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Landsat synthetic stereo interpretation for morphostructural analysis in the Irpinia area

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Abstract
The advantages of using Landsat images for morphostructural photo-interpretation reside mainly in their small scale, while the greatest disadvantage is the lack of a stereo perspective.
The present study focuses on the overcoming of this drawback by means of suitable processing techniques applied to the digital spectral data and involving the creation of a synthetic stereo pair from a single nadiral Landsat image and a high-resolution Digital Elevation Model (DEM).
This procedure has been applied to the area affected by the 1980 Irpinia earthquake.
The Landsat synthetic stereo pair photo-interpretation has provided a remarkable improvement in the morphotectonic analysis and in the detection of morphostructural features; subsequent studies of the local topography have confirmed the small-scale interpretation.
Finally the relationships between the 1980 Irpinia fault trace and the interpreted structures have been established.

1. Introduction

Nowadays satellite image analysis is commonly used in several type of small- and medium-scale applications. Satellite (LANDSAT) images have been used extensively in structural geology studies, particularly for the detection of geological structures from their morphological evidence.

The advantages of using satellite images, instead of traditional aerial photos, are represented by the multiple spectral sampling of satellite data (7 bands for the Landsat Thematic Mapper), by the synoptic view these images provide (allowing regional-scale investigation), by the multitemporal data acquisition and, in some cases, by their digital format. The latter character makes it possible to apply digital processing techniques in order to obtain a substantial image enhancement.

In many cases, however, it is possible to extract much more morphological and morphotectonic information from a stereo pair of high-altitude aerial photographs than from a Landsat image at the same scale; not only because of the better resolution the former provides, but mainly for the irreplaceable aid the stereo perspective gives to the interpreter.

It would therefore be extremely advantageous to make use of a stereo pair of satellite images allowing us to integrate the spectral information with the morphological one. In the present study this goal has been achieved by creating a synthetic stereo pair of the satellite image obtained by introducing a user-defined parallax in the spectral bands, based on elevations from a Digital Elevation Model (DEM) (Batson *et al.*, 1975; Batson *et al.*, 1976; Salvi, 1989). An application of this procedure is presented for the area affected by the 1980 November 23 (Southern Italy) earthquake.

2. Geological setting

The area considered in this study (fig. 1) is located in the central part of the Southern Apen-

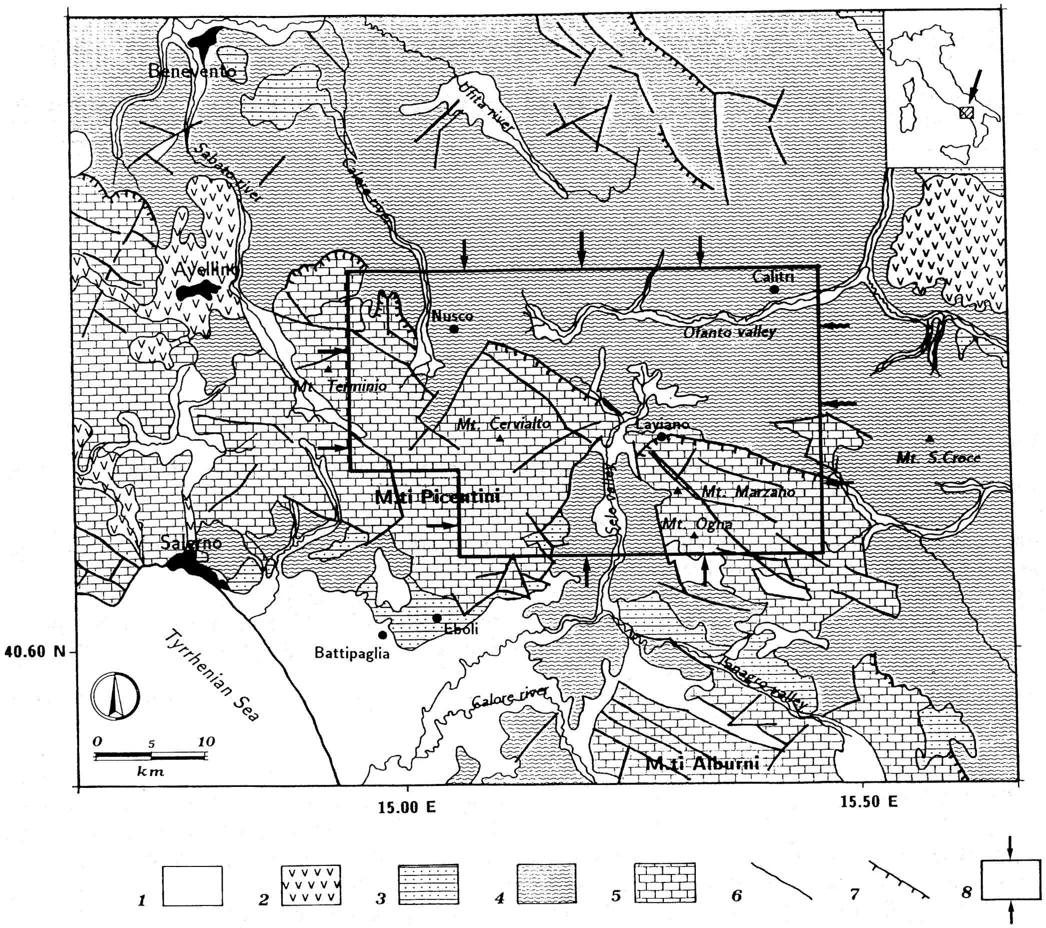


Fig. 1. Schematic geological map of the Irpinia area (modified from Bonardi *et al.*, 1988). Legend: 1) alluvium and colluvium (Holocene); 2) volcanic Units (Quaternary); 3) terraced lacustrine deposits and faulted alluvial conglomerates (Middle-Lower Pleistocene); 4) silico-clastic and carbonatic deposits and radiolarites, marls, claystones, calcarenites and fine sandstones (Middle Pliocene-Upper Cretaceous); 5) dolostones, marls, calcarenites, carbonate platform and margin deposits (Alburno-Cervati Units. Upper Cretaceous-Upper Triassic); 6) major faults; 7) overthrusts; 8) area shown in fig. 2 and plates 2 and 3.

nines and includes the Picentini Mts. group, the Marzano Mt. and Ogna Mt. ranges, the upper valleys of the Ofanto and Sele rivers and the Tanagro Plain.

