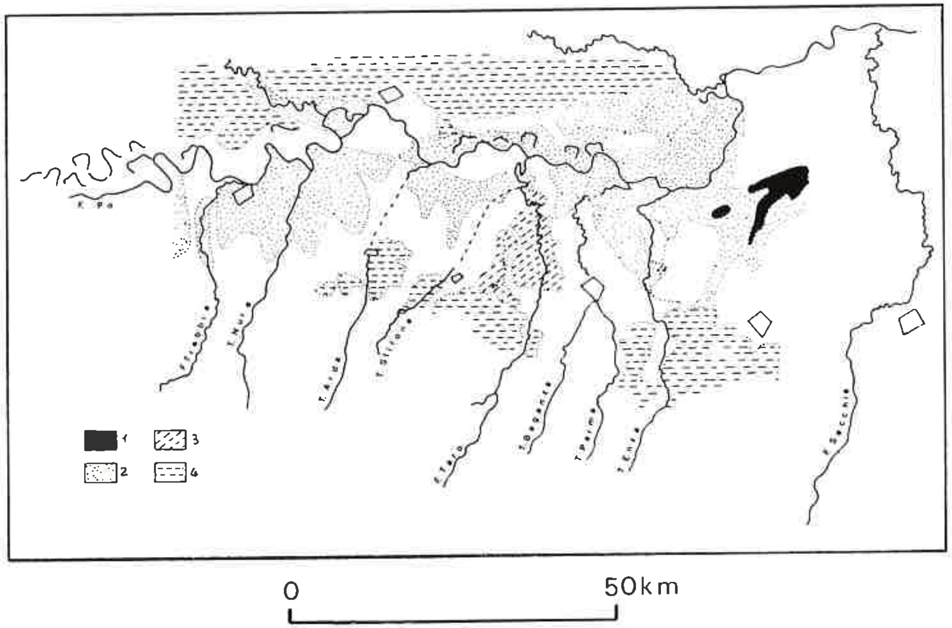


Fig. 19. Equal density analysis of spectral reflectance characteristics (from BERNINI et al. 1980) 1=classes 1+2, 2=classes 3+4, 3=classes 7+8, 4=class 8. 1=maximum photographic density and high amount of soil water; 4=minimum photographic density and minimal amount of soil water.

photographic density and with which a greater quantity of soil water is assumed to be associated, to class 8 which indicates minimum photographic density and minimum quantity of soil water.

Synthesis of bibliographical research, regional remote sensing and other data. – As described already, Phase A terminates with the construction of a synthetic map similar to fig. 10. The only additional point is that tectonic elements that are probably active and lineaments linked to possible active tectonic elements may be obtained from a spectral reflectance map such as fig. 19. For example, those tectonic elements that are known from the literature and that correspond to a clear-cut break between areas of different densities may be inserted among the probably active tectonic elements.

Other data that may be relevant include a map of seismic epicentres.

Phase B: Assemblage of information on various aspects of the local environment

This phase aims to produce in map form a general picture of the area's evolution during the latest periods of the Quaternary. In this way it is hoped to locate recent movements of the buried, folded and disjunct tectonic structures.

The aspects of the environment to be studied include:

a) geomorphology
b) the natural and man-made drainage network;
c) archaeological and historical data;
d) superficial deposits;
e) subsurface alluvial deposits;
f) relationships between fresh and salt water.

The investigations involve various fields of expertise. Thus the geomorphologist will be assisted by researchers from other disciplines, such as hydrogeologists and archaeologists.

These studies will be described in the following sections with the aid of selections from thematic maps.

a) *Geomorphology.* – This study is conducted through detailed aerial photograph interpretation and field surveys. A first step is to prepare a relief map with closely spaced contours (for example, a contour interval of 1–2 m on a scale of 1:25 000). This will probably have to be constructed by interpolation from available spot heights. The map may show up topographical anomalies or irregularities attributable to palaeo-drainage patterns.

Detailed photographic interpretation, using large-scale black and white and/or colour aerial photographs, should focus on locating landforms linked to abandoned fluvial courses. The identification of abandoned palaeodrainage channels in intensively cultivated areas such as the Po Plain is possible on aerial photographs since the abandoned course is marked by a winding strip of colour that is darker than the surrounding terrain. This is due to the greater quantity of water held in the ground and also because the orientation of the fields cultivated within an abandoned channel is adapted to the winding course of the latter, showing clear discordance with the land divisions of the surrounding areas. Scarps and areas characterized by darker tones in the surrounding zones and by regular man-made drainage systems indicating interfluvial depressions may also be identified.

Subsequently, field surveys and checks must be carried out. The results of the study are incorporated on a geomorphological map (fig. 20), to which other data will also contribute. For example, dating of the palaeodrainage may be derived from archaeological and historical data; and dating of alluvial deposits may be achieved from other published work. All such sources must be checked by means of stratigraphic and pedological investigations as this map is fundamental for understanding the palaeogeographical evolution of the area.

b) *Analysis of natural and man-made drainage systems.* – The starting point should be to prepare a map of the drainage network as illustrated in fig. 21. The evolution of alluvial plains is conditioned by two groups of factors which interact at times in a conflicting manner: natural factors (tectonic and sedimentary evolution, with resulting changes in drainage) and anthropogenic factors (the work carried out by communities to render the drainage system compatible with agricultural and settlement needs). The drainage net, especially the minor network which is directly determined by the pattern of land holdings, is the outcome of a variety of events that in time and space have brought about the formation of the plain. Analysis of this network permits one to discern such events and, with the aid of historical and archaeological data, to date them.

