COOPERATIVE TECTONIC STUDIES FROM SEISMIC NETWORK IN CENTRAL ITALY

L. Seeber
C. H. Scholz

Lamont-Doherty Geological Observatory of
Columbia University in the City of
New York

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Principal Investigators

L. Seeber
C.H. Scholz

Government Technical Officer

Dr. Jack F. Evernden

The purpose of the subject contract work was to explore the possibility of tectonic research-work based on seismic data from a local network carried out as a cooperative effort between the Instituto Nazionale di Geofisica (ING), Rome, and Columbia University (L-DGO), New York. This effort has been rather successful, and we hope to be able to continue this collaboration in the future.

The work was carried out in the fall (September-November) 1979 and was directed as follows:

1. Establishing new stations for the telemetered seismic network in central Italy;
2. Analysis of the seismic network data from the September 29, 1979 Norcia earthquake and morphotectonic analysis of the area of this earthquake from field observations and satellite imagery;
3. Getting familiar with the literature concerning the recent tectonic history of the Apennine arc.

In this report I outline first a number of fundamental features of the Apennine arc which suggest that the presently active structure is uniform along the arc although the tectonic history of different sections of the arc are probably distinct. I then compare the Apennine and the Himalayan arcs. These two structures are different in scale but exhibit some important similarities, particularly in reference to the seismic behavior.

Some of the preliminary results obtained from the seismic network data and from the morphotectonic overview of the September 19, 1979 Norcia earthquake are discussed in terms of the broader tectonic framework I propose. Finally, I discuss the status and expected development of the seismic network in central Italy.

Tectonic Framework

The tectonic phases that effected the Mediterranean region during the Cenozoic are the expression of the interaction between the Eurasian and the African plates (e.g. Pitman and Talwani, 1972). The complexity of the structures associated with Cenozoic tectonism in the Afro-Eurasian plate boundary is usually ascribed to repeated changes in the relative velocities between these plates, and to the role played by the small and heavily sedimented oceanic portion of these plates along the boundary (e.g. Gorler and Giese, 1978).

The Appennine orogen comprises a prominent portion of the presently active Afro-Eurasian plate boundary. Most workers include in this structural unit the portion of the boundary from the western Alps to, and including, Sicily (e.g. Giese and Reutter, 1978). In this case the Appennine arc is about 1200 km long, bends through about 180° and links the active boundary along the southern margin of the western Mediterranean to the active boundary on the northern side of the eastern Mediterranean and the Balkans (Figure 1). The foreland on the convex side of the arc is the Adriatic promontory of the African plate (Channel and Horvath, 1976); the hinterland on the concave side of the arc is the western Mediterranean, presently part of the European plate.

Along the Appennine arc both hinterland and foreland contain portions of oceanic as well as continental crust. On the foreland side the Adriatic promontary (Channel and Horvath, 1976) is primarily continental (Apulian and Iblean blocks; Figure 1). A small portion of relatively old oceanic crust acts as Appennine foreland between these blocks (Western Ionian basin, probably Mesozoic; Gorler and Giese, 1978). On the hinterland side the western Mediterranean is primarily underlain by young oceanic crust (Tirrenian and Ligurian basin, Upper Miocene; Hamelin et al., 1979; Alvarez, 1972). A small portion of continental crust acts as

Appennine hinterland between these basins (Corso-Tuscan block; Figure 1; Reutter et al., 1979).

The Appennine arc is composed of a number of contiguous segments. Most of the distinctive features of each of these segments may be associated with particular lithospheric types interacting at the plate boundary. In some segments the distinctive features are so prominent that some workers hesitate to consider these segments part of the same structure (e.g. Ogniben et al., 1975). However, there is increasing evidence that the fundamental features of the plate margin, particularly those features that pertain to the present tectonic regime, are rather uniform along the entire Appennine arc as defined above.

The Appennine orogen is prominently asymmetric, and this characteristic is quite uniform along the arc. On the foreland side the basement dips toward the hinterland below the axis of the belt, forming a sedimentary trough (Pietri, 1975; Giese and Ruetter, 1978; Pietri and Groppi, 1975; Finetti and Morelli, 1972; Figure 2). Thrusts and folds in the clastic sediments of the trough (Upper Miocene and younger) as well as thrust sheets with older platform and deep water sediments verge toward the foreland. As in other fold and thrust belts, the deformation is syn-depositional, and migrates progressively towards the foreland (Kligfield, 1979).

The hinterland side of the Appennines is characterized by two prominent phases of deformation: a compressional phase with the same (eastward) vergence as the outer fold and thrust belt, and a subsequent phase where tension across the Appennine trend has replaced the former compression (e.g. Elter, 1975; Figure 3). This change in the stress field on the inner (western) side of the Appennine arc is a recent, and probably time transgressive event, earlier along the Tirrenian coast (Messinian) and later along the outer (eastern) margin of this zone (Quaternary) (Dallan Nardi and Nardi, 1975).

This late tensional phase and the related horst and graben tectonics is accompanied by volcanism. An early volcanic event (Upper Miocene-Pliocene) occurs in the short inner portion of the arc bounded by continental foreland (Corso-Tuscan block). These volcanics are rhyolitic and follow the west-to-east migration of the extension structures (Alvarez, 1972; Figure 3). A later (Quaternary) volcanic event, predominantly alkalic, extends (with some overlap in time and space) from the previous volcanic zone southeastward along the Tirrenian coast. The Neapolitan volcanoes (Versuvins) are the most southeasterly members of this zone and the only ones still active (Lacardi et al., 1975).

The horst and graben tectonics and the alkalic volcanism are typical of extensional rift basins (ensialic basins; Boccaletti and Guazzone, 1974). A classical example of this type of basin is the Basin and Range province in North America (Scholz et al., 1971). However, the earlier rhyolitic volcanic phase is not expected in such a structure. In general, the precise geochemical and tectonic connotation of this recent volcanism in the foreland of the Appennine arc is still controversial.

The paleomagnetic data for the Adriatic foreland supports the concept of an Adriatic promontory which follows closely the movements of the African plate (Channel, 1977). Poles older than Upper Tertiary from Sardinia and Corsica have rotated CCW with respect to Europe (Soffel, 1978) concurrently with the rifting of these blocks away from Southern Europe (Alvarez, 1972). The poles from the outer fold and thrust belt and from the basement of the inner horst and graben belt (presumably autochthonous; see above) tend to agree with African poles, although effects of Appennine deformation are detected (Channel et al., 1978). Alternatively, the poles from the central Appennine can be interpreted as Eurasian poles rotated CCW concurrently with the poles in Corsica and Sardinia (Gorler and Giese, 1978; Figure 4).

The tectonic axis of the Appennines separating the extensional inner side from the compressional outer side also correspond with the transition from low to high Bouguer gravity (Elter, 1975) and from high to low heat flow, respectively. The Bouguer gravity is shown in Figure 5. In a set of profiles the gravity is compared to topography. The minimum in Bouguer gravity is systematically shifted toward the foreland with respect to the topographic high. This systematic offset between topography and Bouguer gravity indicates lack of isostatic compensation in a way that is typical of active subduction zones.

The distribution of heat flow is shown in Figure 6. The molasse filled trough on the foreland side of the Appennine is associated with a pronounced low in the heat flow. No such low in the heat flow is found along the Helvetic molasse trough on the northern side of the Alps. This suggests that the Appennine is an active subduction zone, while the Alps is not active. Loddo and Mongelli (1978) interpret the heat flow pattern in the Italian region as resulting from two active arcs: a "continental" arc in the northern Appennines, and an oceanic arc in the southern Appennines.

Deep seismic refraction data for the Appennines, has contributed greatly to the tectonic understanding of this arc. In the southern Appennines the profiles indicate subduction of the Adriatic, Ionian and Iblean foreland below the Tirrenian hinterland. In Gorler and Giese (1978) interpretation the sinking oceanic lithosphere is continuous along Calabria. Further north where the arc has collided with the Auplian continental lithosphere the oceanic lithosphere is detached (Figure 7). The recent deep (476 km) earthquake along the Tirrenian coast of Italy between Rome and Naples (41°N), where otherwise there is no evidence of a Benioff zone, may support this hypothesis (Figure 10).

Deep seismic refraction data for the northern Appennines is more difficult to interpret. This data indicates northeast subduction of the Corsica continental crust below Tuscany (Figure 8) in apparent contradiction to the southwest subduction along the Appennine arc. Reutter et al. (1979) suggest a split of the Adriatic continental lithosphere whereby the lower lithospere sinks to the southwest while the crust remains at the surface and overrides the Corsican lithosphere. The model proposed by Reutter et al. for the northern Appennines is very reminiscent of the model prepared by Bird (1978) for the Himalaya. An alternative interpretation of the refraction data, which we wish to explore is that the northeasterly dip of the Corsican crust below Tuscany is part of the Alpine subduction zone, now fossil. This would imply that the collision between Toscany and Corsica (Kligfield, 1979) predates the opening of the Ligurian sea and the Appennine orogen. This interpretation is in agreement with paleomagnetic data (Figures 4 and 9).

In conclusion, the hypothesis that seems to fit best the available data for the Appennines is that of a marginal basin-arc-trench system advancing onto the Adriatic promontory (Boccaletti and Guazzone, 1972). Where the Adriatic plate (Africa) is oceanic, along the Calabrian arc, this plate is being consumed under the spreading Tirrenian basin. Along the rest of the arc where the Adriatic and Iblean foreland are continental, the Appenninees are an arc-continent collisional orogen (Figure 9).

In general, the complexity of the structures and inhomogeneities along strike may be related more to different prior histories among the various units involved in this collision than to differences in the tectonic regime along the arc. Thus, the most fundamental tectonic element is the overthrusting of the Appennine onto the Adriatic foreland forming an active shallow-dipping thrust (detachment) that dips down toward the hinterland and is continuous along the arc. The seismic potential of this fault and the implication for earthquake hazard are discussed in the next section.

Seismicity Along the Apennines

Any epicentral data set for the Italian region will probably show a prominent broad active belt along the Appennine arc (e.g. Caputo and Postpischl, 1975). However, when we try to focus-in closer for some insight into the active structures that underlie the Appennines, the picture gets very complex and diffuse. Similarly, the pattern of focal mechanisms is rather complicated although a tendency for the p-axis to prefer a direction perpendicular to the Appennine trends can be statistically recognized (Cagnetti et al., 1978).

We see at least two reasons for these complex patterns presented by the earthquake data. First a sizable portion of the available data are of poor quality and introduce noise. Secondly, the Appennine orogen is probably typified by different tectonic regimes active at different depths and by horizontal decoupling layers (see later discussion of the Norcia 19/9/79 event). Clearly, a simple map view of such a layered tectonic environment can only be confusing. Sectional views of well determined hypocentral data are required to study this kind of structure using earthquake data. In northern Pakistan, where we are monitoring with a seismic network the active fold and thrust belt of the Himalaya, we find a layered tectonic system (Seeber and Armbruster, 1979). In conclusion, it has not been possible to resolve the fundamental from the secondary active structures in the Appennines using the seismic data, and this data has not been an important constraint to any tectonic model of the Appennines, as yet.

Figures 10 and 11 are the latest seismicity maps produced by the ING. These maps cover only the last 1.5 years of data, and they may not be representative of the long term seismicity, however, they probably comprise the most accurate set of hypocentral data for the Italian region. Recent improvements in the station coverage, the timing accuracy, the analytical procedures, and the selection criteria have all contributed to a recent rapid improvement of the quality of the hypocenters determined by the ING from the National Network.

The subcrustal seismicity that extends northwest from Calabria has since long been recognized as a Benioff zone dipping in this direction (Ritsema, 1969; McKenzie, 1972). The 476 km deep event at 41°N seems to extend this zone further down and to the northwest than previously estimated. However, the obvious anomaly in the hypocentral depth-distribution that corresponds with the Benioff zone is not the only recognizable pattern in the deep crustal or subcrustal seismicity along the Appennine arc (hypocentral depths greater than 33 km are indicated in Figures 10 and 11). The east-west trending seismic zone north of Sicily contains subcrustal hypocenters but no hypocenters below 100 km. From Calabria north to the Anzio-Ancoma line (AA' in Figure 10) the recent seismicity seems to occur exclusively at crustal depths. North of the AA' line we can recognize a northwest trending belt of possibly subcrustal hypocenters that approximately follows the outer limit of the Appennines toward the Foreland. The southeastern terminus of this feature seem to correspond with the Anzio-Ancoma (AA') line. For this feature, which has not been previously recognized, we cannot offer even a tentative interpretation.

In the recent compilation of fault plane solutions by Gasparini et al. (1979; Figure 14) we tentatively recognize 3 families of solutions: (1) right-lateral strike-slip on faults subparallel to Appennine trends. Of the conjugate fault planes we choose the one striking northwest because generally it corresponds to the strike of the most prominent lineaments and it also in some cases to prominent epicenter alignments (Eva et al., 1978) this set includes the two largest earthquakes in central Italy that occurred in this century one of which is the very destructive Avezzano earthquake of 1915 (marked by A in Figure 14); (2) primarily normal faults, but also strike slip earthquakes, with T axis parallel to the strike of the

Appennines. This kind of solution is predominant in the northern part of the central Appennines. The September 19, 1979 event is in this category (N in Figure 14); (3) thrust fault earthquakes. This kind of solution is found in the extreme northern and southern portion of the Appennine arc. Four of the seven thrust solutions compiled by Gasparini et al. can be interpreted as shallow dipping thrusts consistent with the underthrusting of the foreland below the Appennines. In our hypothesis, the heterogeneity in the stress field implied by the intermixing of the different fault plane solutions pertains to the entire seismically active layer. However, each of the families of solutions may apply to a restricted depth range, and within each of these layers the stress field may be rather well behaved.