Almost all the principal stratigraphic-structural units of the Southern Apennines crop out in the studied area, showing complex geometric and tectonic relationships.

The lowest outcropping terrains belong to the Lagonegro Units tectonically overlaid by the carbonate platform deposits of the Alburno-Cervati Units and the Sicilide («Argille Varicolori») Units. The latter two units are unconformably overlaid by sin- and late-tectogenetic units (Irpinian basin Units, Villamaina Units, Ariano Units, Pliocene-Pleistocene sedimentary deposits).

These principal units consist of Upper-Triassic to Upper-Cretaceous limestones and dolostones (shallow-water carbonates), Upper-Triassic to Lower-Cretaceous siliceous claystones and marlstones (terrigenous or basin sediments), Middle-Cretaceous to early-Miocene calcarenites and marly clays and, finally, Tortonian to late-Pleistocene sandstones and conglomerates (intra-Apenninic basins).

The structural setting of the area exhibits a crustal thickening due to a severe shortening (Middle Miocene-Upper Pliocene) and a subsequent deformation caused by extensional tectonics (late Pliocene-Present). Several compressional phases (with variable vergence from N to NE) have been recognized on the basis of the internal geometry of the chain and from the age of the terrains forming both the imbricates and the sediments of the fore- and intradeep basins (D'Argenio *et al.*, 1986).

Since the Pliocene, as the compressive deformation axis migrated eastward, more westerly areas were affected by an extensional regime (D'Argenio *et al.*, 1986), which produced two main systems of normal faults: one striking NW (Apenninic trend), the other SW (anti-Apenninic trend), following in some cases older weakness trends.

A few neotectonic phases, characterized by strong differential uplift and by extremely abundant debris production, have been identified in the Campania-Lucania Apennines (D'Argenio *et al.*, 1986). They alternated with long intervals of morphological sculpturing of the relief and with the formation of subaerial surfaces and peripheral marine terraces, now preserved at different elevation (intra-Apennine sedimentary basins filled with Pliocene and Pleistocene sediments and terraces and recent marine deposits of the Sele Plain (Brancaccio *et al.*, 1987).

3. Geomorphological setting

The geomorphological setting of the area analyzed in the present study results from a close interaction between tectonic phenomena and landform evolution. The most prominent topographic features are often related to the nature of the outcropping rocks. Rocks belonging to the Alburno-Cervati Unit usually crop out at higher elevations, whereas more easily erodible sediments fill valleys, topographic lows and the main structural depressions (Ofanto and Sele valleys).

The observed landscape is essentially the result of the thrusting of highly deformed nappes toward the NE and NNE, and of the superposed widespread normal faulting. A striking example of this setting is given by the three large sectors which can be distinguished, from the structural and morphological point of view, in plate 1 (see also fig. 1).

The first one is that of the Picentini Mts. which represents a large quadrangular horst bounded on all sides by normal faults. According to Ortolani (1975) this block represents a large monocline dipping toward NE and built up by many structural-stratigraphic units one over the other.

The second sector is the Marzano Mt.-Ogna Mt. group, which is again a horst similar to the Picentini Mts. range; it is also considered a SW-dipping monocline, limited and dissected by large normal faults.

Between the two sectors, the general NW trend of the Apenninic chain is interrupted by a major transverse structural discontinuity: the Sele Valley. According to Ortolani (1975) this discontinuity represents a graben-like structure of Pliocene age oriented NNE-SSW, bounded on its eastern and western sides by NNE-trending normal faults.

According to Brancaccio and Cinque (1988) the most evident small-scale landforms, especially those on carbonates, are inherited from older tectonic dislocations. The occurence of exhumed geomorphic features of different size, related to older tectonic regimes, is in fact very common in the Southern Apennines.

For example many of the steep scarps visible along the flanks of the major river valleys or along the contacts between adjacent thrusted sheets result from the recession of large fault scarps produced during the two neotectonic phases dating back from Lower Pleistocene to 0.75 m.y. ago (D'Argenio *et al.*, 1986). Also common are basins and erosional surfaces, located at different topographic levels, which are remnants of original Middle-Pliocene paleosurfaces dissected by successive tectonic movements (Brancaccio and Cinque, 1988).

On the other hand, very little field evidence is available for the most recent extensional phase, whose activity is indeed testified by the occurrence of several large normal faulting earthquakes (Pantosti and Valensise, 1989; Pantosti and Valensise, 1990). The active tectonic belt