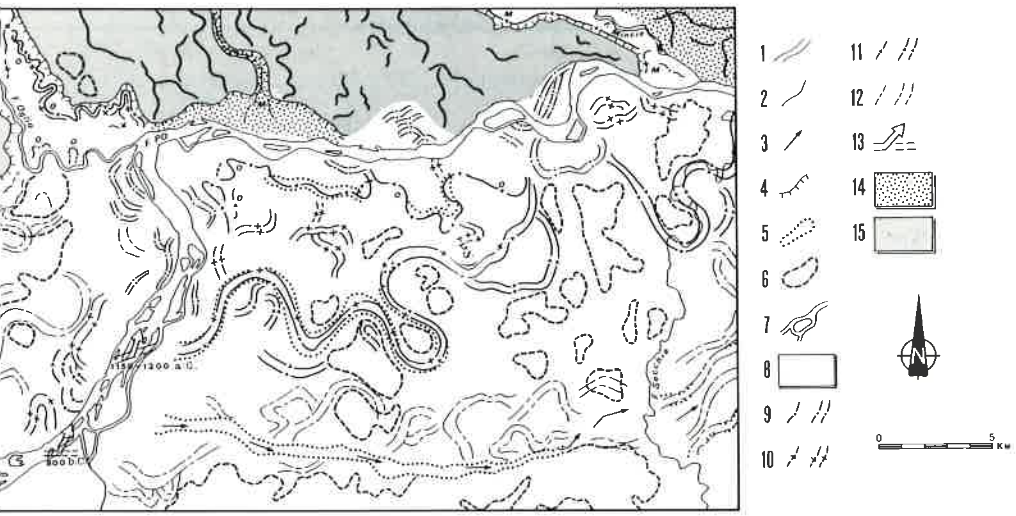


Fig. 20. Example of a geomorphological map (simplified from PANIZZA et al., in press) 1) Po River palaeodrainage; 2) Po River tributary palaeodrainage, indicated with abbreviations: M (Mincio River); O (Oglio River); 3) distributary functioning until 15th–17th centuries; 4) scarp edge; 5) levee ridge; 6) interfluvial depressed area; 7) present course of the Po River; 8) alluvial deposits abandoned by watercourses or by palaeodrainage passing over them; 9) palaeodrainage of late- and post-Middle Ages; 10) palaeodrainage of early Middle Ages; 11) palaeodrainage of Roman period; 12) palaeodrainage of Bronze Age; 13) deviations of the Po River with approximate indications as to age; 14) alluvial deposits attributable to 3000 years B.P. with traces of contemporary palaeodrainage; 15) Würm fluvioglacial terrace with traces of preglacial channels.

As an example, one may distinguish three types of common drainage system in fig. 21, taken from BERNINI et al. (1980):

a) natural drainage: watercourses that are neither canalised nor regulated, interpreted as traces of a palaeodrainage system;
b) early agrarian drainage layout;
c) recent drainage layout.

c) Analysis of archaeological, prehistoric and historical data. – As has already been mentioned, the arrangement of features on an alluvial plain is determined by the relationships between human activities and natural geomorphological phenomena. The distribution of human settlements reflects the geomorphological situation in the chronological period in which they developed. The settlements were constructed in places where the needs of the communities were best met: stable and well-drained land for agricultural use, and proximity to lines of communication, which in such areas were usually represented by waterways. Comparing the distribution of settlements at various times can therefore help in dating the palaeogeographical evidence, and also in reconstructing the evolution of the plain in recent times. The limitations and precision of such a method depend upon the prehistoric, historical and archaeological data available. The data can be consolidated in the form of a