The families of solutions 2 and 3 suggest some interesting comparison with the Himalayan tectonics. Normal faulting with T axis perpendicular to the underthrusting direction (solution 2) is the typical mechanism in the Tibetan Plateau, north of the Himalaya basement thrust (Molnar and Tapponnier, 1978). In both the Himalaya and the Appennines this normal faulting extends very close to where the thrust is recognized at the surface, and in both cases we can infer that this thrust extends down dip below or above this extensional tectonic environment. In the Appennines we know that the extensional environment of solution 2 is rather shallow (see below) and that the thrust must extend below this environment. This suggests that the active normal faults are listric.

We would expect the family of solutions with shallow-angle thrusting (family 3) to be well populated considering the prominent evidence of active overthrusting of the Appennines onto the Adriatic foreland (see above). A comparison with the Himalaya suggests a possible reason for the prominent absence of shallow angle thrust solution in the Appennines.

Most of the seismic energy in the Himalaya is released in relatively rare and very large, shallow-angle thrust earthquakes. These are the great Himalayan detachment earthquakes typically with magnitudes $\geq$ 8 (Seeber et al., 1980). During the relatively long interseismic periods between these great earthquakes the detachment fault is not active and smaller and frequent shallow angle thrust earthquakes are not detected. Similarly, in the Appennines the prominent absence of shallow-angle seismicity may be interpreted as interseismic quiescence on the Appennine detachment between rare but great events (Figure 3). It is also possible that slip on the Appennine detachment is accomodated by aseismic creep rather than by large infrequent earthquakes. (The western portion of the Himalayan detachment is associated with a thick evaporite layer and may be in an aseismic slip mode; Seeber et al., 1980).

Several of the larger earthquakes in the Italian historic record (e.g. Baratta, 1900) may well be great detachment earthquakes. Some examples are shown in Figure 15. Prominent surface rupture which may be associated with the causitive faults are not reported for any of these events. This is strongly suggestive of shallow-angle faulting in view of the large area of rupture which must be associated with these earthquakes.

In conclusion, great detachment earthquakes are expected to play a key role in the seismic hazard along the Appennine. The portions of the detachment where slip occur by these great earthquakes and portions where slip occurs aseismically should be seeked out. Recurrence rates for these great events should also be explored. Earthquake prediction in Italy will have a much better chance of success when these major questions regarding the tectonic environment and the seismic hazard are better understood.

The September 19, 1979 Norcia Earthquake

On September 19, 1979, while L. Seeber was in Italy working on some of the technical aspects of the work related to this project, an intermediate-magnitude event (M = 5.2) occurred near Norcia, slightly northwest of the Anzio-Ancona (A'A in Figure 10) lineament. This area had been already designated of primary interest in this project. Consequently, most of the effort in this project, technical as well as analytical and interpretive, has been concentrated on this event.

A consortium of various research institutes, the ING among them, acting within the scope of the Progetto Finalizzato Geodinamica (CNR), have decided to pool resources and cooperate to produce a single document summarizing all the observations and preliminary results concerning the September 19, 1979 Norcia event. This paper should be completed by March 1980. Some of the preliminary results are listed below:

1. The fault plate solution of the main event has a primary component of normal faulting with a NE strike (Figure 17). The fault solution is similar to several other fault solutions available for the Appennines of central Italy (Figure 14; Gasparini et al., 1979).
2. The distribution of the aftershocks (about 100 hypocenters are plotted in Figure 17) is consistent with a NE striking rupture. The depth distribution (not visible in Figure 2) suggest a northwesterly dip. The main shock is located in the upper crust (h = 8 km, USGS; h = 7 km, ING). Most of the aftershocks are located between h = 5 km and h = 15 km. Two secondary alignments of the epicenters strikes NW. One of these is along a very prominent fault system with evidnece of recent movement.
3. The distribution of seismicity prior to the September 19 earthquake is dependent in space and time with the 9/19/79 event (Figures 12 and 13). The seismicity up to June 1979 (up to 2 1/2 months prior to the event) clearly suggest the formation of a "doughnut".

4. The station MNS is a reliable high-gain station operative since 1978 and located at about 40 km from the epicentral area of the September 19 event. The data from this station has been fully analyzed to provide statistical control on the 1979 seismic period in southern Umbria. This analysis suggests:

   a. at least 3 distinct seismic sources. This is consistent with the preliminary aftershock map in Figure 17;

   b. the b-value increases significantly from the foreshocks to the aftershocks. Also a decrease in b-values is detected from the beginning to the later part of the aftershock sequence;

   c. the seismicity in the general area of the 9/19/79 event (4 sec $\leq$ S-P at MNS $\leq$ 10 sec) is quite high in August and the first week of September (average of 1 earthquake with M $\geq$ 2 every 2 days). This activity is probably higher than the background seismicity in this area. Two weeks before the event the rate of seismic energy released decreases markedly although the rate of earthquake occurrences changes little. A swarm of 13 events characterized by low magnitude (M < 2.3) occurs between 4 to 1 days before the main shock. No earthquakes are detected at 18 hours before the main shock (Figure 18).

The above preliminary results suggest that a very interesting space-time-magnitude distribution of seismicity can be decifered from the existing data for the 9/19/79 event.

Technical Work

The configuration of the National Network operated by the ING prior to the work discussed here (January 1979) is shown in Figure 20. Most of the seismic stations consist of a 1 Hz vertical geophone (S-13) recorded at 60 mm/min on heat-sensitive paper (helicorder). In central Italy AQU (also the site of a WWSSN station) and DU1 are telemetered by telephone and MNS is telemetered by radio to the central recording station at RMP. Similar small networks of telemetered stations are being developed in other areas of Italy as in the eastern Alpine region (Friuli) and in the Messina strait area.

From September to November (3 months), 1979, six new telemetered seismic stations were installed in southern Umbria near the border with Lazio about 100 km north of Rome (Figure 20). Of these, AML, POL, and SER are permanent additions to the National Network and are telemetered to RMP via radio. The other 3 stations have been operated for about one month, approximately from September 23 to October 20, as part of an 11 station temporary network deployed to record the aftershocks of the September 19, 1979 Norcia earthquake (Figure 17). The three temporary stations operated by the ING were telemetered to a truck-borne recording system (helicorders). The other eight stations were telemetered to two portable tape recording systems and were operated by other collaborating research institutes.

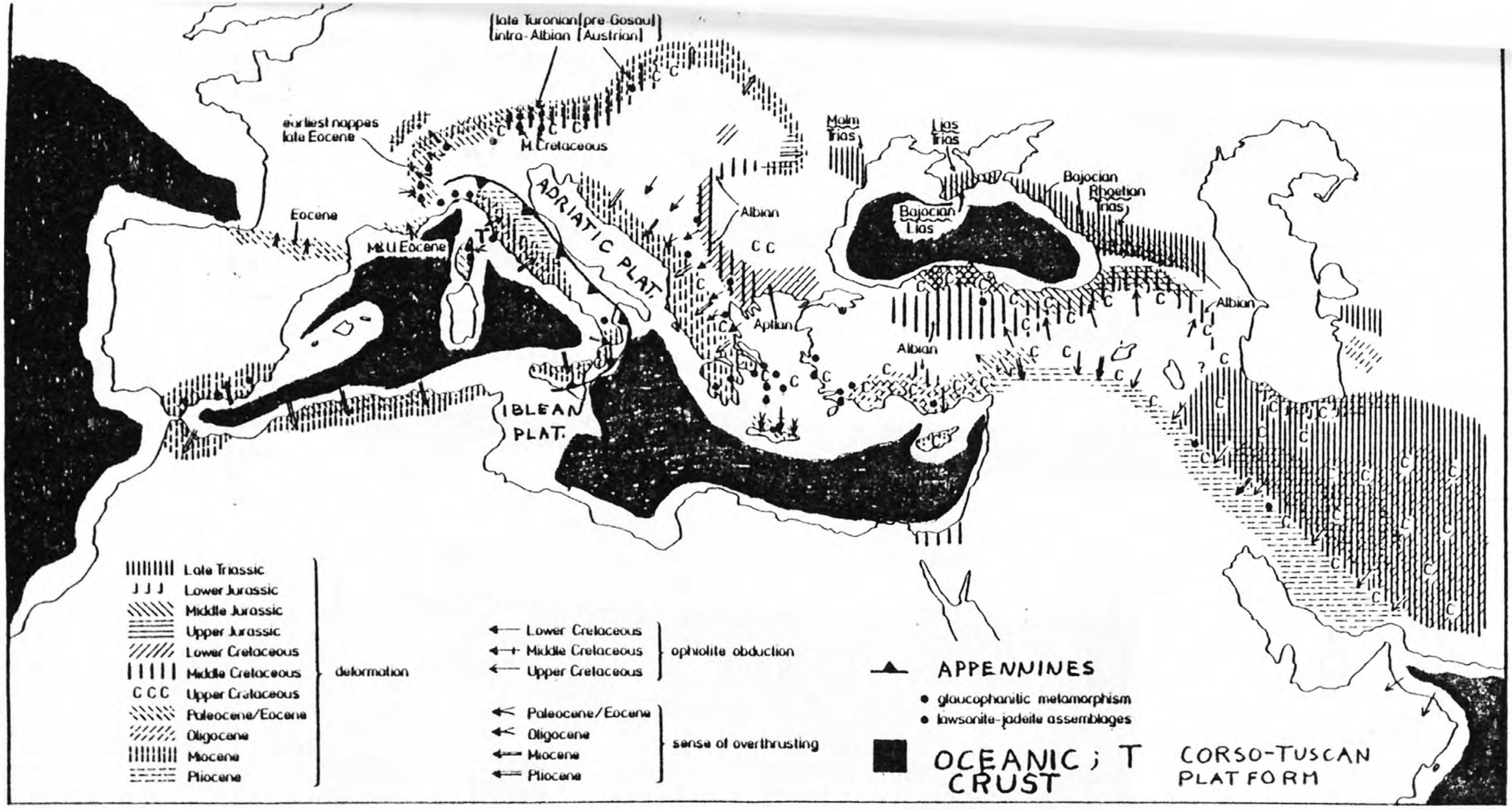


Figure 1. Orogenic belts of the Alpine system along the Africa-Eurasia plate boundary (Modified from Dewey and others, 1973).