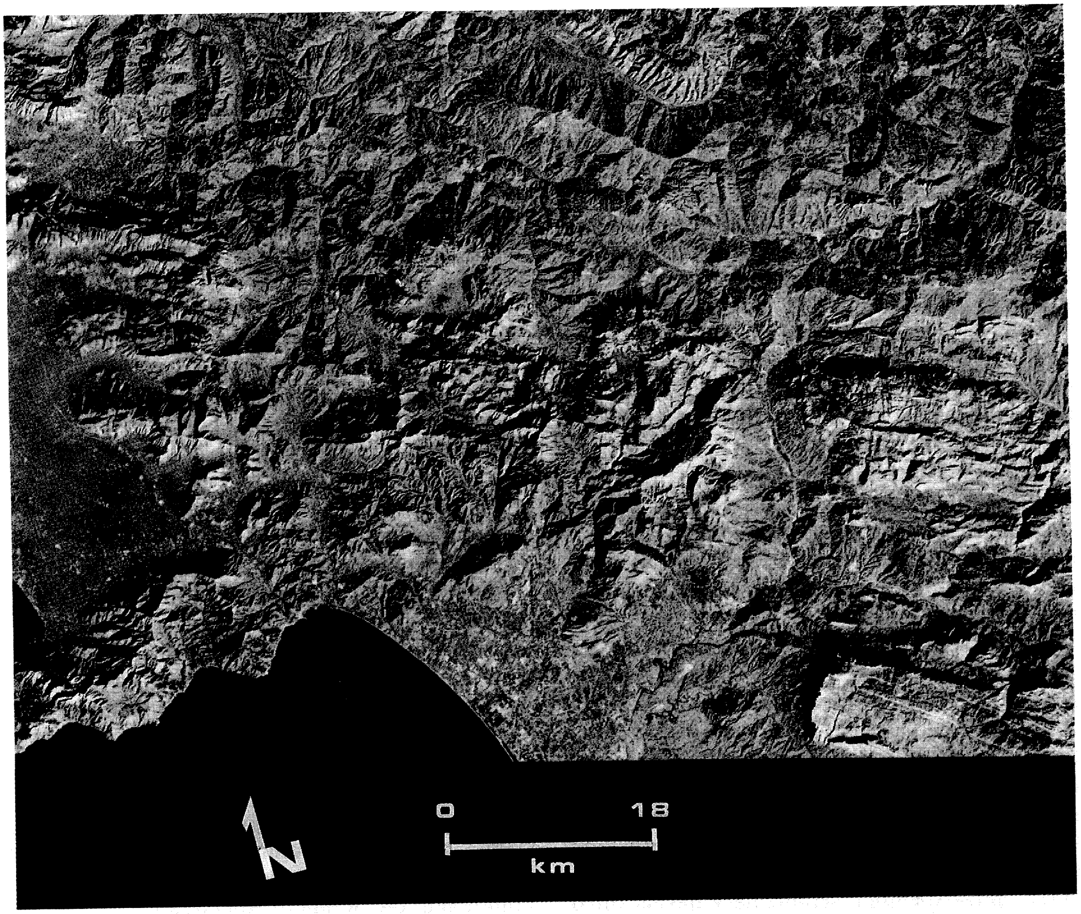


Plate 1. False Color Composite of bands 237 of the 1/16/1989 Landsat TM image, showing the area encompassed between the Sele and Ofanto valley. The spectral data have been registered to the DEM and are in UTM projection.

delineated by the strongest historical seismic events that occurred in the area has an Apenninic direction (Postpischl, 1985) and extends rather continuously, from the upper Agri Valley to the upper valleys of the Ofanto, Calore and Biferno rivers (Pantosti and Valensise, 1989).

4. Data sets and processing

The two original data sets at our disposal were: 1) digital data relative to a Landsat 5 TM image acquired on 1/16/1989, *Track* 189 *Frame* 32; 2) contour lines digitized from the 1:25 000 national topographic maps of Italy, directly provided by the Italian Military Geographic Institute (IGMI).

These data were suitably processed in order to obtain, as a final result, a syntethic stereo pair of Landsat TM False Color Composites.

Orographic data, supplied in vectorial format by IGMI, were previously interpolated and transformed into a raster format; the gridding step chosen (pixel size) was 20 by 20 metres.

The preliminary processing of the Landsat data started with the elimination of a strong periodic noise (destriping) for bands 2 and 3 (Chavez, 1975). We then calculated the Optimum Index Factor (OIF; Chavez *et al.*, 1984) for the 6 visible and near infrared bands, in order to select the most suitable triplets of spectral bands in terms of information content (Chavez *et al.*, 1984). The combination of bands 1, 4 and 7 showed the highest OIF value.

Before proceeding to the creation of the stereo pair it was necessary to bring the two data sets to the same geometry: Landsat bands were therefore registered to the DEM in order to acquire a UTM geometry useful for the subsequent photointerpretation; the spectral images were also resampled at 20 m per pixel to match the resolution of the DEM. We decided to use a 20 m pixel size for the final images to take full advantage of the high resolution of the DEM.

The final step in the data processing was the creation of a stereo pair for every TM band. This was accomplished by tilting the TM bands, that is by calculating a parallax for the position of each spectral pixel according to the corresponding value of the elevation pixel in the DEM (Batson *et al.*, 1976; Salvi, 1989).

The left and right images from the 1/4/7 Landsat TM stereo color composite are shown in plates 2 and 3; they can be viewed using a normal pocket lens stereoscope.

5. Interpretation

The photointerpretation of the Landsat synthetic stereo pair is performed directly on the color films using a table stereoscope at two different scales: 1:400 000 and 1:125 000. The relatively small working scale is imposed by the pixel dimension (20 m); the synoptic overview allows the interpreter to tentatively frame each detectable landform into a morphotectonic and structural evolution model. Afterwards, larger-scale (1:33 000) aerial photo analysis is carried out in order to verify the hypothesized model, which is also checked against geological data.