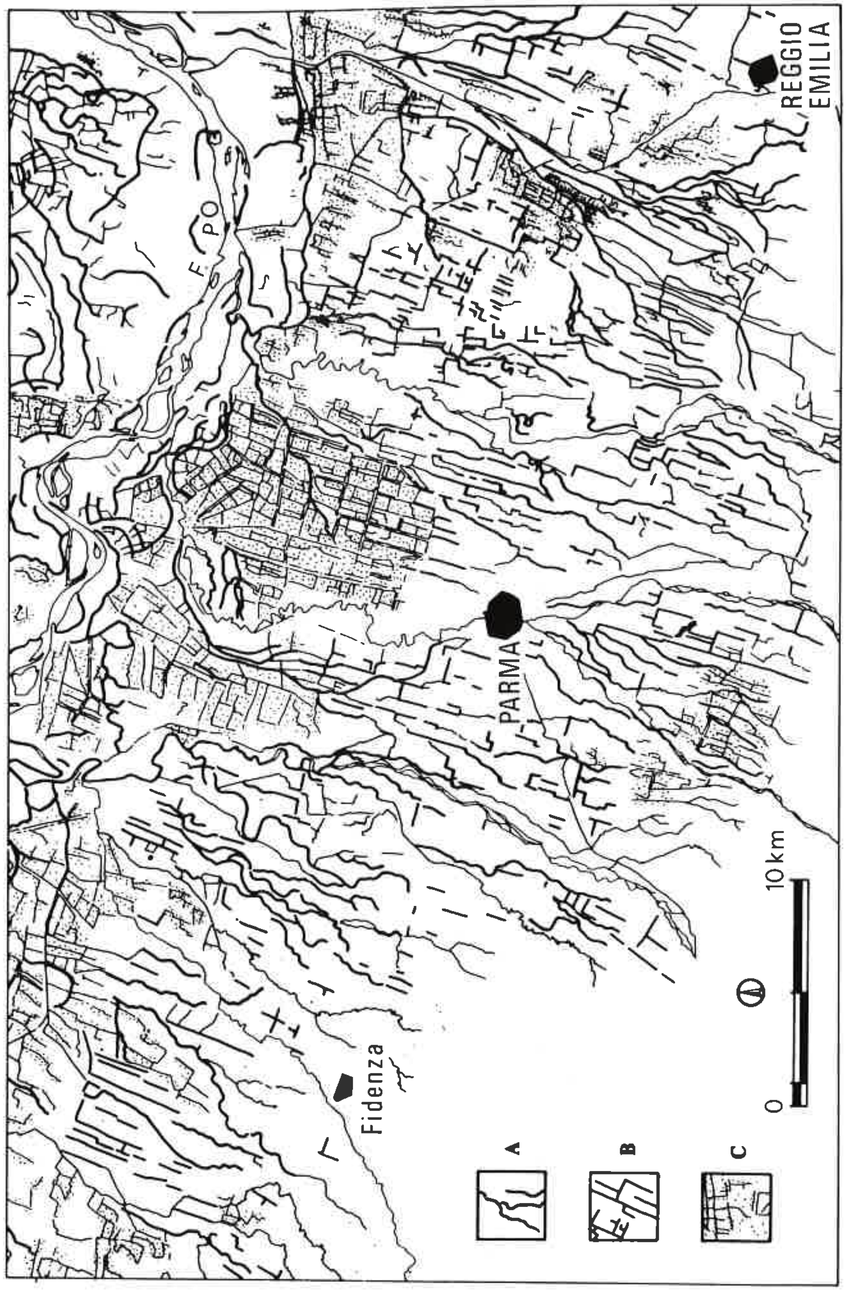


Fig. 21. Example of a map of a drainage network (from BERNINI et al. 1980) A=natural drainage (palaeodrainage network), B=early agrarian drainage layout, C=recent agrarian drainage layout.

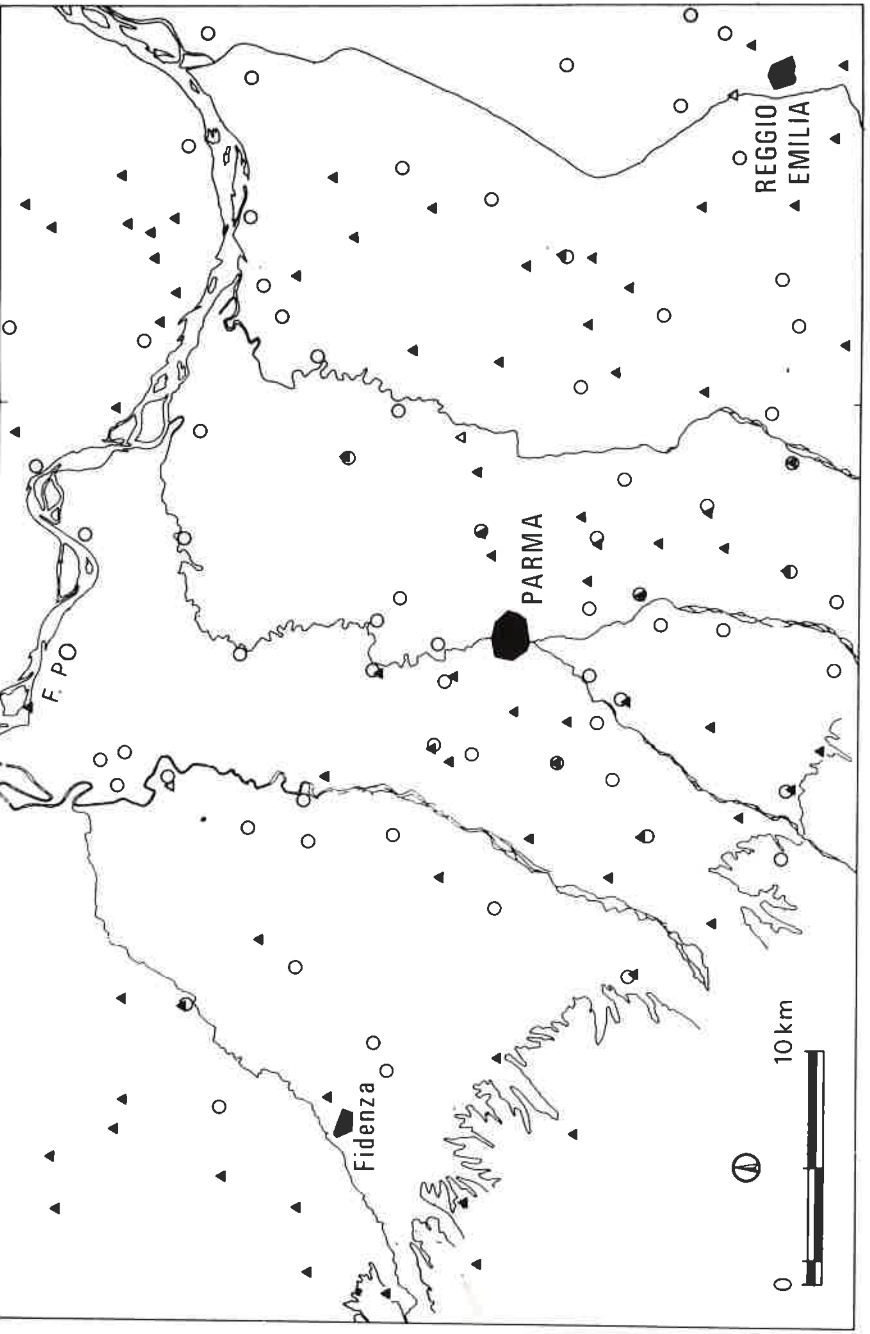


Fig. 22. Map of settlements of the Bronze Age and Early Middle Ages (from BERNINI et al. 1980) 1) surface Bronze-Age settlements (triangles); 2) buried Bronze-Age settlements (circles); 3) settlements of the Early Middle Ages (named).