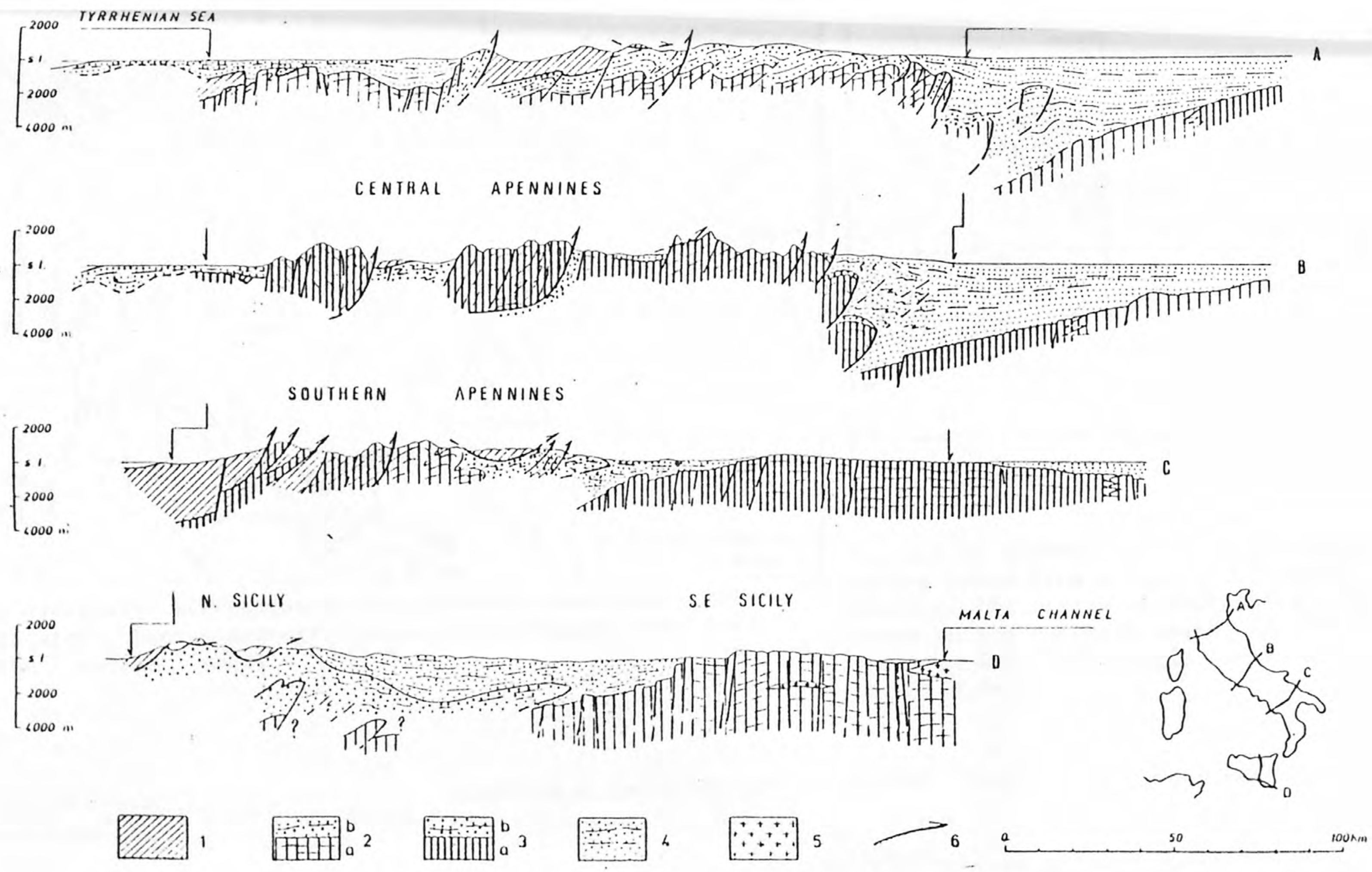
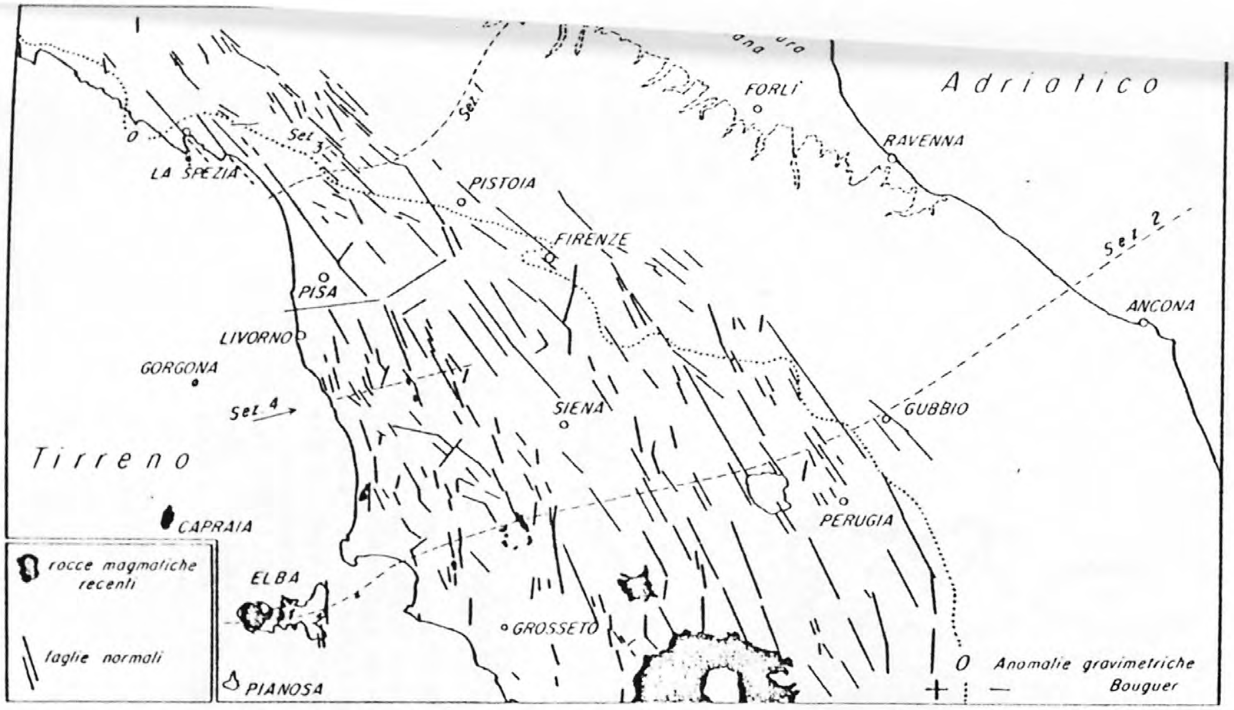
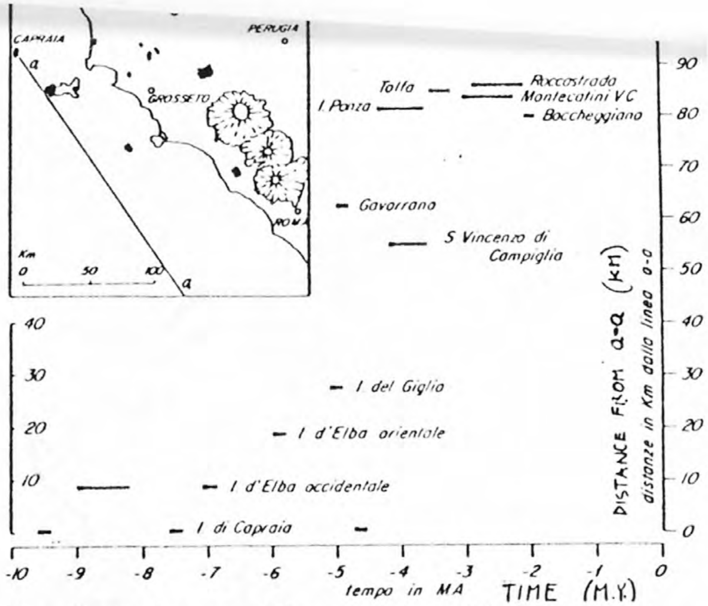


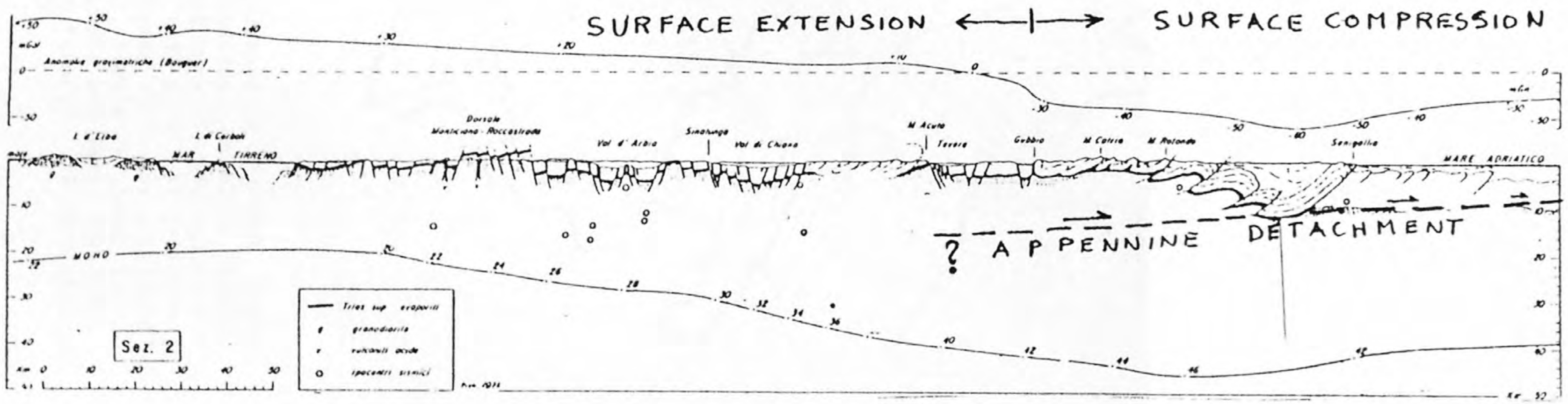
Figure 2. Schematic geological cross-sections through the Italian Peninsula and Sicily. 1, eugeosynclinal allochthonous units; 2a, miogeosynclinal "furrow" carbonatic section (Mesozoic to Tertiary); 2b, miogeosynclinal flysch section (Tertiary); 3a, miogeosynclinal "Gavrovo type ridge" carbonatic section (Mesozoic to Tertiary; 3b, miogeosynclinal flysch section (Tertiary); 4, postgeosynclinal clastic section; 5, volcanics; 6, main overthrust surfaces (from Pietri, 1975).



A. Sketch map of the distensive structures in the northern Apennines. Only normal faults are indicated. Recent magmatic rocks in full black. The dotted line represents the 0 Bouguer isogal.



B. Age of magmatic events. Distances in km are taken from a line a–a, running parallel to the strike of distensive structures in the northern Apennines. In the location map the magmatic bodies are indicated in full black.



C - Geological section across the Apennines from Elba to the Adriatic Sea (section 2 in A) Evaporites overlying the pre-triassic basement are in full black. In the western part of the section, allochthonous units are indicated only in eastern Elba. maximum difference in height of the pre-triassic basement between the Tyrrhenian slope and the Adriatic sea can reach more than 10 km. As in section 1 the light crust is thinned under the tyrrhenian slope of the Apennines, thickened at its eastern margin.

Figure 3. A), B), C) from Elter et al., 1975. Plio-Pleistocene block-faulting in the Apennines. The boundary between extensional and compressional tectonics seems to correspond to a steep gradient in the Bouguer gravity anomaly.

Fig. 4. Generalized summary of palaeomagnetic data from the Alps, Italy, Sardinia, Corsica, Sicily and Greece. Arrows indicate direction (declination only) of remanence of rocks of different ages. Directions of remanence computed for a place in Central Italy (13° E, 42° N) from the European and African polar wander paths (McElhinny 1973) are presented separately for comparison. T_u, T_m, T_l = Upper, Middle and Lower Tertiary respectively. K, K_m, K_u = Cretaceous, Middle and Upper Cretaceous respectively. J = Jurassic. Tr = Triassic. P = Permian. C = Carboniferous. ? = preliminary result. (From Soffel, 1978).

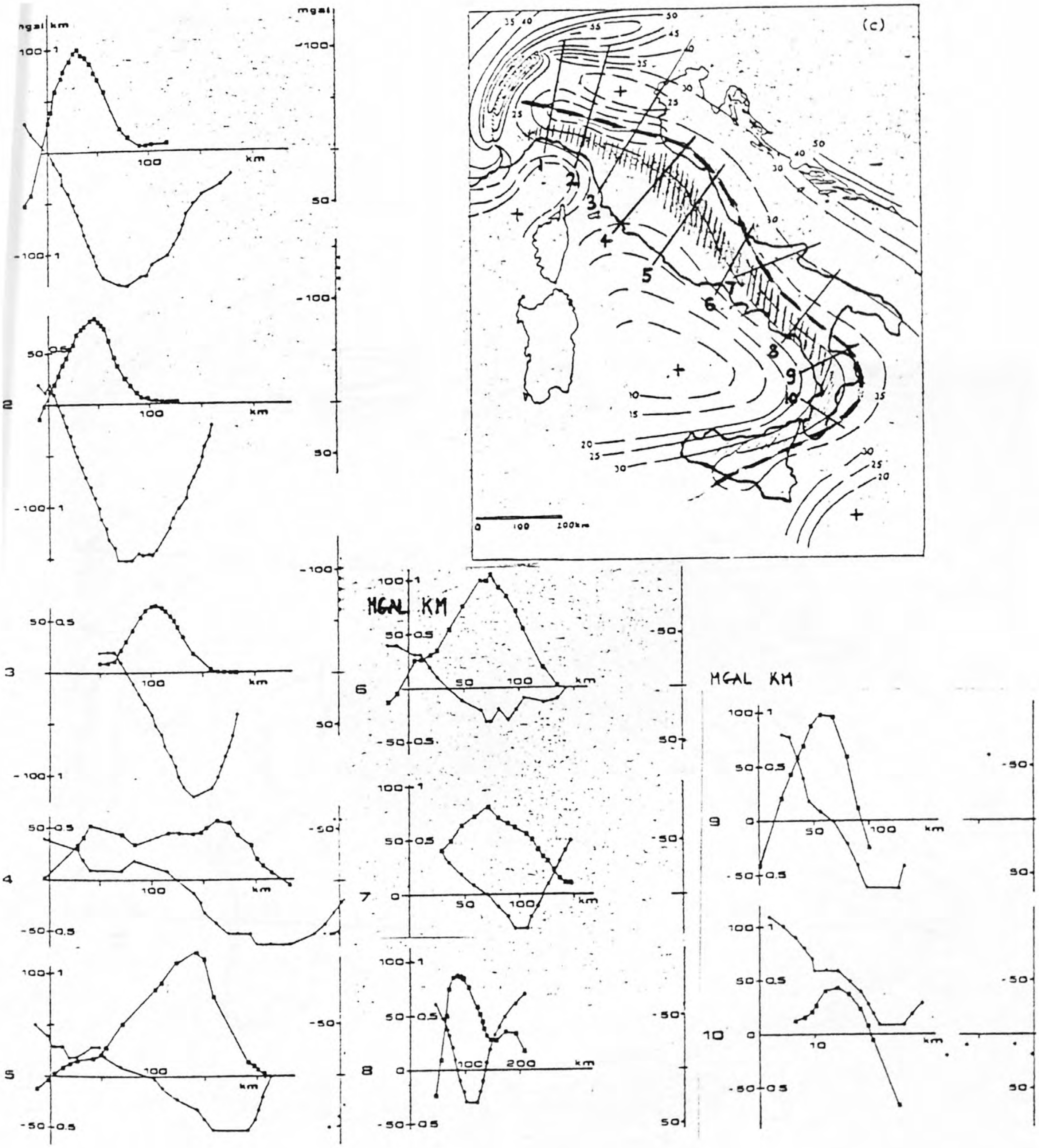


Figure 5. Topography and Bouguer gravity anomaly in a series of sections across the Apennine arc (from Mongelli et al., 1975). The axis of the gravity anomaly (heavy dashed line) is consistently displaced toward the outer part of the arc from the zone of high relief (hatched). The contours give the depth of the Moho in km determined from seismic and gravity data (Giese and Morelli, 1975).