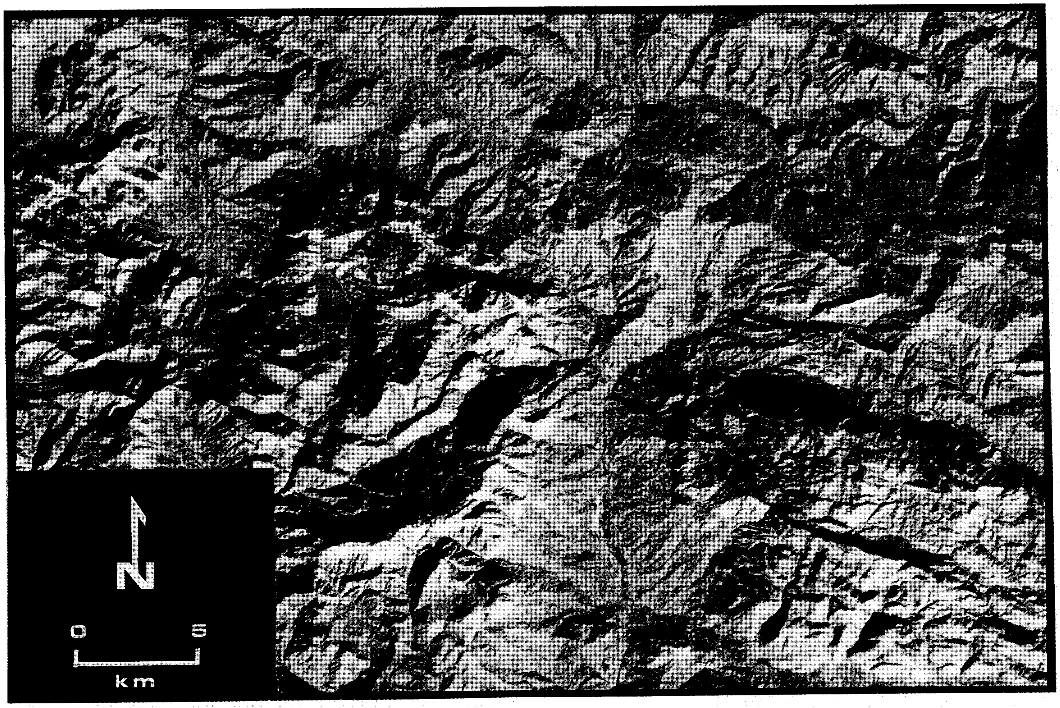
Figure 2 shows the most interesting morphotectonic elements which have been identified in the area affected by the 23 November 1980 earthquake. The following considerations are focused on the Marzano Mt.-Ogna Mt. ridge, where the earthquake produced surface faulting along a previously unmapped fault (Pantosti and Valensise, 1990).

The area encloses three approximately parallel ranges. All of them exhibit well-defined mountain fronts on the NE side, with the Pennone Mt.-Paratiello Mt. (A) and Marzano Mt.-Carpineta Mt. (B) being the most pronounced, with up to 900 m elevation differences with respect to the adjacent plains. They are characterized by: N 300° direction, a length of about 15 km, a more or less rectilinear trend, a steep and planar slope which is more dissected in A than in B, very low *mountain front sinuosity* (Bull and McFadden, 1977). The Ogna Mt.-Cucuzzone Mt. range C does not show a single continuous front like the previous ones: its striking appearance on the stereo pair is due to a clear alignment of smaller but steep slopes.

The areas in between the ranges appear a rather peculiar (plates 2 and 3): a low relief surface with an overall southwestern dip, thoroughly dissected by a complex pattern of fractures and scarps (the associated larger-scale landforms are clearly visible also on the aerial photos), which never cut across the main range fronts. They seem to represent an articulate network of small faults with the most frequent directions being parallel and perpendicular to the range axis; as confirmed by available geological maps (Servizio Geologico Nazionale, 1970).

While the structures A and B are mapped as normal faults on the 1:100 000 geological map (Servizio Geologico Nazionale, 1970) and are also easily detectable on the aerial photos, the structure C can only be recognized as a single morphotectonic feature on the Landsat stereopair. Note also that on a single non-stereo image (plate 1) the structure C is far less evident.

Moreover, according to the topographic information supplied by the stereoscopic vision, the geometrical relationships among the morphotectonic elements detected make it possible, once the small-scale data have been checked against larger-scale ancillary information, to frame the tectonic features detected into an interpretative structural evolution model. Such model, explaining in a schematic form the kinematic relationships among the faults as they have been interpreted from the Landsat stereo, is proposed in fig.



Plates 2 and 3. Synthetic stereo pair of TM band composition 147, obtained by the joint processing of spectral and elevation data. The Picentini and Marzano-Ogna ranges along with the intervening Sele Valley are displayed (see also fig. 2 for geographical reference). By viewing the stereopair through a pocket lens stereoscope, the morphotectonic structures interpreted (fig. 2) will be readily visible.

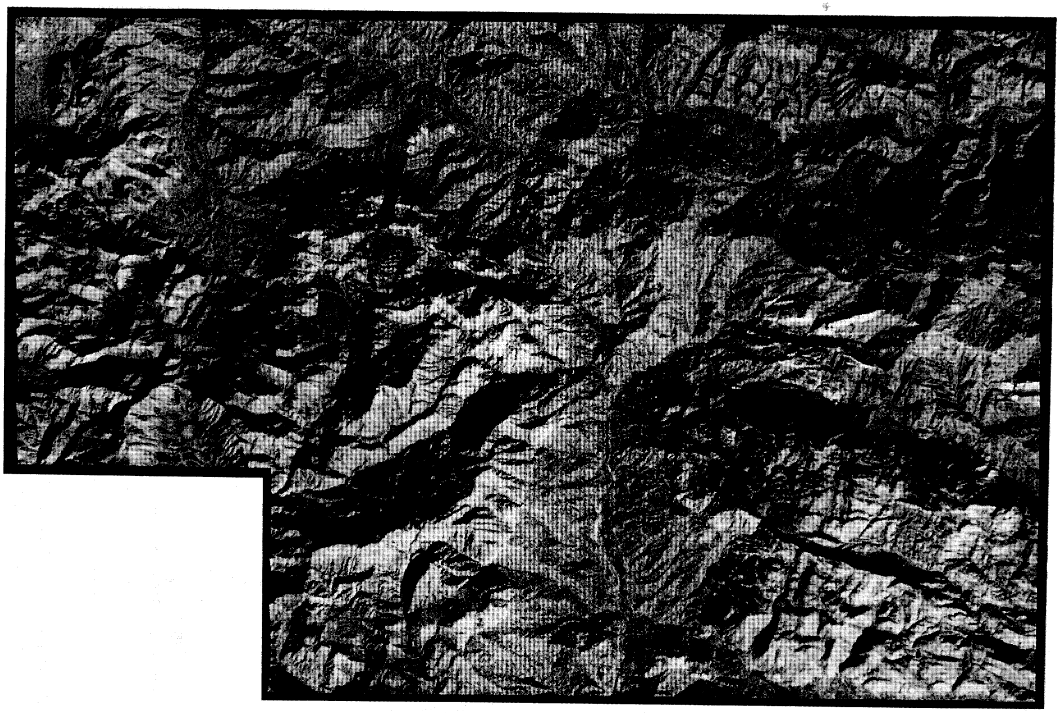
3. The three parallel ranges A, B and C are thought to represent the top part of faulted blocks bounded on the NE side by major normal faults and partially dissected on the SW side by a complex set of conjugate counter-faults to the underlying block (Ramsay and Huber, 1987).