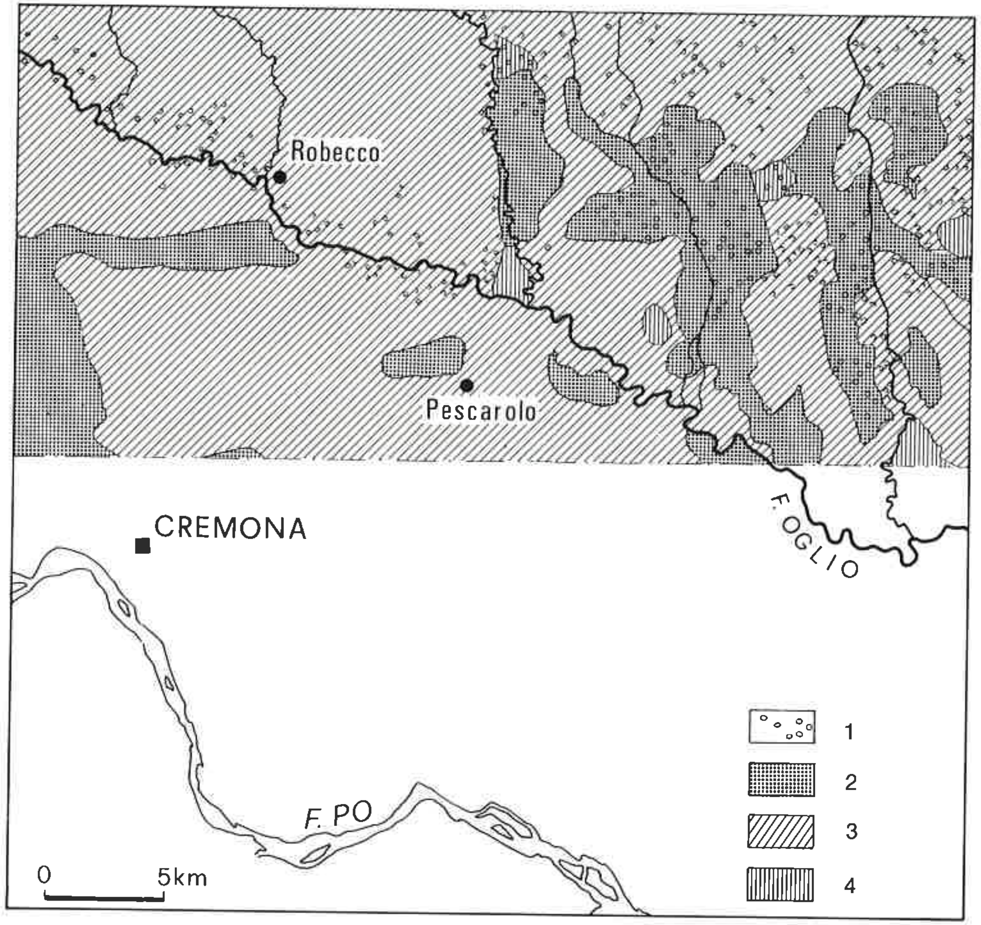


Fig. 23. Example of a map of superficial deposits (from BARONI et al. 1980 with modifications) 1) mainly gravel; 2) mainly sand; 3) mainly silt; 4) mainly clay.

map of the type shown in fig. 22 which was drawn up by BERNINI et al. (1980) for the same area as that of fig. 21.

In an archaeological context, the present level of the site is significant. If it is still on the surface today, this indicates that the area has not been flooded since. On the other hand, if it is buried, this indicates an area that has been covered by more recent sediment, affected by flooding and possibly undergoing subsidence. Whereas the distribution of recent deposits on the surface has a certain areal significance, the outcropping of older buried deposits is fortuitous, linked to the excavation of an artificial channel or building foundations, or even to the erosion of a natural watercourse. The significance of buried deposits is therefore localized and may only be extrapolated within a well-defined geomorphological context.

d) *Study of the superficial deposits.* – The term superficial deposit refers to a deposit positioned immediately beneath the agricultural soil that has been tilled and humified. A map of the distribution of superficial deposits in terms of their particle size (fig. 23) can provide important evidence for determining the migration or evolution of watercourses. It is sufficient for particle size classes to be limited to four principal groups as follows: 1) mainly gravel; 2) mainly sand; 3) mainly silt; 4) mainly clay. The map may be prepared using bibliographical sources as a base, along with field checks (as in fig. 23) or by resurveying the area. In the latter case, it is advisable to use relatively quick methods which do not require exacting laboratory work.

e) *Study of the subsurface alluvial deposits.* – This aspect is extremely important, for the stratigraphic and structural reconstruction of the Quaternary – normally neglected in exploratory drilling for oil and gas – allows one to determine tectonic movements that occurred even in the earliest part of the Quaternary. Such reconstruction may be carried out by detailed examination of the lithostratigraphic units revealed in wells and boreholes. The resulting data may be displayed as a tectonic map of the alluvial cover (fig. 24 A) and in geological sections (fig. 24 B).

Reduced thicknesses in the alluvial cover may indicate stable or rising areas, just as increased alluvial thicknesses may indicate subsidence. Lack of correlation between similar horizons in adjacent lithostratigraphic units may constitute evidence of displacement, which must be confirmed by comparisons with other maps and documents. However, one should keep in mind that the inter-relationships of the particle-size classes are very complex, considering the alluvial origin of the deposits.