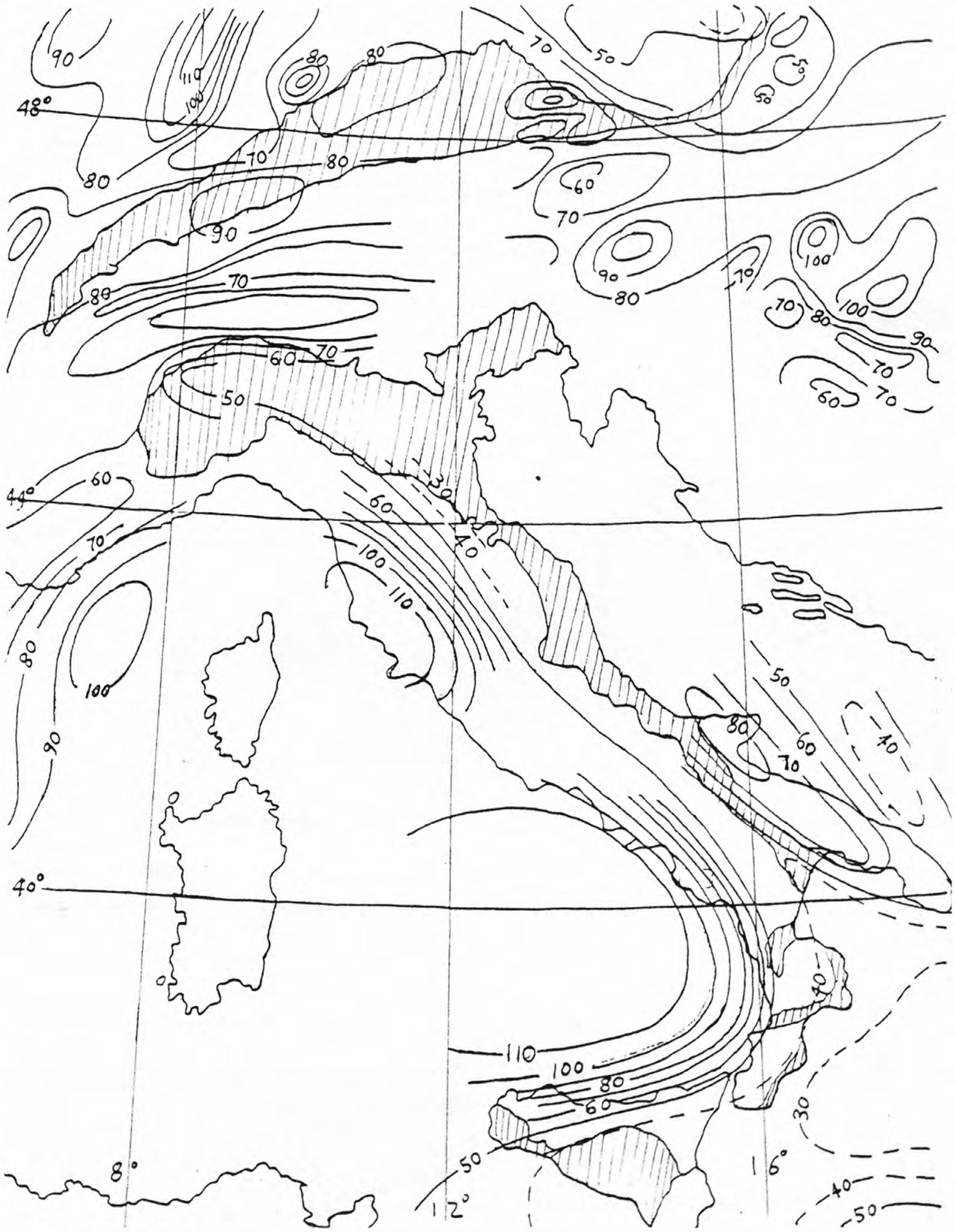
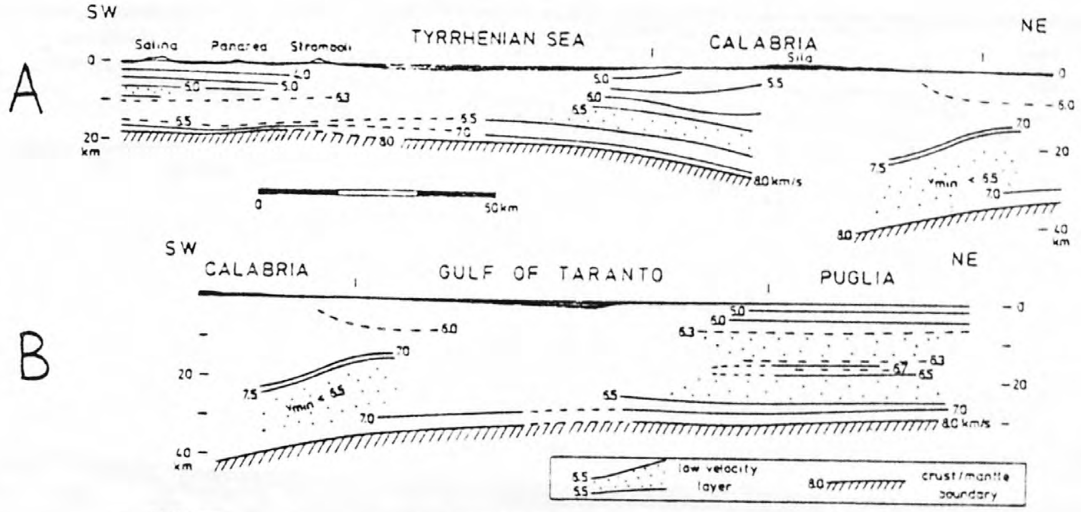
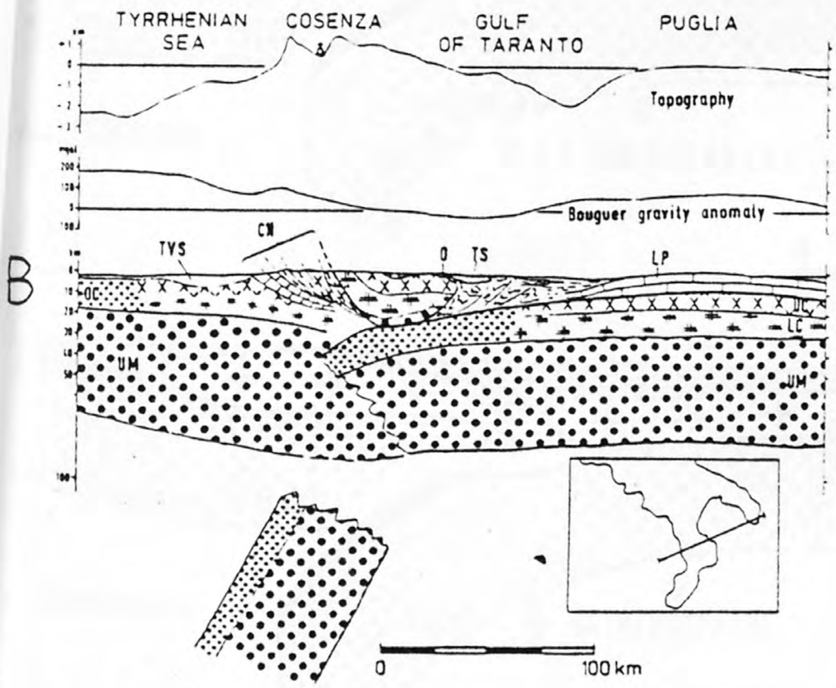
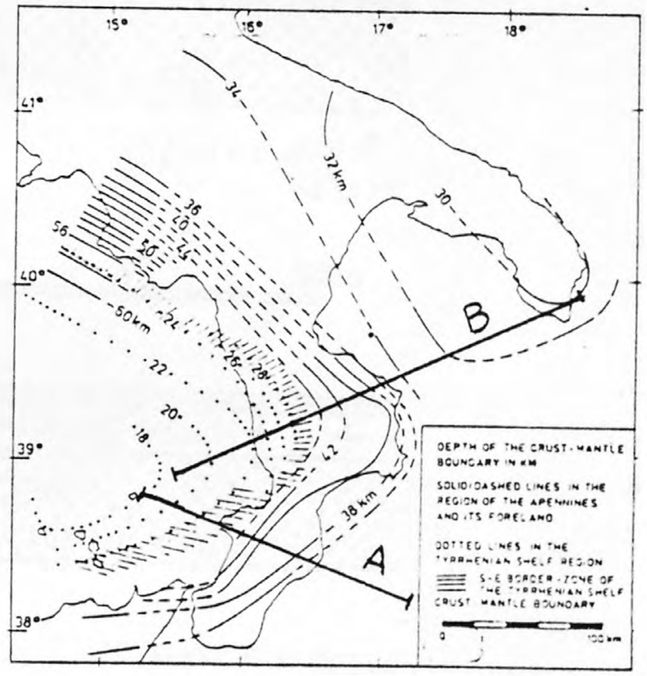
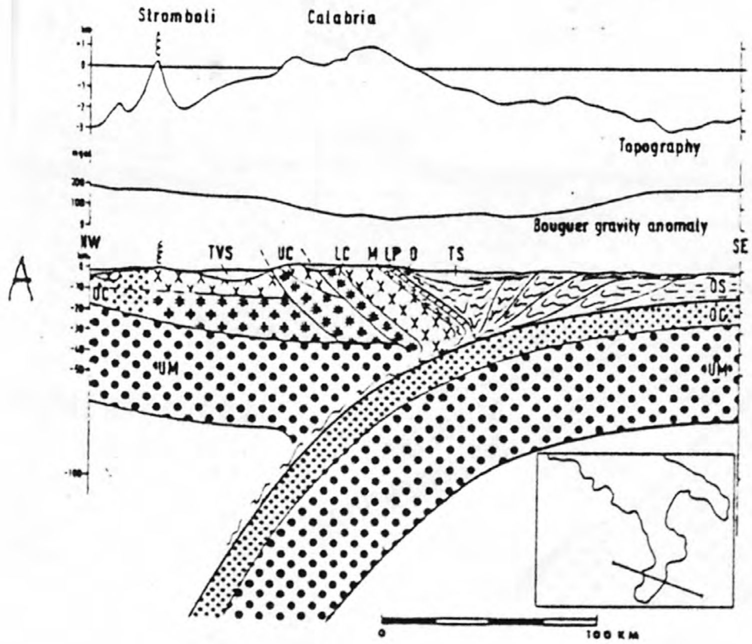


Figure 6. Heat flow in the Italian region (10 MW/in^2) from a compilation by Cermak et al. (1976). Equiflow lines for flow less than 500 MW/in^2 are dashed. Upper Cenozoic molasse basins are hatched. Note the correspondence between low heat flow and the Appennine flredeep. No such correspondence is detected in the now inactive foredeep on the northern side of the Alps.









Schematic crustal sections through Northern and Southern Calabria. UM - upper mantle, OC - oceanic crust, OS - oceanic sediments, LC - lower continental crust, UC - upper continental crust, LP - limestone platform, TS - terrigenous sediments, O - olistostromes, TVS - terrigenous sediments with volcanic components, CN - nappes of northwestern Calabria, M - metamorphites, arrows indicate the mudflow directions.

Figure 7. The refraction results are from Schutte (1978). The interpretation is from Gorler and Giese (1978).

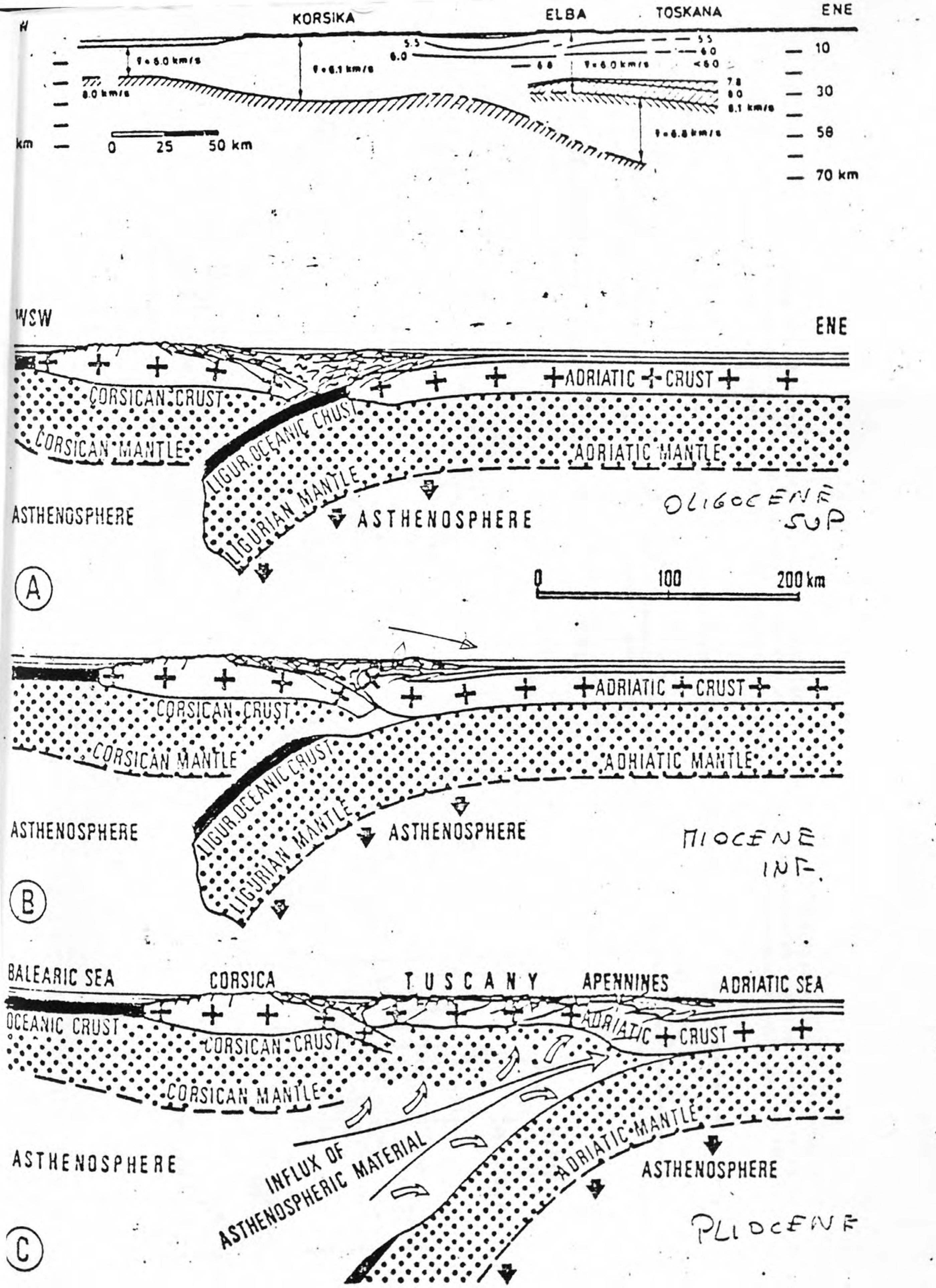


Figure 8. A speculative sequence of tectonic events that led to the structure of the crust between Corsica and the Appennines. (From Reutter et al., 1980).