A relative dating of the structures based on the evolutive stage of the associated landforms is proposed: structure A, which shows the most dissected slopes and a well-developed drainage network, with large, regularly shaped alluvial fans at the foot, is supposed to be the oldest. Structure C cuts across several entrenched valleys, lowering the uphill part of the streams (see fig. 2, fig. 4 and plates 2 and 3) and shows the smallest relief difference, suggesting a younger age than both A and B. The observation (from aerial photo interpretation) that karst landforms are better developed in the areas between A and B than between B and C also supports the age relationships suggested above.

6. Discussion

During the 23 November 1980 Irpinia earthquake a fault scarp about 40 chilometres long formed, cutting across the Marzano Mt.-Ogna Mt. group with a NW-SE direction (fig. 2). Successive field studies showed that the surface throw was between 50 and 120 cm (Pantosti e Valensise, 1990) and that at least 4 other displacement events, showing similar characteristics, occurred along the same fault during the past 11 000 years (Pantosti *et al.*, 1989; Boschi *et al.*, 1990).

The 1980 fault scarp is of course a too small morphological feature to be studied by satellite



imagery. On the other hand, examples from similar situations throughout the world (Slemmons, 1957, Bull and McFadden, 1977; Wallace, 1984) show that, given particular boundary conditions, a regional geomorphic expression of the fault is visible. The balance between the duration of the surface deformational process and the average geomorphic construction rate (the latter being the difference between the tectonic deformation and the erosion rates) is the main factor which eventually rules the formation of small-scale morphotectonic landforms.

However, in the Irpinia area such features can be detected on the Landsat stereopair only where the 1980 fault scarp runs close or actually follows older structures (fig. 2).

The scarp trace does not follow the general trend of the interpreted small-scale morphotectonic structures A, B and C but actually intersects them at an angle of about 30° (fig. 2). This seems to suggest that the latter are not tectonically active any more (Jackson and McKenzie, 1983).

In order to investigate at a larger scale the relationships between the tectonics of the area and landform evolution, a morphological analysis has been carried out on the streams cutting across the Ogna Mt.-Cucuzzone Mt. range C. Five stream profiles (fig. 4) have been drawn from the 1:25 000 topographic maps; for the most part they flow across carbonatic bedrock.

Profile traces are shown in fig. 4 along with the intersection points with the Irpinia fault trace (IFT) and the interpreted morphostructure C (SCT).

The observation of this figure makes it clear that:

- all the streams have non-equilibrium profiles with well-defined knickpoints;
- in all profile traces the intersections with SCT and, where present, with IFT correspond (taken into account data approximation) to knickpoints or flat areas.

In profile c)-d) the threshold corresponding to SCT, together with the general geological and geomorphological setting of the area, strongly suggests the presence of a sedimentary trap (Piano il Parco) similar to the one already ident-