More precise information on the buried surface beneath the alluvium may be obtained through seismic surveys. These are particularly suited to areas where the existence of probably active tectonic elements or lineaments linked to probably active tectonic elements has been demonstrated in Phase A.

f) *Analysis of the relationships between fresh- and salt-water.* – This type of study will yield a map of the fresh-water–salt-water-interface (fig. 25). Areas presenting anomalies in the chemical composition or temperature of groundwater may also be shown on this map. The interface between fresh-water and salt-water, revealed by electrical resistivity surveys, does not correspond to a precise stratigraphical level, but is clearly controlled by structures present and tends to emphasise their trends. There is often a clear correspondence, then, between the fresh-water–salt-water interface isobaths and the structural patterns.

Phase C: Field surveys

Field surveys should be aimed at checking and completing the data already presented. They are carried out simultaneously with Phase B.

Fig. 24 A. Example of a tectonic map of an area with an alluvial cover (from CASTALDINI et al. 1979, with modifications) 1) fault detectable from field data; 2) fault detectable through correlation between lithostratigraphic units derived from water wells; 3) isobaths of the top of marine formations (depths in metres refer to sea-level); 4) positions of the geological sections shown in Fig. 24 B.

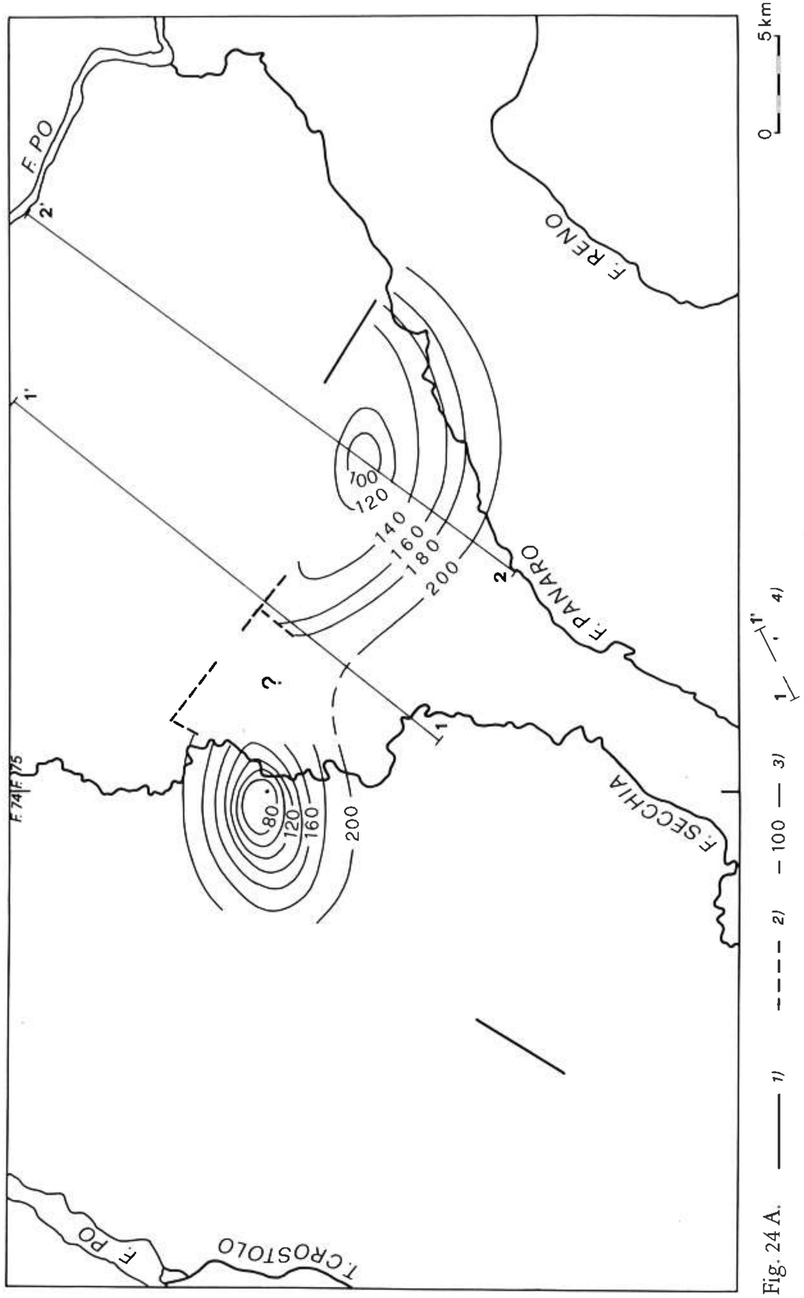


Fig. 24 A.