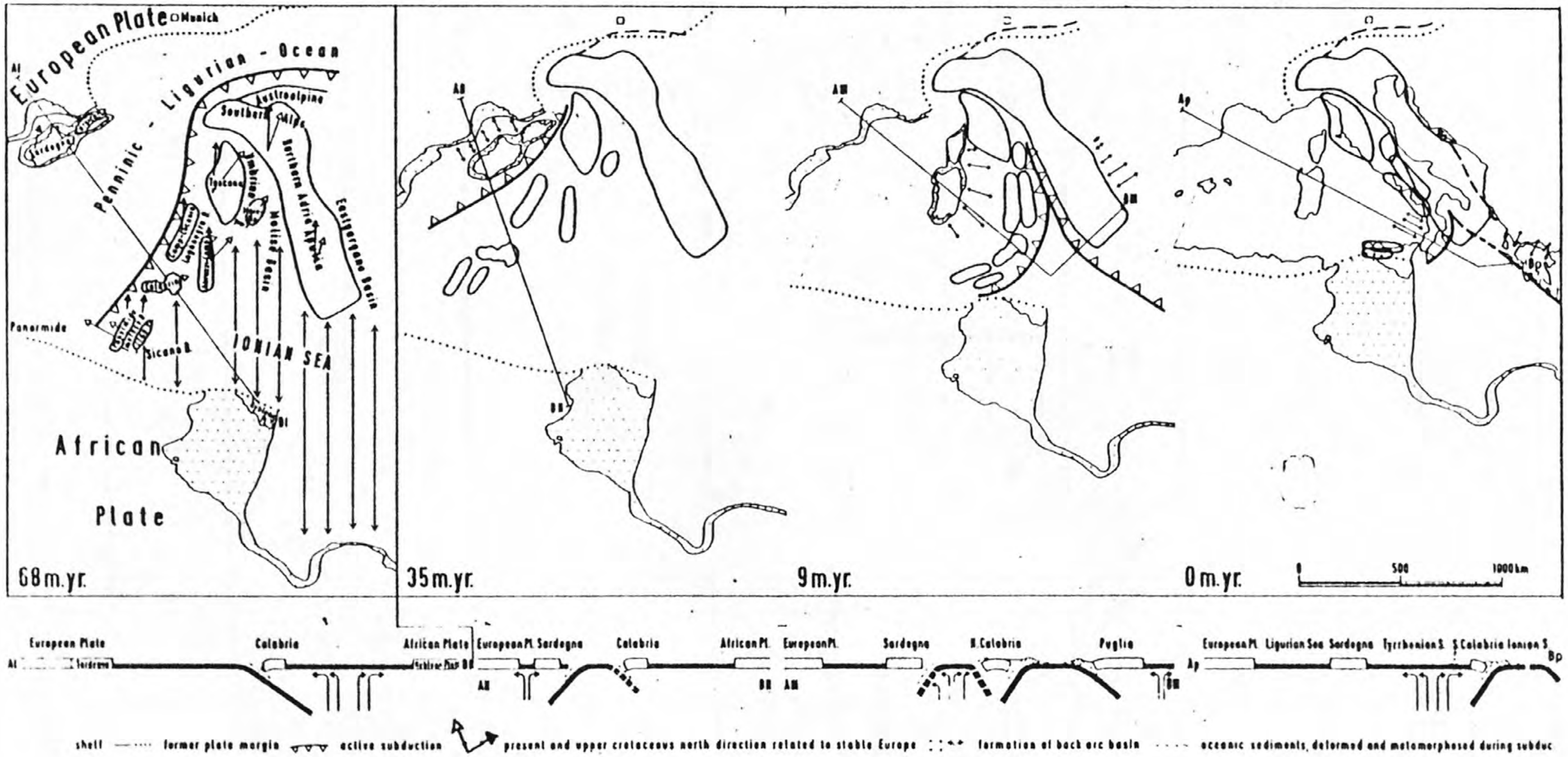


Fig. 9. Tentative reconstruction of the geodynamic evolution of the central Mediterranean region from Upper Cretaceous to present. Based on published models for the Africa displacement with respect to Europe (Pitman & Talwani 1972; Kristoffersen 1977; Bijų Duval et al. 1977) and the available paleomagnetic data (s. text).

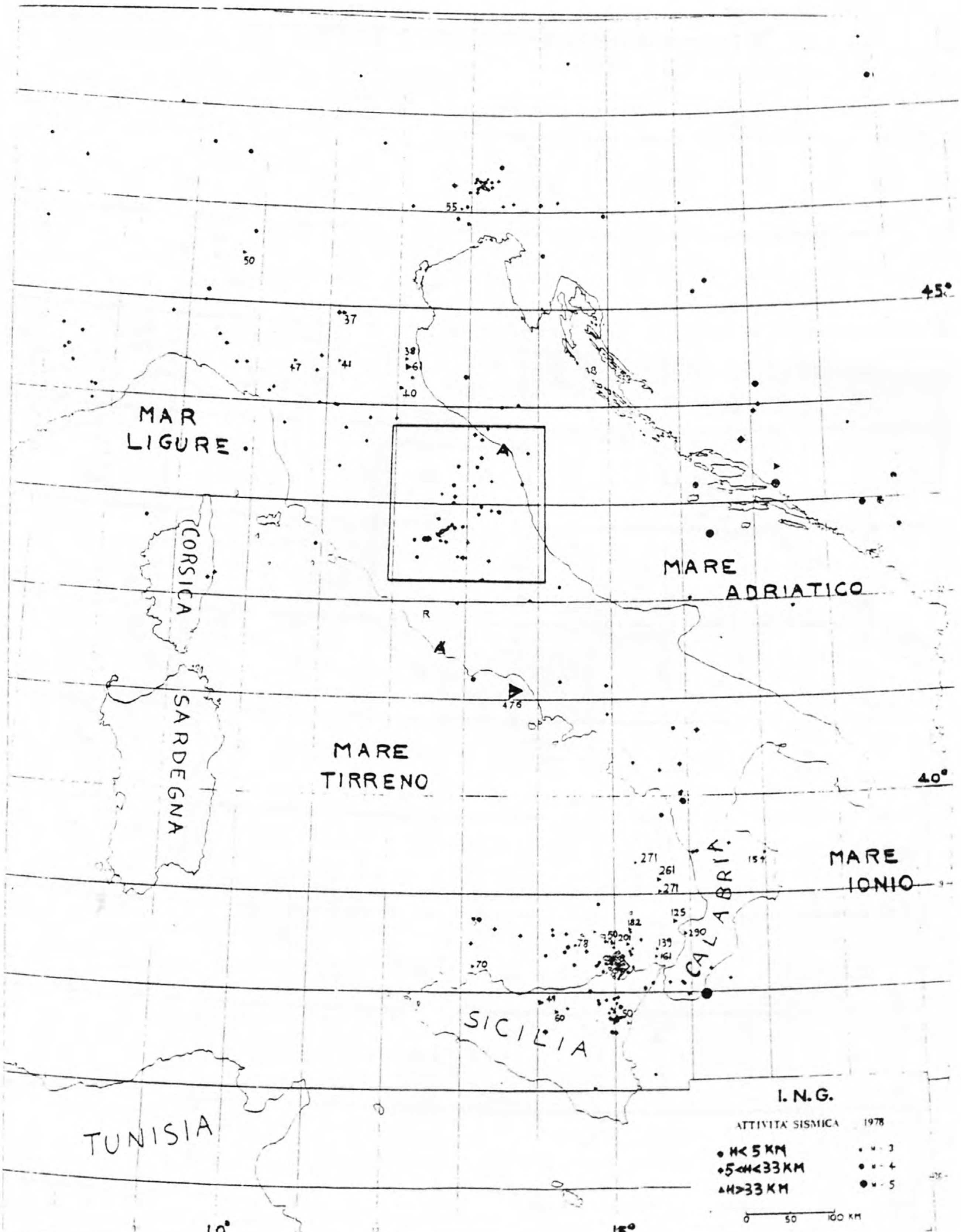


Figure 10. Hypocenters during 1978 determined by the ING from the National Network data. The box refer to Figure 12. The depth in km for hypocenters deeper than 33 km is indicated. Note the concentration of seismicity near the Anzio-Ancona (A'-A) line which may be a long term precursor of the Norcia 19/9/79, M = 5.2 earthquake (near the center of the box).

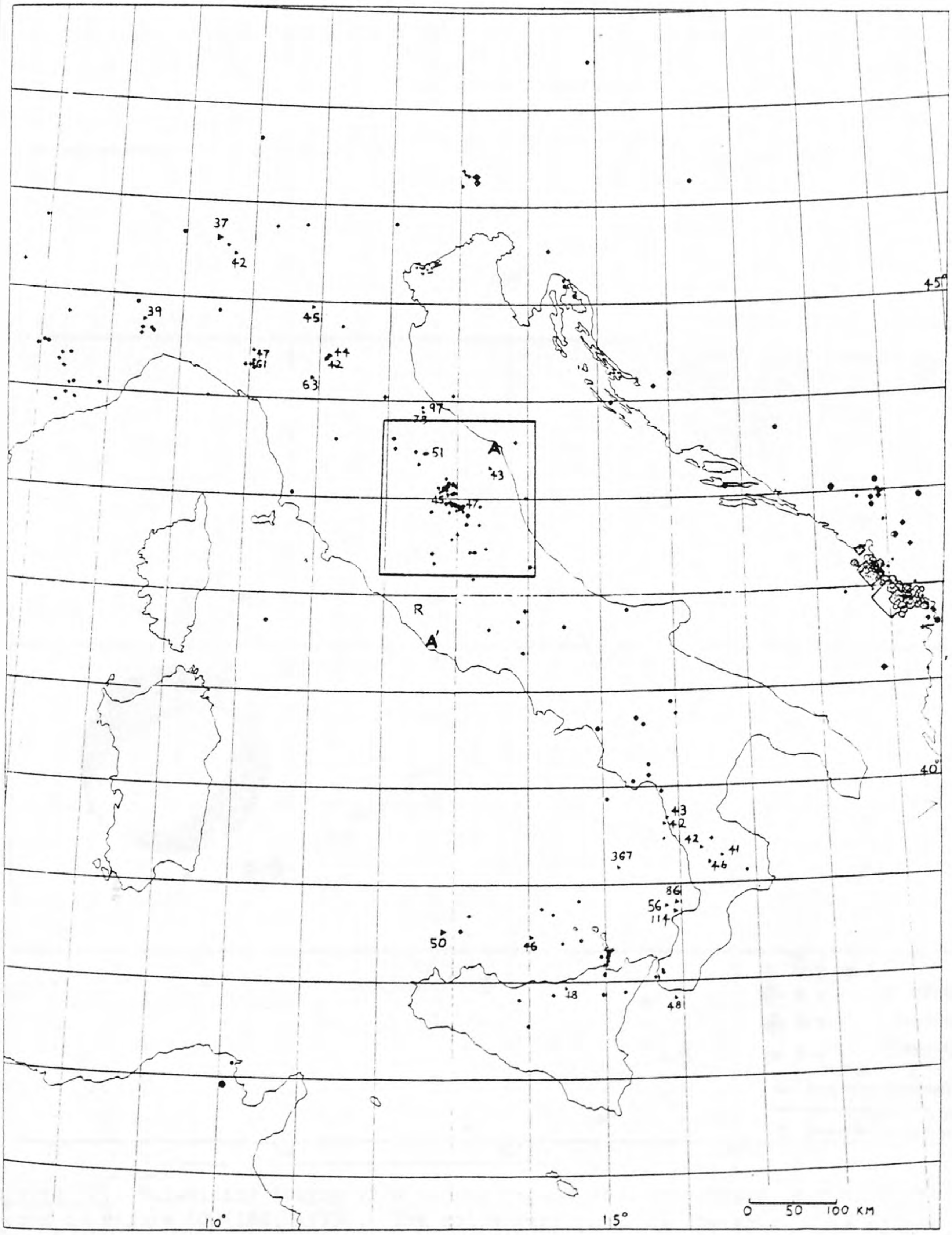


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Figure 11. Hypocenters during January-June 1979 determined by the ING for the data of the national network. (See Figure 10 for a legend). The box refers to Figure 13. The depth in km for hypocenters deeper than 33 km is indicated. Note the precursory concentration of seismicity in the area of the Norcia earthquake (19/9/79, M = 5.2) approximately at 43°N and 13°E, near the center of the box.