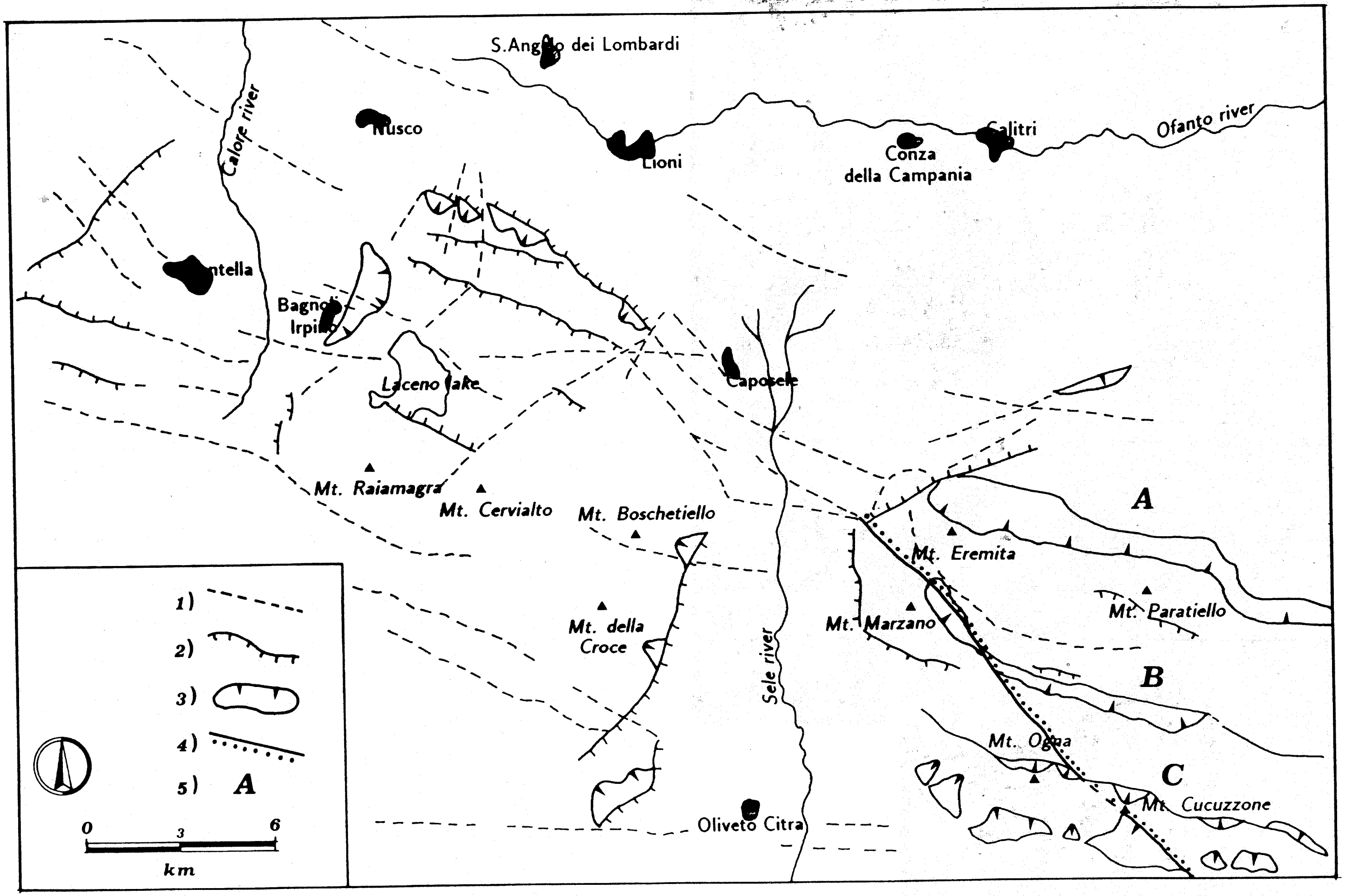


Fig. 2. Landsat image synthetic stereo interpretation. Legend: 1) Lineaments (*sensu* O'Leary *et al.*, 1976); 2) scarps and slope breaks of possible tectonic origin; 3) fault generated mountain fronts (the arrows show the slope attitude); 4) trace of the fault scarp produced during the 1980 Irpinia earthquake (IFT) (dots indicate downthrown side); 5) morphotectonic structures referred to in the text.

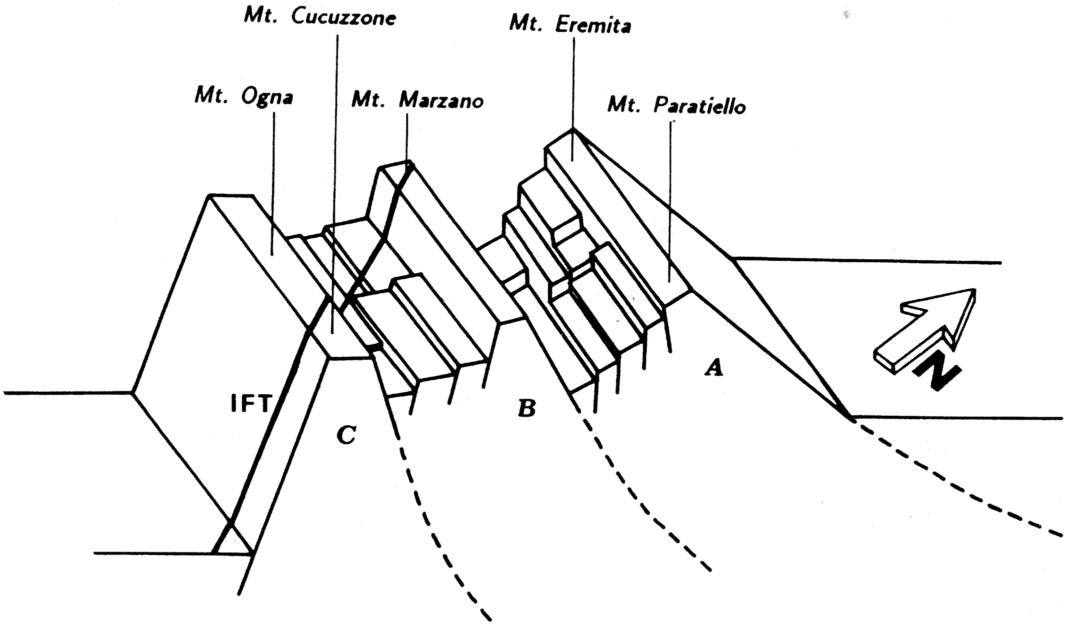


Fig. 3. Morphostructural interpretation of the Marzano Mt.-Ogna Mt. area; vertical scale is expanded for clarity. Also shown is the Irpinia fault trace (IFT, see text).

ified along the IFT by Pantosti *et al.* (1989) (Piano di Pecore).

Profile e)-f) shows a similar structural setting, but in this case no well-defined threshold is present; the lack of the 1980 fault scarp in this area suggests that local effects may prevent surface faulting from occurring during all the earthquakes. We must also take into account the effect of increased erosion on a hypothetical counterslope fault scarp due to the greater discharge of streams with a larger drainage basin and channel length.