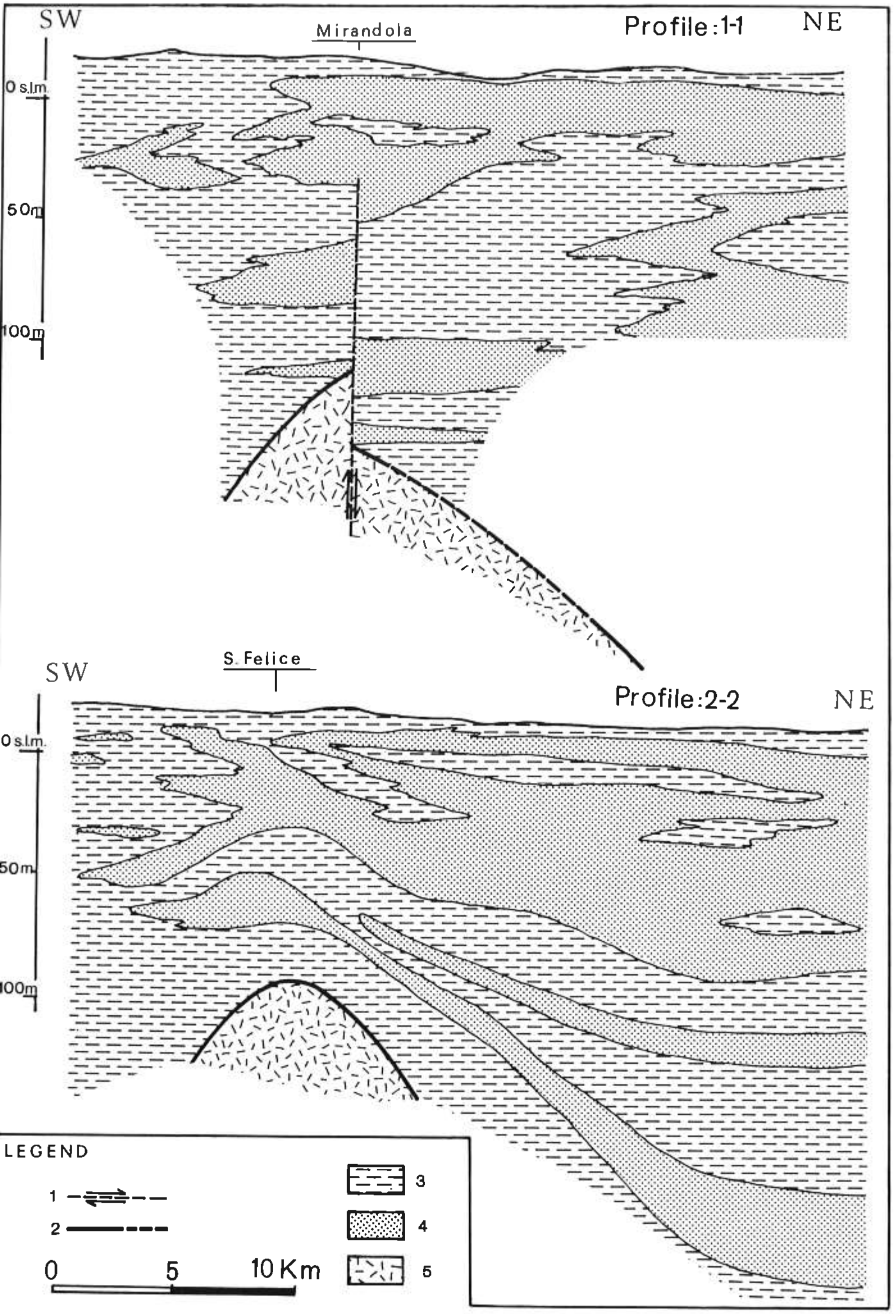


Fig. 24 B. Geological sections 1–1 and 2–2 pertaining to Fig. 24 A (from Istituto Geologia Universitá di Modena 1978) 1) probable faults; 2) top of marine substratum, dated between the Messinian and the Calabrian stages; 3) silty-clayey alluvial deposits; 4) predominantly sandy alluvial deposits with layers of gravel; 5) marine substratum, generally composed of argillites and marl.

