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RIVER TERRACES IN THE FIUME TRONTO DRAINAGE BASIN, Marche Region: A CONTRIBUTION TO MORPHOTECTONIC INVESTIGATIONS

ABSTRACT: DELLA SETA M., FREDI P., LUPIA PALMIERI E., NESCI O., SAVELLI D. & TROIANI F., *River terraces in the Fiume Tronto drainage basin (Marche Region): a contribution to morphotectonic investigations.* (IT ISSN 1724-4757, 2005).

The aim of this work is to provide a methodological input based on geostatistical topographic analyses for the detection of morphological anomalies induced by neotectonic activity on fluvial terrace surfaces.

The study area corresponds to the distal portion of the Fiume Tronto drainage basin (Southern Marche region of Central Italy); the basin developed on Plio-Pleistocene marine terrigenous deposits and its arrangement was strongly influenced by Quaternary uplift and regional WSW-ENE and E-W trending fault zones.

Detailed surveys allowed to verify the location of surfaces, at several levels; they are the remnants of Quaternary fluvial terraces, formed in response to both climatic oscillations and regional uplift. Several points at the top of the surfaces were sampled by GPS and then geostatistically processed (Kriging method) to provide an unbiased interpretation of the chronological sequence of terraces.

The geometrical setting of the terraces seems strongly influenced by the regional uplift and by the activity of the Tronto major fault. Results of geostatistical analysis, compared to the DTM indicated that minor Quaternary faults dislocated the terraces. This is in agreement with the outcomes of previous works, thus confirming the usefulness of this methodological approach in the study of fluvial terraces as neotectonic indicators.

KEY WORDS: Morphoneotectonics, Geostatistical analysis, Fluvial terraces, Central Italy.

RIASSUNTO: DELLA SETA M., FREDI P., LUPIA PALMIERI E., NESCI O., SAVELLI D. & TROIANI F., *I terrazzi fluviali del bacino idrografico del Fiume Tronto (Marche): contributo agli studi morfotettonici.* (IT ISSN 1724-4757, 2005).

Scopo del lavoro è fornire un contributo metodologico, basato sull'analisi geostatistica, per l'individuazione di anomalie morfologiche delle superfici dei terrazzi fluviali, connesse alla neotettonica.

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L'area di studio corrisponde alla porzione terminale del bacino idrografico del Fiume Tronto, nelle Marche meridionali. Essa si sviluppa su depositi marini trasgressivi del Plio-Pleistocene e presenta un assetto morfostrutturale fortemente influenzato da un sollevamento differenziale quaternario e dall'attività di faglie regionali ad andamento da WSW-ENE a E-W, che suddividono la regione in differenti blocchi morfotettonici.

Rilevamenti dettagliati hanno permesso di localizzare superfici a diversi livelli che rappresentano i lembi residui di terrazzi fluviali quaternari, formati in risposta alle oscillazioni climatiche e al sollevamento regionale.

Sono stati campionati con un GPS vari punti quotati alla sommità delle superfici terrazzate e i dati ottenuti sono stati elaborati geostatisticamente (metodo del Kriging) al fine di interpretare in modo oggettivo la sequenza cronologica dei terrazzi.

L'assetto geometrico dei terrazzi fluviali sembra essere stato fortemente influenzato dal sollevamento regionale e dall'attività della faglia principale del Tronto. I risultati dell'analisi geostatistica, confrontati con il DTM suggeriscono la presenza di faglie minori quaternarie che dislocano i terrazzi. Tali risultati sono in accordo con quelli ottenuti in precedenti lavori, a conferma dell'utilità di questo approccio metodologico nello studio dei terrazzi fluviali come indicatori neotettonici.

TERMINI CHIAVE: Morfotettonica, Analisi geostatistica, Terrazzi fluviali, Italia centrale.

INTRODUCTION

In tectonically active regions, neotectonic events that leave their imprints on the present landscape to different extents. Therefore, the analysis of geomorphic records can be a valuable tool in the reconstruction of neotectonic events and it becomes crucial where outcropping lithologies have low susceptibility to preserve in a pervasive way the evidence of tectonic deformations.

In recent times morphotectonic investigations have turned specifically to the quantitative approach. Appropriate geomorphic indices have been elaborated; in different geomorphological settings, they are capable to express the tectonically controlled shift of landscape features from their morphological «correct» assessment.

Drainage basins and networks are the traditionally preferred topic of Quantitative Geomorphology; therefore, they have been often the object of morphotectonic studies (Strahler, 1952; Hack, 1973; Ciccacci & alii, 1986; Cox, 1994; Keller & Pinter, 1996; Belisario & alii, 1999; Currado & Fredi, 2000; Fredi & Peppoloni 2002; Currado & alii, 2002).