In profile a)-b) the intersection points of the SCT and the IFT are no more close to each other: the IFT cuts across the stream bed at the outlet of Piano Neurale, a setting that once again resembles those of Piano di Pecore and Piano il Parco. The SCT is instead located downstream, forming a well-defined knickpoint on the carbonatic bedrock, as in profile g)-h). The last profile i)-l) does not show any knickpoint at the SCT intersection and this is probably due to the presence of softer and more erodible Pliocene sediments overlying the bedrock.

The discussion presented above may be resumed into the following points:

- the interpretation given for structure C in the schematic morphotectonic model of fig. 3 (north-east dipping normal fault) is consistent with the morphological analysis of the stream profiles. The intersection of the structure C trace (SCT) with the single profiles generally corresponds to points where the upstream reach has been lowered.
- The 1980 Irpinia fault trace (IFT) has a similar behaviour, with more pronounced effects (formation of active sedimentary traps), apparently reactivating the older structure C where they run close together.
- Structure C, given the proximity to an active fault with almost the same orientation, should be considered inactive, but the fact that local-scale landforms still preserve signs of surface displacement indicates that the locking of fault C is very recent. According to Salvi and Nardi (1991), it likely occurred in the interval 35 000-300 000 years B.P.

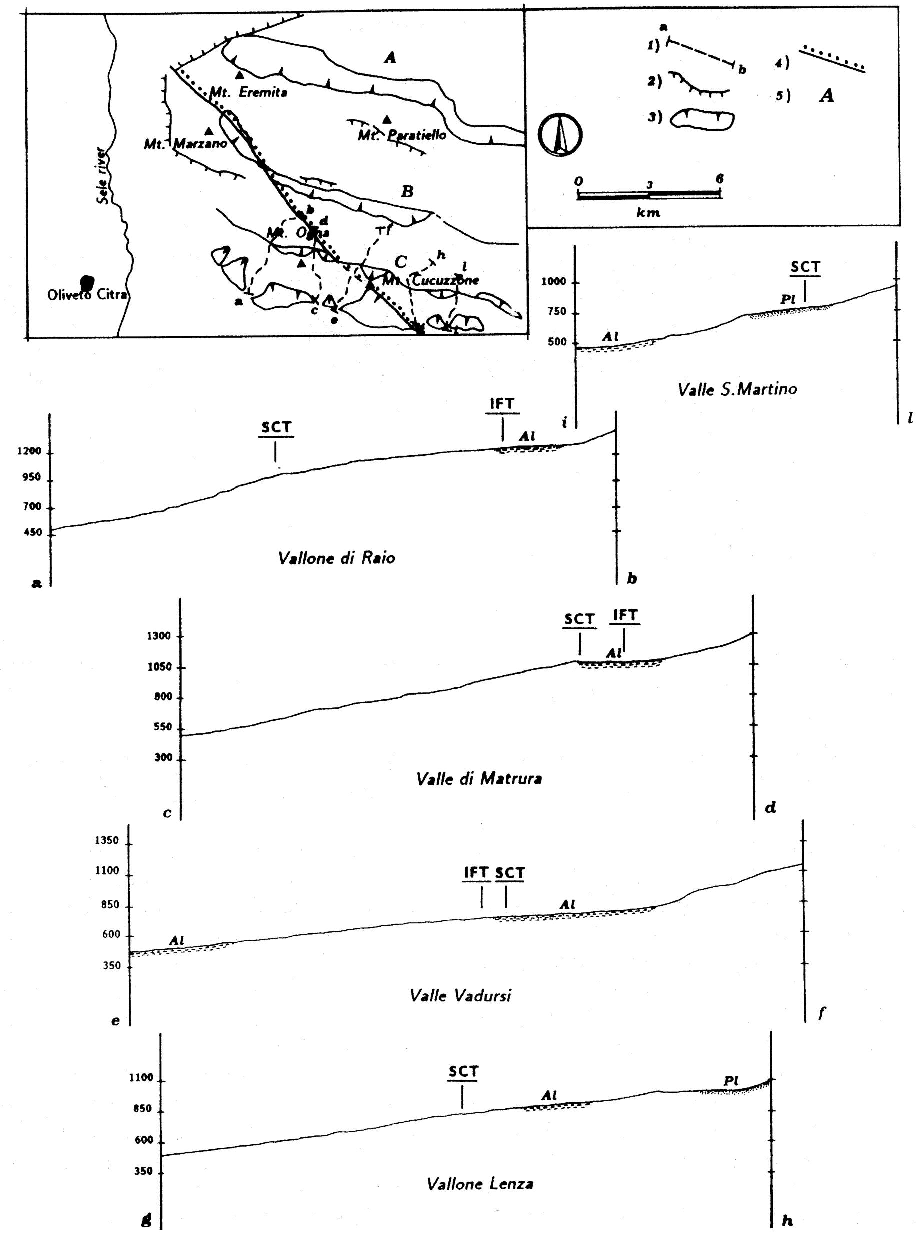


Fig. 4. Schematic topographic profiles of five streams cutting across the Ogna Mt.-Cucuzzone Mt. range C. Legend: 1) profile traces (base/height = 1:1); 2) scarps and slope breaks of possible tectonic origin; 3) fault generated mountain fronts (the arrows show the slope attitude); 4) trace of the fault scarp formed during the 1980 Irpinia earthquake (dots indicate downthrown side); 5) morphotectonic structures interpreted from Landsat synthetic stereo pair; IFT = 1980 Irpinia fault trace; SCT = profile intersection with the morphostructure C trace inferred from synthetic stereo pair analysis. Also shown are: alluvium and colluvium (Holocene) as dashed areas (Al); Pliocene sandy deposits as dotted areas (Pl).

7. Conclusions

The joint analysis of TM spectral data and a Digital Elevation Model for Landsat synthetic stereo generation has a considerable effect on improving the morphotectonic information extraction from satellite images.