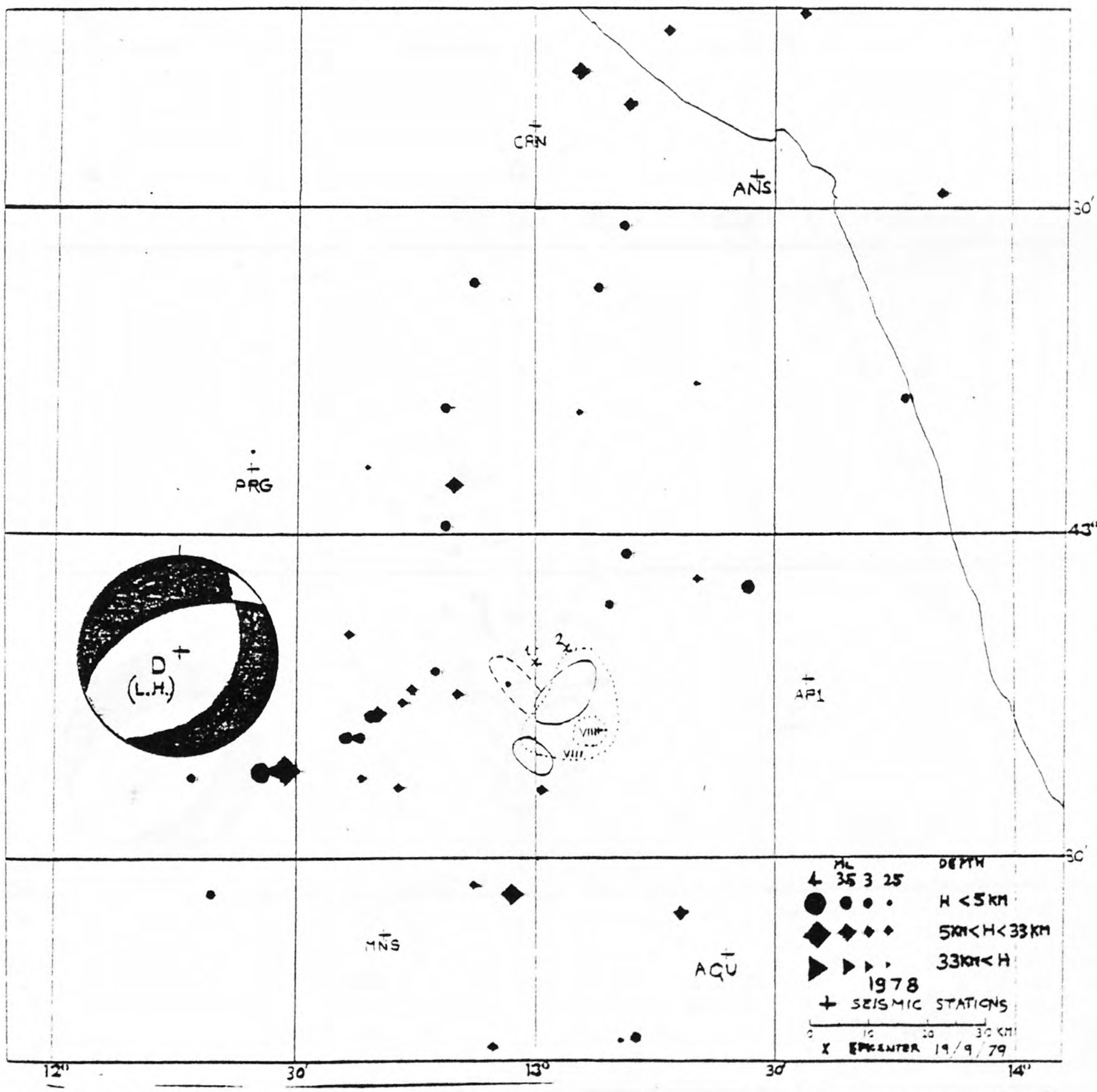


Figure 12. Seismicity during 1978 in the region of northeastern central Italy boxed in Figure 10 (ING, 1979). The epicenters (1 is by the ING: 2 is by the USGS), the preliminary aftershock areas as indicated by about 100 aftershock epicenters (solid and dashed line; see Figure 2), the mezoseismal area (dotted line) and the fault plane solution (lower hemisphere) of the 19/9/79 earthquake are indicated. The seismic stations are of National Network operating before the earthquake.

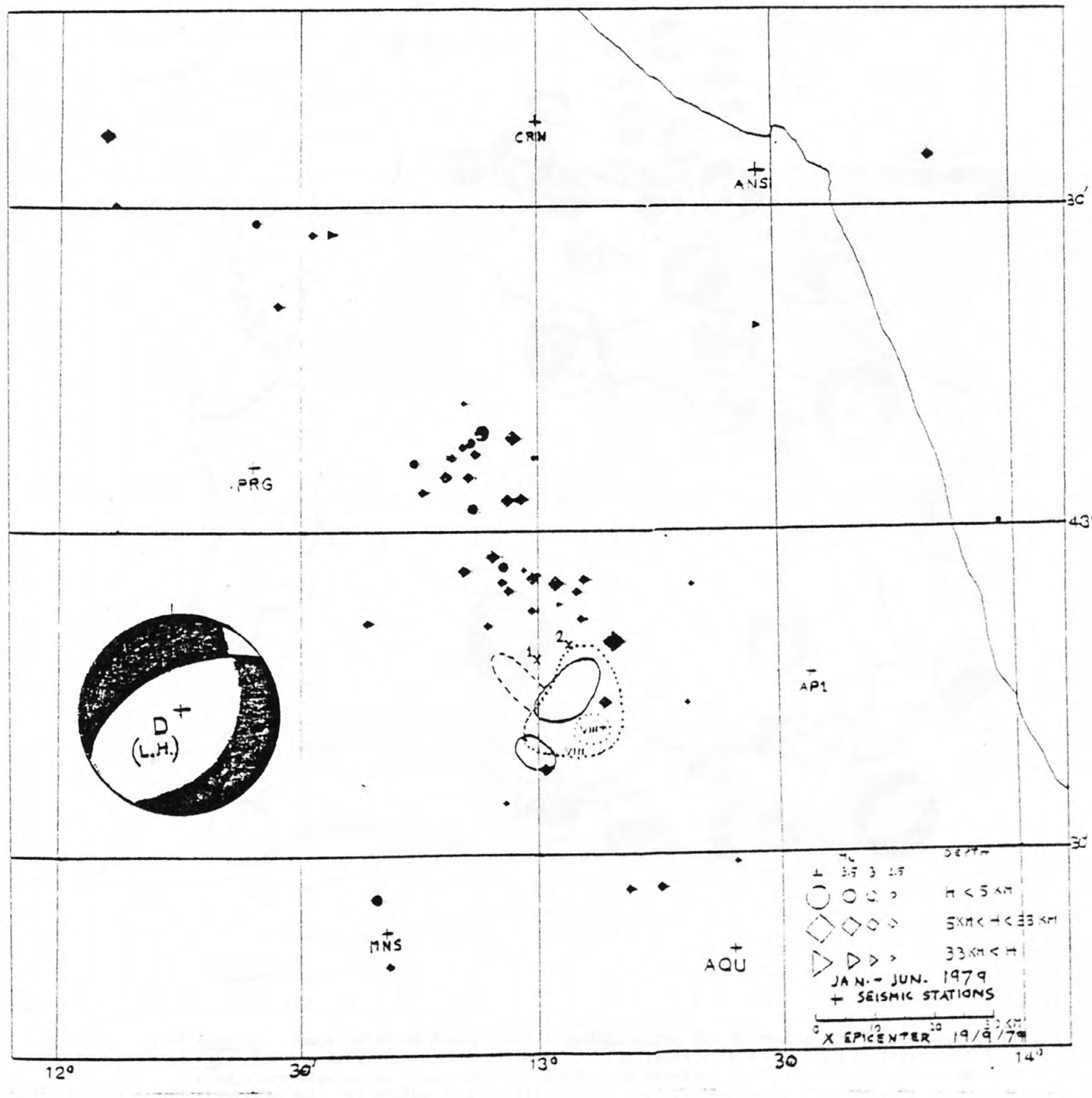


Figure 13. Seismicity during January-June 1979 in the region boxed in Figure 11. See caption of Figure 12. Note the concentration of the seismicity near the future epicentral area of the 19/9/79 event (compare with Figure 12). The fault plane solution of the 19/9/79 event is also shown (lower hemisphere, compression quadrants blackened).

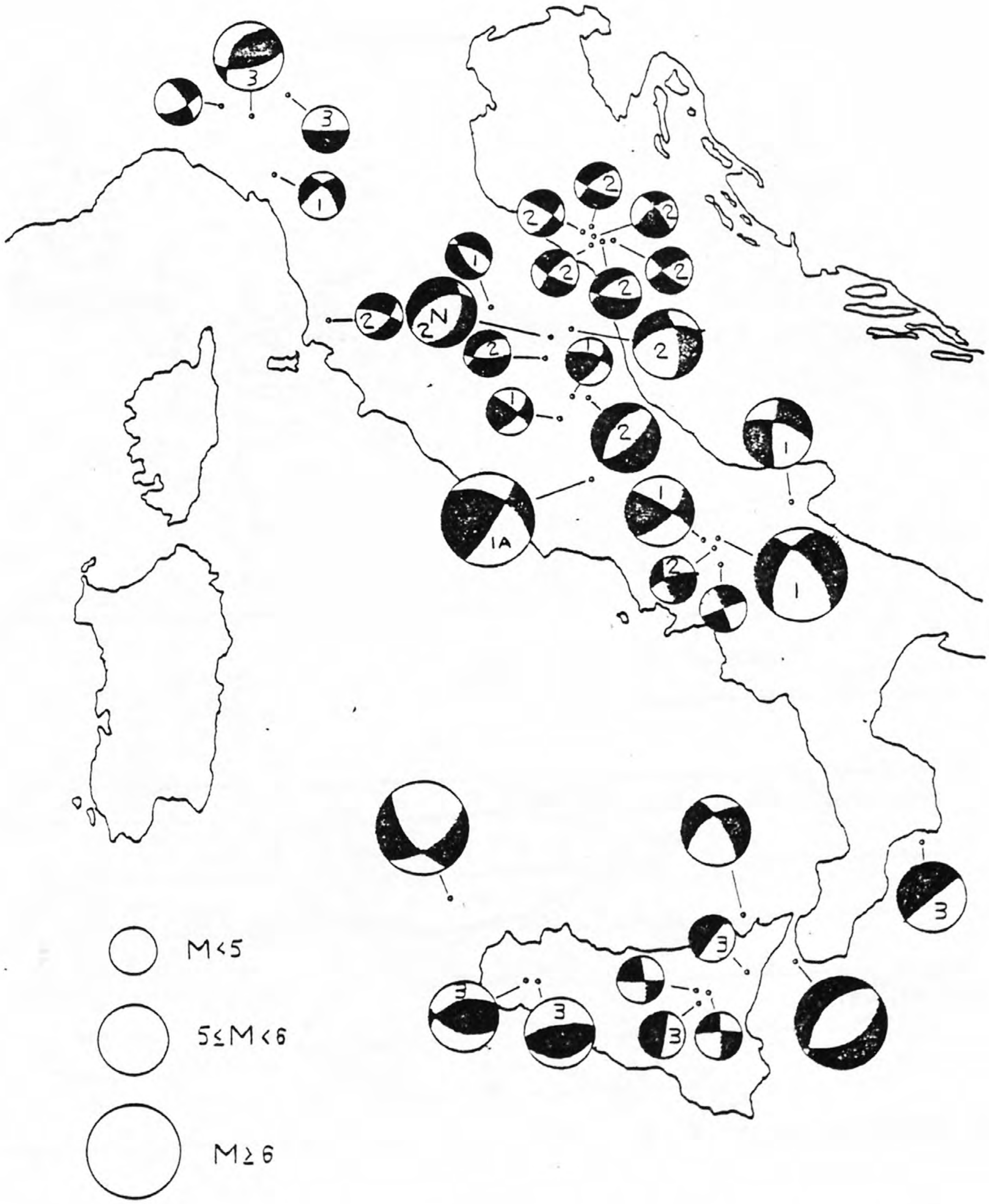


Figure 14. Compilation of fault plane solutions along the Appennine arc by Gasparini et al. (1979). Lower hemisphere projections, quadrants with compressional first arrivals are blackened. The numbers refer to the distinct families of solutions (our interpretation): 1) strike slip faults. Where a preferred plane of rupture is picked, it is the plane striking NW; 2) normal faulting and strike slip faulting with P axis perpendicular to the Appennine trends. The Norcia 19/9/79 event (N) is in this family; 3) thrust earthquakes. Thrust solutions are only found in Sicily and the northern Appennines.