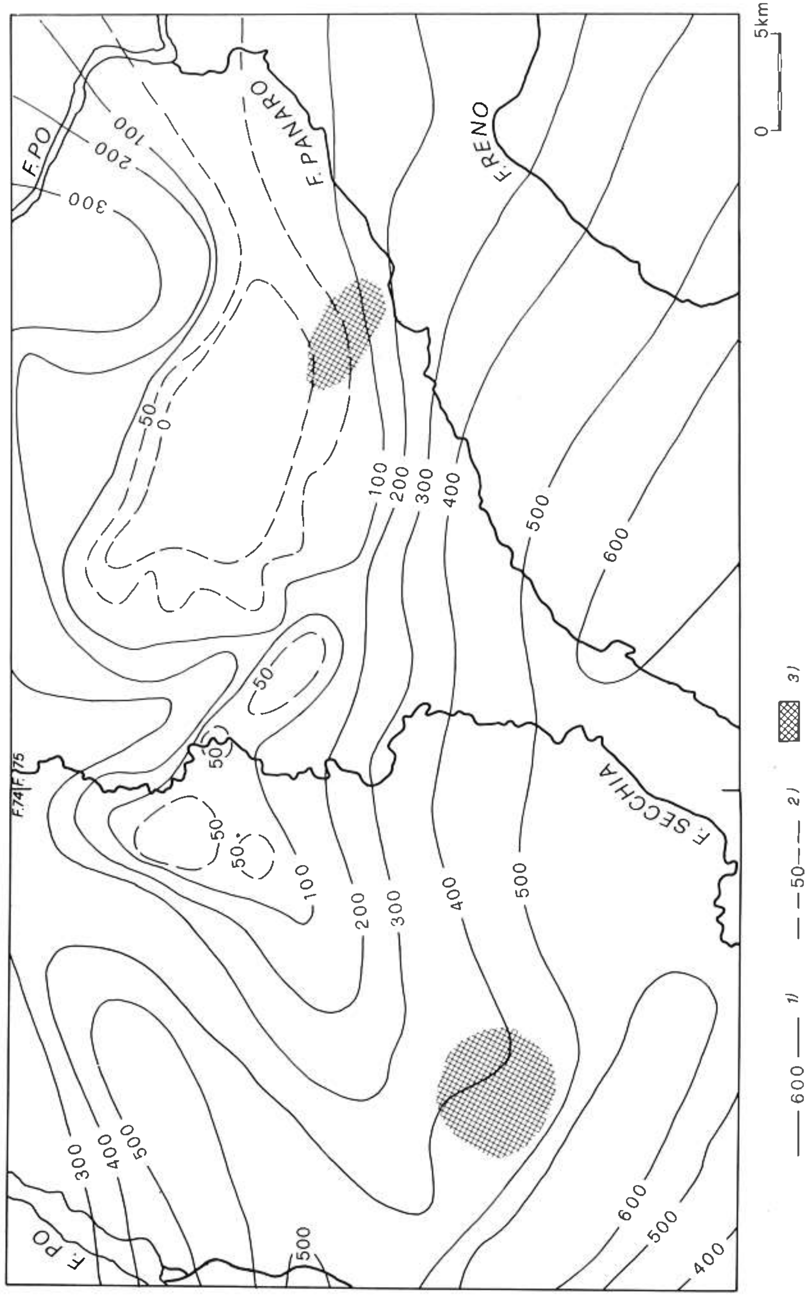
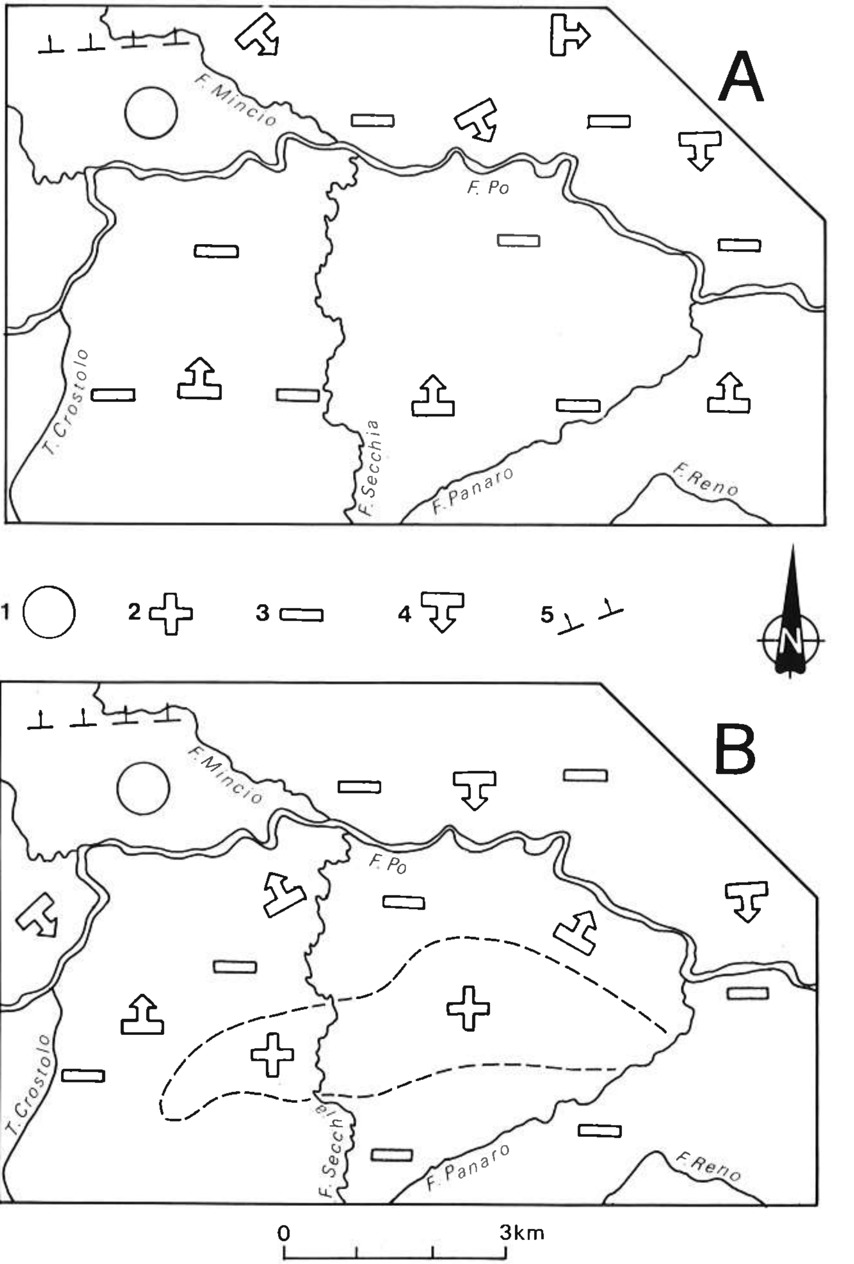
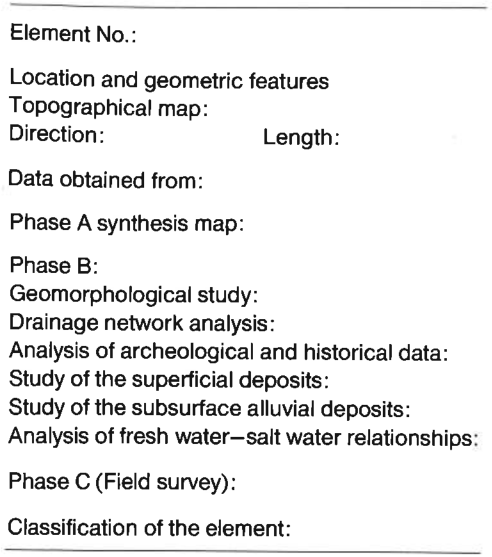


Fig. 25. Example of a map of the fresh-water–salt-water interface (from CASTALDINI et al. 1979). 1) isolines at 100 m intervals; 2) isolines at 50 m intervals; depths refer to sea-level; 3) areas with hydrochemical anomalies.



ig. 26. Example of a final synthetic map for morpho-neotectonic studies in alluvial plains (from PANIZZA et al., in press) A) neotectonic situation around 3000 years B. P.; B) neotectonic situation ttributable to the Iron Age, Roman period and Middle Ages; 1) stable area; 2) area undergoing plift; 3) area undergoing subsidence; 4) differential subsidence (arrow points towards lowest area);) axis of deformation held to be active (arrow points towards area undergoing subsidence).