The interpretation of a very high altitude stereopair is the best way to accurately interpret small-scale landforms as single features. Establishing the tectonic significance of these latter involves the understanding of the link between long-term deformative movements and their superficial expression.

In this case the stereo model interpretation allowed us to recognize several small-scale morphotectonic landforms and to frame them in a schematic structural model which was used as a starting point for a more detailed analysis. Further investigation at larger scale confirmed the satellite image interpretation and gave new insights on the relationships between active and relict morphotectonic landforms.

In particular the results of our study indicate that sometime during the Upper Pleistocene, the regional stress field changed enough to originate a new extensional phase. This is expressed in the geological record by the different orientation of the recent deformation (represented by the Irpinia fault surface effects) with respect to the previous structures (represented by morphostructures A, B and C).

The timing of this change is difficult to determine on the base of geomorphological data only. More data are needed especially on average erosion rates during Middle-Upper Pleistocene, but the overall geomorphic expression of either the 1980 fault trace and the most recent inactive morphotectonic landforms suggests a rather young age for the former, probably not more than 200 000 years.

REFERENCES

BATSON, R.M., K. EDWARDS and E.M. ELIASON (1975): Computer-generated shaded relief images, *J. Res. U.S. Geol. Survey*, **3**, No.4; 401-408

BATSON, R.M., K. EDWARDS and E.M. ELIASON (1976): Synthetic stereo and Landsat pictures, *Photogr. Engin. Remote Sensing*, **42**, No.10; 1279-1284.

BONARDI, G., B. D'ARGENIO and V. PERRONE (1988): Geological Map of Southern Apennines, in *74th Congresso Soc. Geol. It., Sorrento, 1988.*

BOSCHI, E., D. PANTOSTI and G. VALENSISE (1990): Paradoxes of Italian seismicity, *EOS Transactions A.G.U.*, **71**, 1787-1788.

BRANCACCIO, L. *et al.* (1987): Evoluzione tettonica e geomorfologica della Piana del Sele (Campania, Appennino meridionale), *Geogr. Fis. Dinam. Quat.*, **10**, 47-55.

BRANCACCIO, L. and A. CINQUE (1988): L'evoluzione geomorfologica dell'Appennino campano-lucano, Invited paper at the *74th Congresso Soc. Geol. It.*, pp. 45-48.

BULL, W.B. and L.D. MCFADDEN (1977): Tectonic geomorphology north and south of the Garlock fault, California, in *Geomorphology of arid regions*, edited by D.O. DOEHRING (London, Allen and Unwin), pp. 115-138.

CHAVEZ, P.S. (1975): Simple high speed digital image processing to remove quasi-coherent noise patterns, *Proceedings of the American Society of Photogrammetry, Falls Church, Virginia*, pp. 595-600.

CHAVEZ, P.S. JR., S.C. GUPTILL and J.A. BOWELL (1984): Image processing techniques for Thematic Mapper data, *Proceedings of the 50th ASP Symposium, Washington D.C.*

D'ARGENIO, B. *et al.* (1986): Geology of the Southern Apennines, a brief outline, *Proceedings of the International Symposium on «Engineering geology problems in seismic areas», Bari.*

JACKSON, J. and D. MCKENZIE (1983): The geometrical evolution of normal fault systems, *J. Struct. Geol.*, **5**, 471-482.

O'LEARY, D.W., J.D. FREIDMAN and H.A. POHN (1976): Lineaments, linear, lineation: some proposed new standards for old terms, *Geol. Soc. Am. Bull.*, **87**, 1463-1469.

ORTOLANI, F. (1975): Assetto strutturale dei Monti Picentini, della Valle del Sele e del gruppo di Monte Marzano-Monte Ogna (Appennino meridionale). Implicazioni idrogeologiche, *Boll. Soc. Geol. It.*, **94**, 209-230.

PANTOSTI, D., L. SAGNOTTI, G. VALENSISE and G. CALDERONI (1989): Paleosismicità lungo la faglia del terremoto del 23 Novembre 1980, in press on *Proceedings of the VIII Meeting G.N.G.T.S.* (CNR, Rome).

PANTOSTI, D. and G. VALENSISE (1989): Riconoscere il «terremoto caratteristico»: il caso dell'Appennino meridionale, in *I terremoti prima del mille. Storia archeologia sismologia* (S.G.A. editore, Bologna), pp. 536-553.

PANTOSTI, D. and G. VALENSISE (1990): Faulting mechanism and complexity of the 23 November, 1980, Campania-Lucania earthquake, inferred from surface observations, *J. Geophys. Res.*, **95**, 15319-15341.

POSTPISCHI, D. (1985): Atlas of isoseismal maps of Italian earthquakes, *Quad. Ric. Sci., CNR*, **114**, 2A.

RAMSAY, J.G. and M.I. HUBER (1987): *The techniques of modern structural geology* (Academic Press, London).

SALVI, S. (1989): Analisi di immagini Landsat in coppie stereoscopiche: metodologia ed applicazione geologica, in *Proceedings of the III Meeting of the Italian Association for Remote Sensing (A.I.T.), L'Aquila, Italy.*

SALVI, S. and A. NARDI (1991): Contribution of Landsat synthetic stereopair to morphotectonic analysis in the Irpinia area (Southern Italy), *Il Quaternario*, **4**, 107-120.

Servizio Geologico Nazionale (1970): Carta Geologica d'Italia - Geological Map of Italy, F. **186**.

SLEMMONS, D.B. (1957): Geological effects of the Dixie Valley-Fairview Peak, Nevada, earthquakes of December 16, 1954, *Seism. Soc. Am. Bull.*, **47**, 353-385.

WALLACE, R.E. (1984): Fault scarps formed during the earthquakes of October 2, 1915, in Pleasant Valley, Nevada, and some tectonic implications, *U.S. Geol. Survey Profess. Paper*, **1274A**.