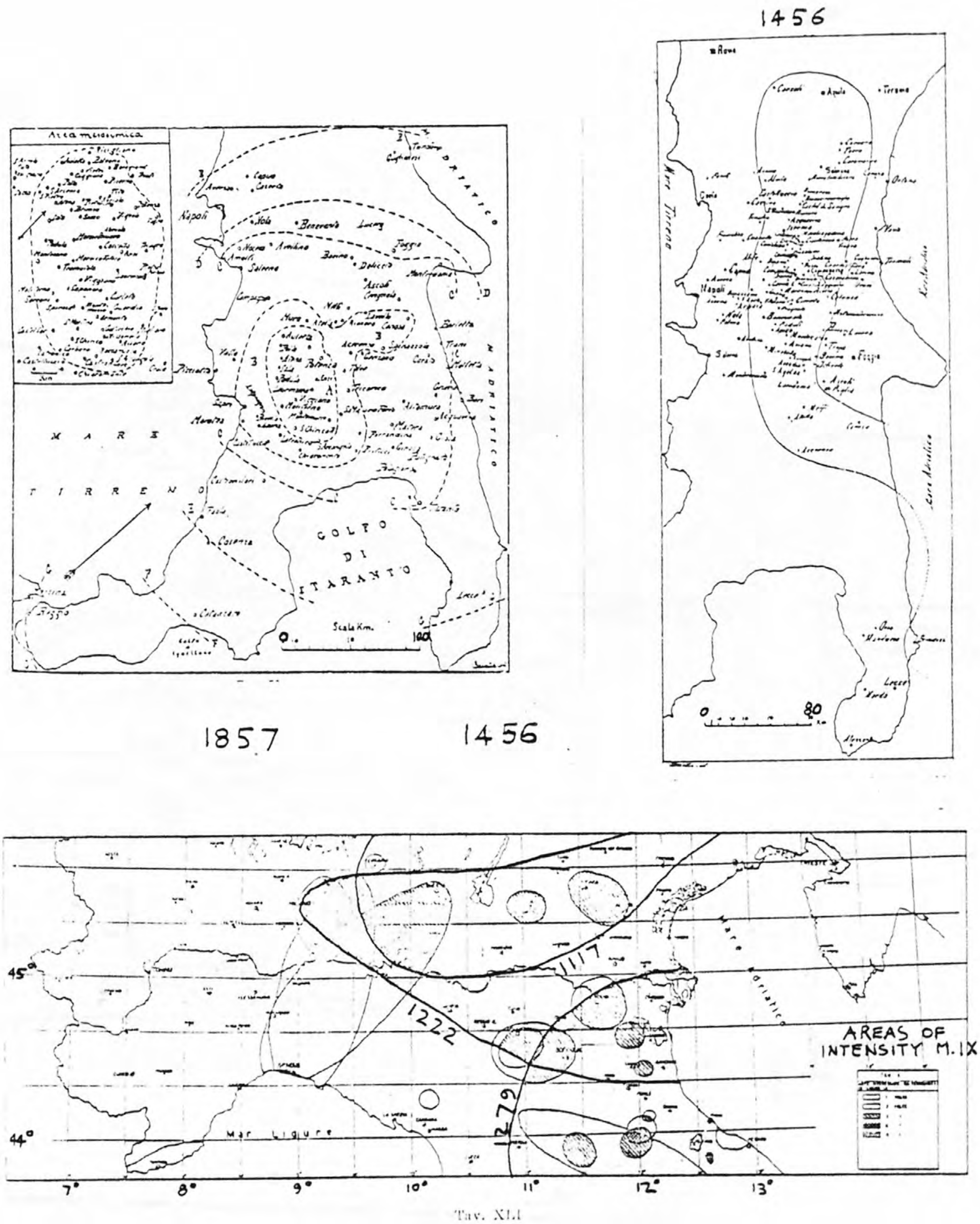
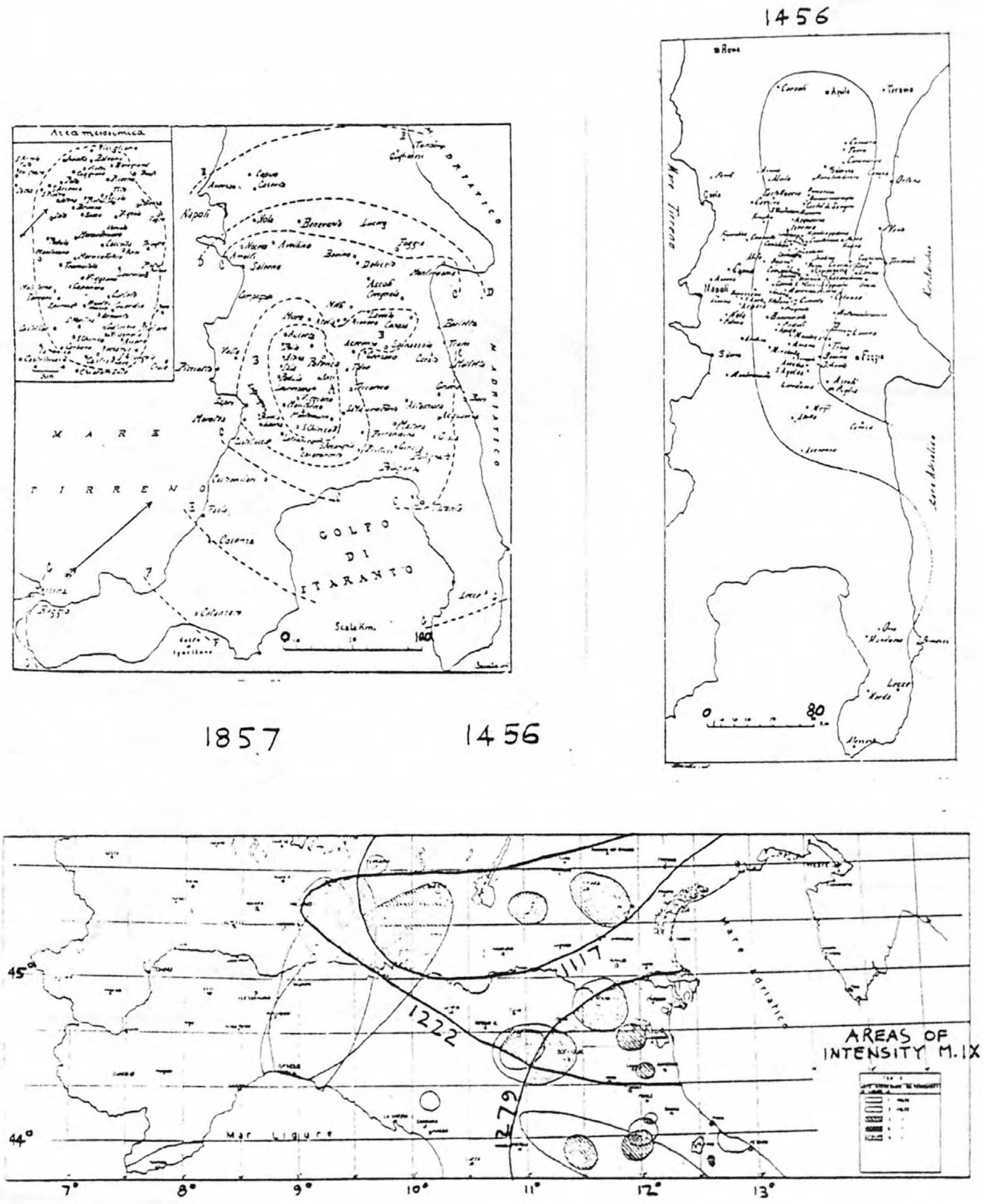


Figure 15. Some very large historic events (Baratta, 1900; Caloi et al., 1970). These earthquakes are probably ruptures along the shallow-dipping Appennine detachment. This detachment may be aseismic during long interseismic periods.



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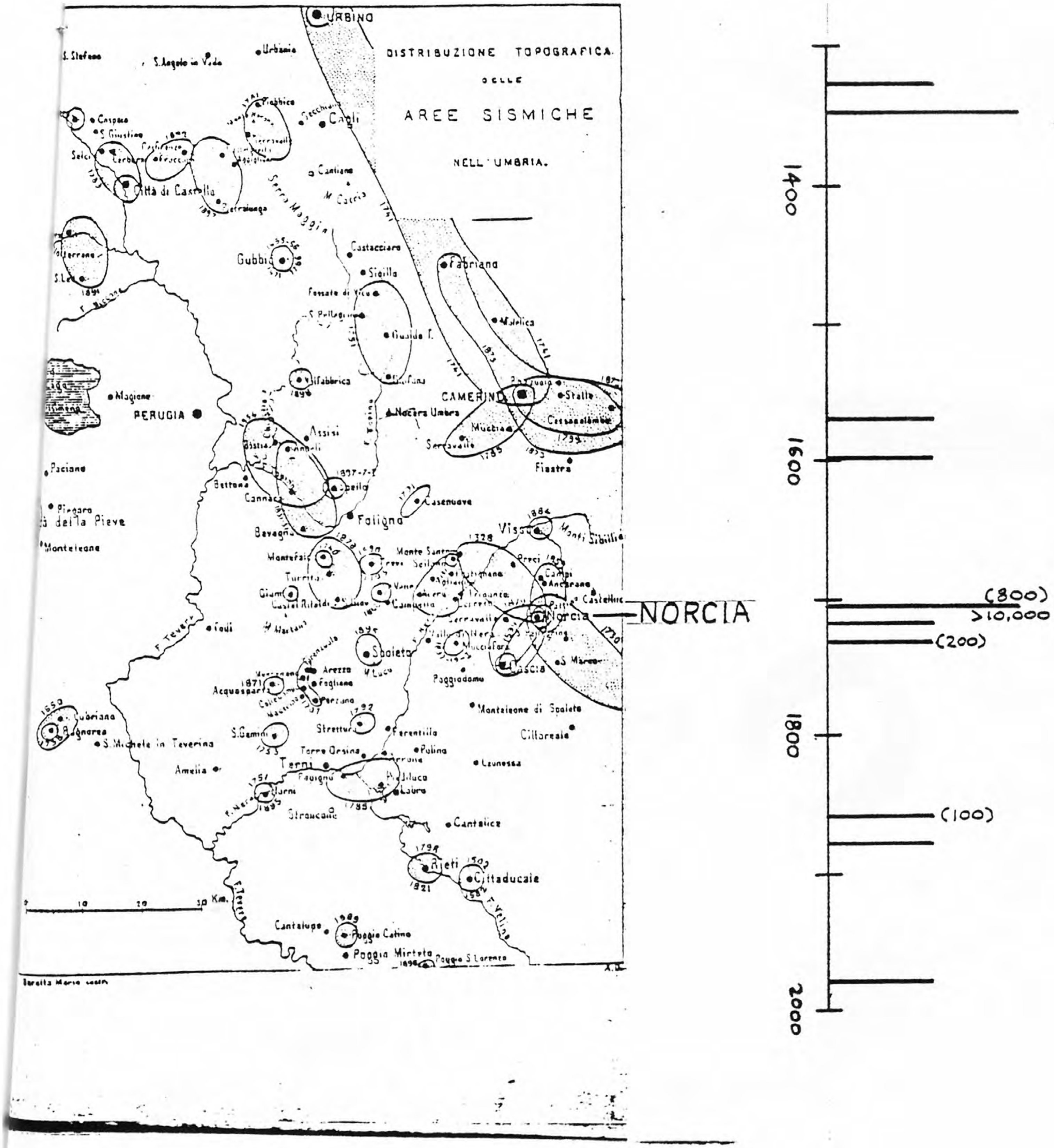

Figure 16. Historic data for the Norcia area of southern Umbria (Baratta, 1900). On the right the earthquakes causing destruction in Norcia are indicated in time (in parenthesis the number of deceased in Norcia; total deceased not in patenthesis). The shorter bars are local earthquakes, probably similar to the 19/9/79 event. Longer bars refer to earthquakes effecting a very large area (not shown on the map). These larger events may be detachment earthquakes. Note that events usually occur in multiplets with a repetition time of about 130 years for each multiplet.

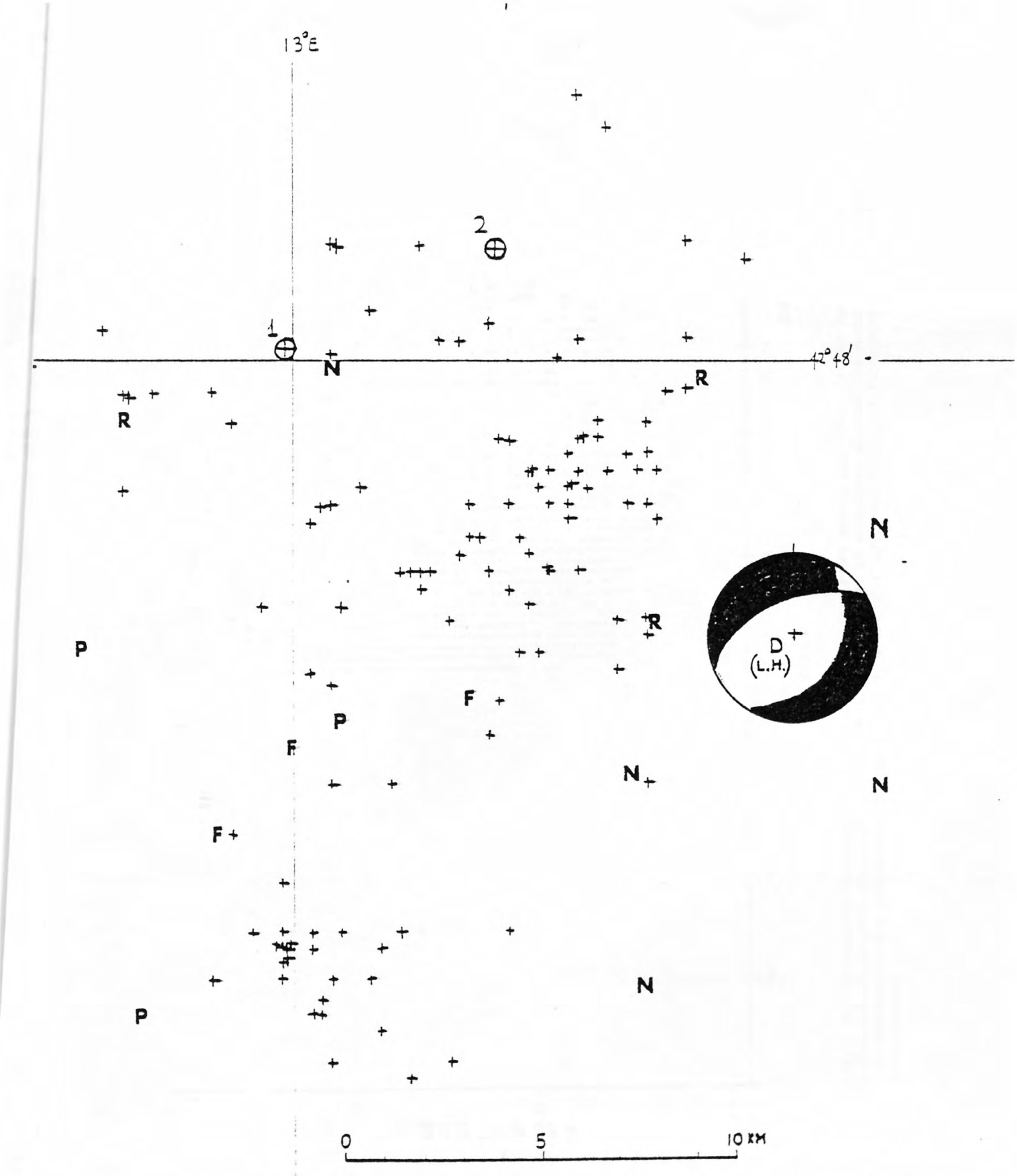

Figure 17. Preliminary aftershock distribution for the 19/9/79, M_L = 5.5 earthquake. Circles epicenters are of the main shock: 1, ING determination; 2, USGS determination. The letters represent the preliminary stations: R, Instituto Nazionale Geofisica (Roma); N, Instituto Vesuviano (Napoli); F, Universita di Firenze; P, CNRS (France). The fault plate solution is a projection of the lower hemisphere.