Element No.:

Location and geometric features
Topographical map:
Direction: Length:

Data obtained from:

Phase A synthesis map:

Phase B:
Geomorphological study:
Drainage network analysis:
Analysis of archeological and historical data:
Study of the superficial deposits:
Study of the subsurface alluvial deposits:
Analysis of fresh water–salt water relationships:

Phase C (Field survey):

Classification of the element:

Fig. 27. Example of a summary sheet for the elements reproduced on the final synthetic map.

Phase D: Final synthesis

The outcome is a final synthetic map, preferably on a small scale. Its compilation should draw on the comparison between the Phase A synthetic map and all the maps prepared in Phase B. The comparison should not be limited to a mere superimposition of the maps which, as specified earlier, must be reproduced on the same scale, but rather, the comparison should be a selective one. To sum up, the tectonic elements held to be active and the lineaments linked to possible tectonic elements (as derived from Phase A) are all influenced by the morphology, the present and past drainage network, and the distribution of superficial and subsurface deposits.

The classification of the tectonic elements and lineaments adopted for the final synthetic map could be the same as that illustrated on page 192, especially for the sake of uniformity of the terminology in studies having the same aims. It must be stated, however, that active tectonic elements will seldom be identified with such certainty as the displacement or deformation of deposits or significant landforms in alluvial plains. On the other hand, tectonic elements held to be active are easier to postulate, as in the case, for example, of structures revealed by oil and gas prospecting which have clearly influenced the evolution of the drainage network and alluvial sedimentation. These structures may be characterised by the presence of seismic epicentres and areas with hydrochemical anomalies.

Elements classified as qualified lineaments may also be extracted from the data obtained in Phase B. If such lineaments are confirmed from bibliographical references, they will become included as tectonic elements held to be active.

In the case of areas for which archaeological and historical stratigraphic data are available, whether they be of a lithological or pedological type, if they enable the principal

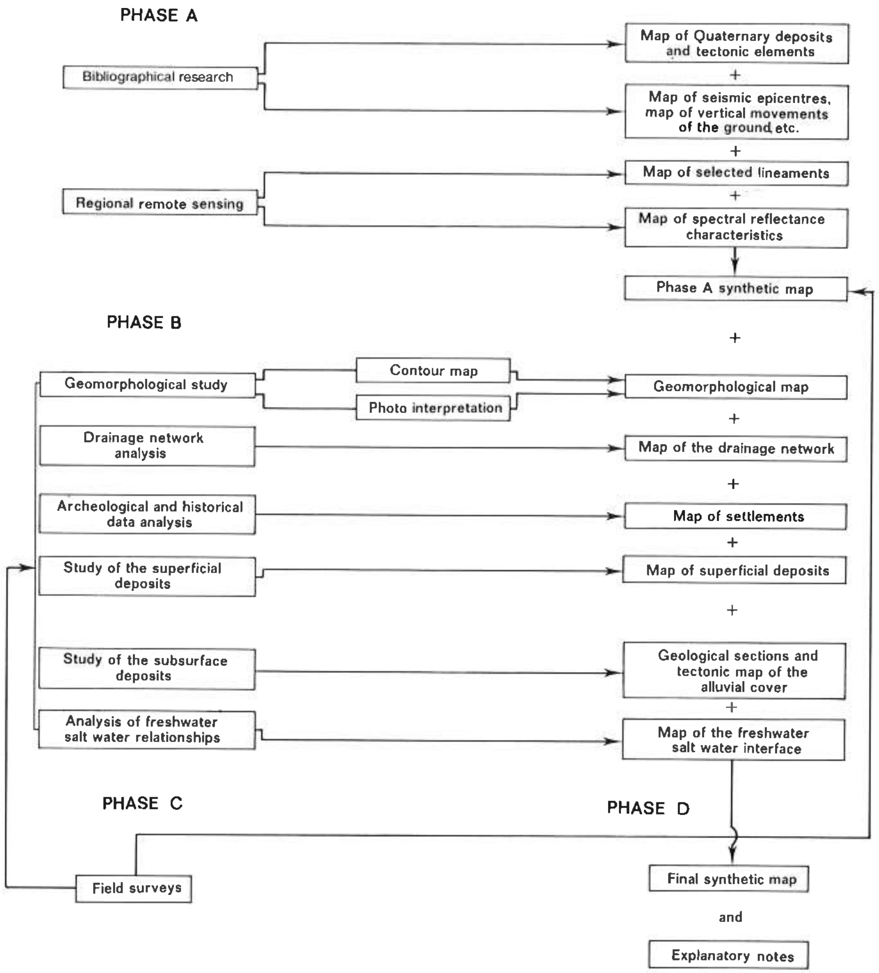


Fig. 28. Summary diagram of morpho-neotectonic studies for major projects in alluvial plains.

stages of evolution of the plain area to be dated with sufficient precision and if the principal events identified are considered to be linked to deep tectonic structures with reasonable certainty, one may then begin to prepare final synthetic maps for various time periods (fig. 26). As in the case of fig. 16, data on areal movements may also be inserted on the final synthetic map. The linear elements represented here, whether they be tectonic structures or lineaments, should be given a final serial number and described on data sheets (fig. 27). The data sheets provide a summary of all the data characterising the elements themselves and their respective classifications. The areal elements (subsidence, uplift, etc.) on the other hand, should be described and justified in the explanatory notes accompanying the study.

In conclusion, the various phases and the investigations for the studies illustrated here have been summarised in the flow chart shown in Fig. 28.

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