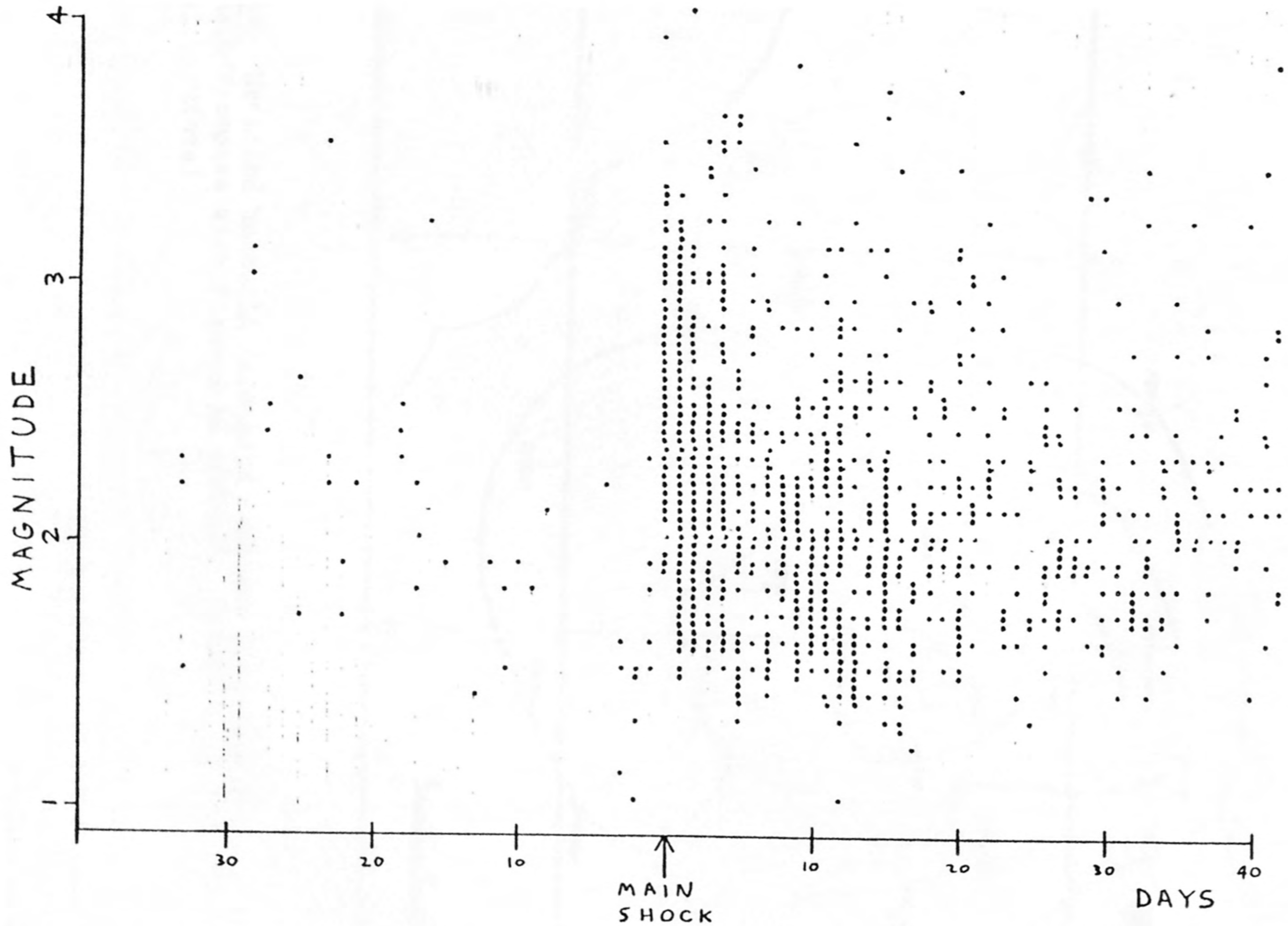

Figure 18. Earthquakes recorded by the station MNS (see Figure 20) with 4 sec ≤ S-P ≤ 10 sec for a two-month period before and after the 19/9/79 event. Note the 5 day lull of seismicity and then the swarm of small magnitude earthquakes that immediately preceeded the main shock (M = 5.2). Magnitudes are determined with the coda-length method.

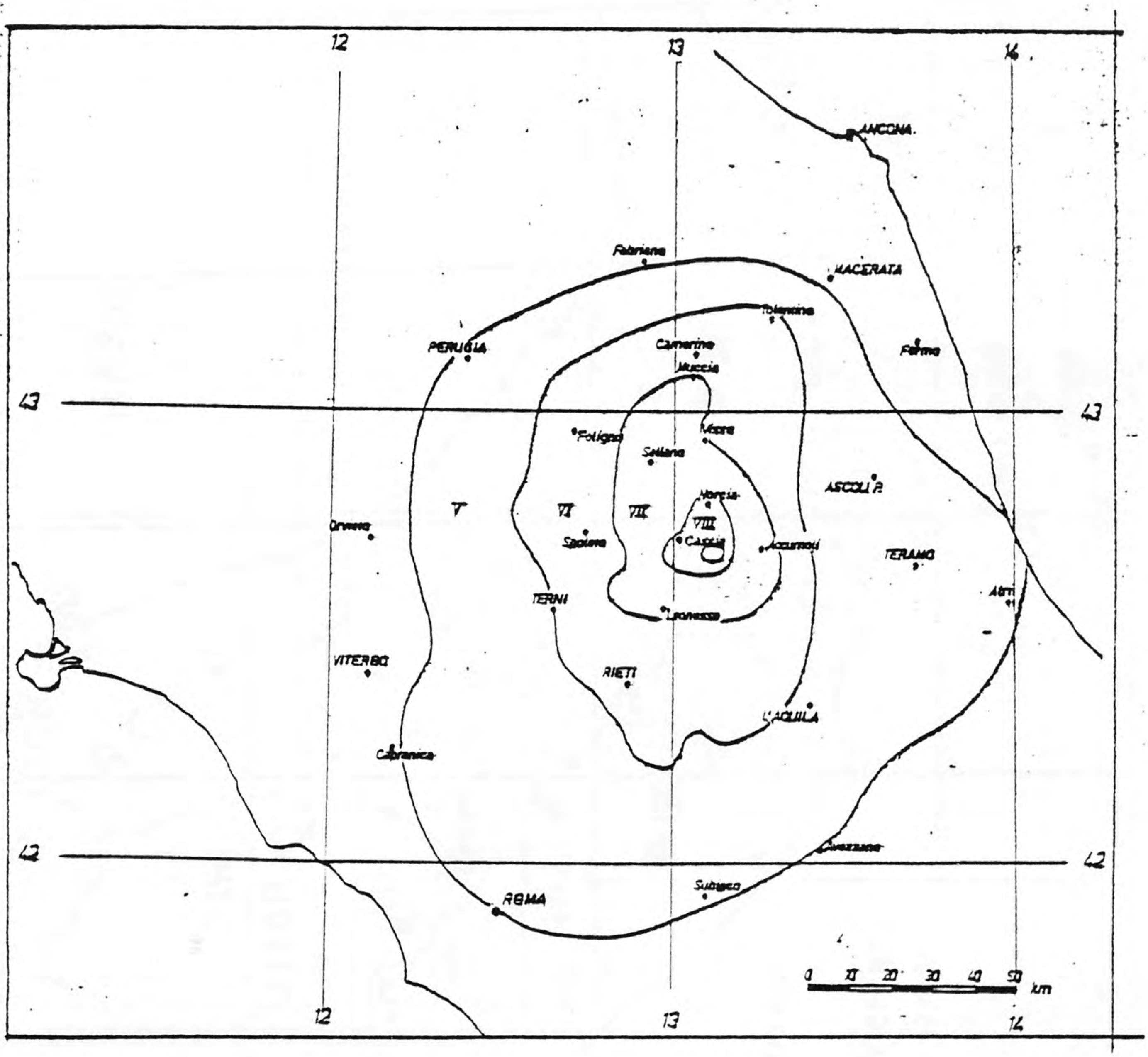

Figure 19. Modified Mercalli intensity contours (preliminary) for the 19/9/79 earthquake (compare with Figures 12 and 13). Compiled by the ING (SPADEA and collaborators).

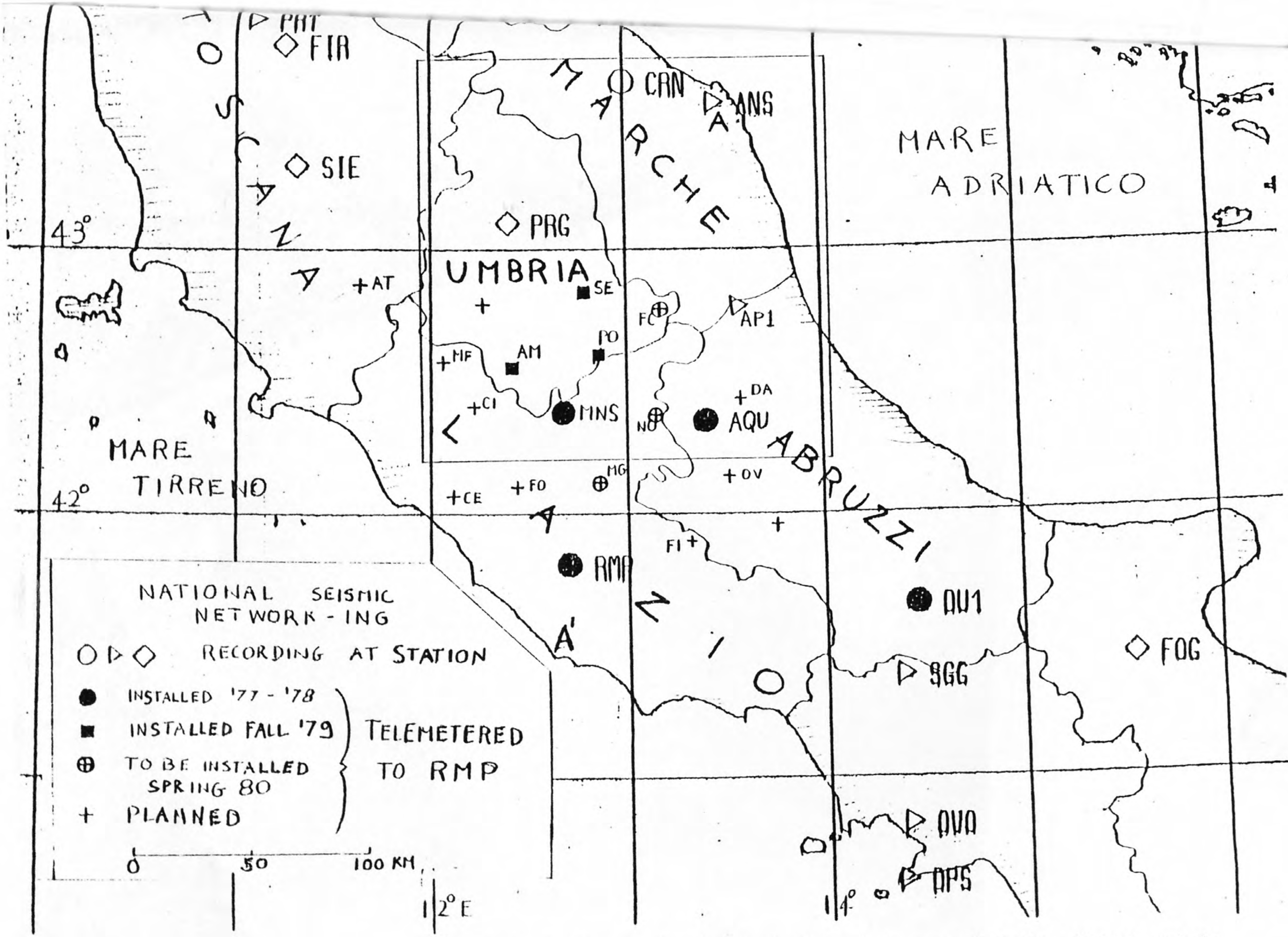

Figure 20. The portion of the Italiam National Seismic Network in central Italy. Filled symbols represent stations telemetered at RMP, the recording observatory, 25 km east of Rome.