In traditional geomorphological investigations, fluvial terraces are probably the most widely used among basin landforms to detect recent tectonic activity (Merritts & alii, 1994, and references therein). In fact they have a regional occurrence and therefore they can record large-scale tectonic uplift (Chen & Liu, 2000). As fluvial terraces represent approximate geomorphic timelines, they are useful also in timing the tectonic deformations and in quantifying the vertical displacements of individual faults (Li & alii, 1999; Houtgast & alii, 2002). In spite of the multiple significance of fluvial terraces, their morphometric analysis has been usually disregarded.

In this work traditional morphological analyses are combined with the quantitative geomorphic approach in the study of Quaternary fluvial terraces in the distal portion of the Fiume Tronto drainage basins (southern Marche region). The aim is double: to attempt the reconstruction of the morphotectonic history of this portion of Fiume Tronto basin and to test the reliability of fluvial terraces as neotectonic indicators. To these ends the outcomes of field survey have been coupled with the geostatistical topographic analyses, performed to detect the morphological anomalies of the terrace surfaces due to tectonic activity.

GEOLOGICAL AND MORPHOLOGICAL SETTING

The drainage basin of Fiume Tronto extends for 1,192 km² between Abruzzo and Marche regions. The main stream flows initially northwards, then it turns to the East and, cutting transversely the major Apennine structures, flows into the Adriatic Sea. The lower portion of Fiume Tronto basin, on which this research is focused, lies specifically in the southern sector of Marche Apennines.

In the western part of the study area, turbiditic deposits (Tortonian-Upper Messinian) crop out (fig. 1). They represent the filling up of a foredeep basin (Cantalamessa & alii, 1986) and were strongly folded by compressive tectonics that acted during the Pliocene, along N-S to NW-SE oriented axes (Ambrosetti & alii, 1986). In the eastern part, a Plio-Pleistocene trasgressive terrigenous sequence of pelites and sands (Lower Pliocene-Lower Pleistocene) is present that shows, at different stratigraphic heights, conglomeratic and arenitic beds, bodies and lenses. These transgressive deposits unconformably overlie the turbiditic deposits and show an east-north-eastward dipping homoclinic arrangement strongly influenced by the Quaternary differential uplift that affected the Apennines, with decreasing rates from the chain axis towards its margins (D'Agostino & alii, 2001).

The morphological arrangement of the lower portion of the Fiume Tronto basin clearly reflects the regional

structural setting of the peri-adriatic foothills, whose Plio-Quaternary evolution was substantially driven by the regional uplift. The ENE and NE dipping Plio-Pleistocene deposits (fig. 1) crop out in wide seaward-dipping *cuestas*. Moreover, large alluvial fans near the coastline testify to the increased sediment supply, most likely induced by headward erosion of the main rivers as a result of the differential uplift (D'Agostino & alii, 2001; Nesci & Savelli, 2003).

Recent studies on the Southern Marche evidenced both regional and local morphotectonic features suggesting that the uplift process went along with block tectonics tied to the activity of regional WSW-ENE and E-W major fault zones, often run by the main rivers (Gentili & alii, 1998; Coltorti & alii, 1996).

A detailed analysis of the morphological indicators of tectonics pointed out the Fiume Tronto valley to be a fault angle depression (fig. 2), confirming the presence of a main fault along the river and evidencing the existence of minor dislocations variously oriented (WNW-ESE, NNE-SSW, SW-NE, NW-SE and N-S) (Della Seta & alii, 2004). Obviously, the analysis of morphotectonic indicators implied, along with aerial photo interpretation, a series of field surveys, in order to discard all the features induced by lithological or litho-structural constraints.

QUANTITATIVE GEOMORPHOLOGY AND MORPHOTECTONICS

More recently quantitative geomorphological analyses allowed to improve the knowledge about the morphostructural arrangement of the study area; these analyses aimed particularly at providing further and objective information about vertical displacement and regional uplift and about the kinematics of morphologically inferred faults.

In particular, the spatial variations of the parameter *amplitude of relief* (A_r), already tested as morphotectonic indicator (Centamore & alii, 1996), suggested that both regional and local uplifts occurred within the Tronto drainage basin (Della Seta & alii, 2004). The A_r parameter was calculated as local relief per unit areas of 1 km². Resulting values were geostatistically processed by the kriging method, in order to get a contour map of A_r distribution. In the study area, the amplitude of relief regionally decreases from WSW to ENE, according to the regional differential uplift; moreover the A_r distribution clearly reflects the asymmetry of the Tronto basin. The map of A_r residual values (fig. 3), obtained following the method by Ciotoli & alii (2003), evidences that A_r negative anomalies mark a large portion of the Fiume Tronto basin; this suggests that local lowering occurred with south-southeastward tilting of the left slope (downthrown block) along the Fiume Tronto inferred fault. The positive anomalies at the top of the right slope (upthrown block) support this hypothesis.

The kinematics of faults that acted along with the regional uplift was tentatively determined by the *azimuthal transect method* (Belisario & alii, 1999). This method was applied to the faults inferred from the alignments of morphotectonic indicators, and specifically to the Tronto main

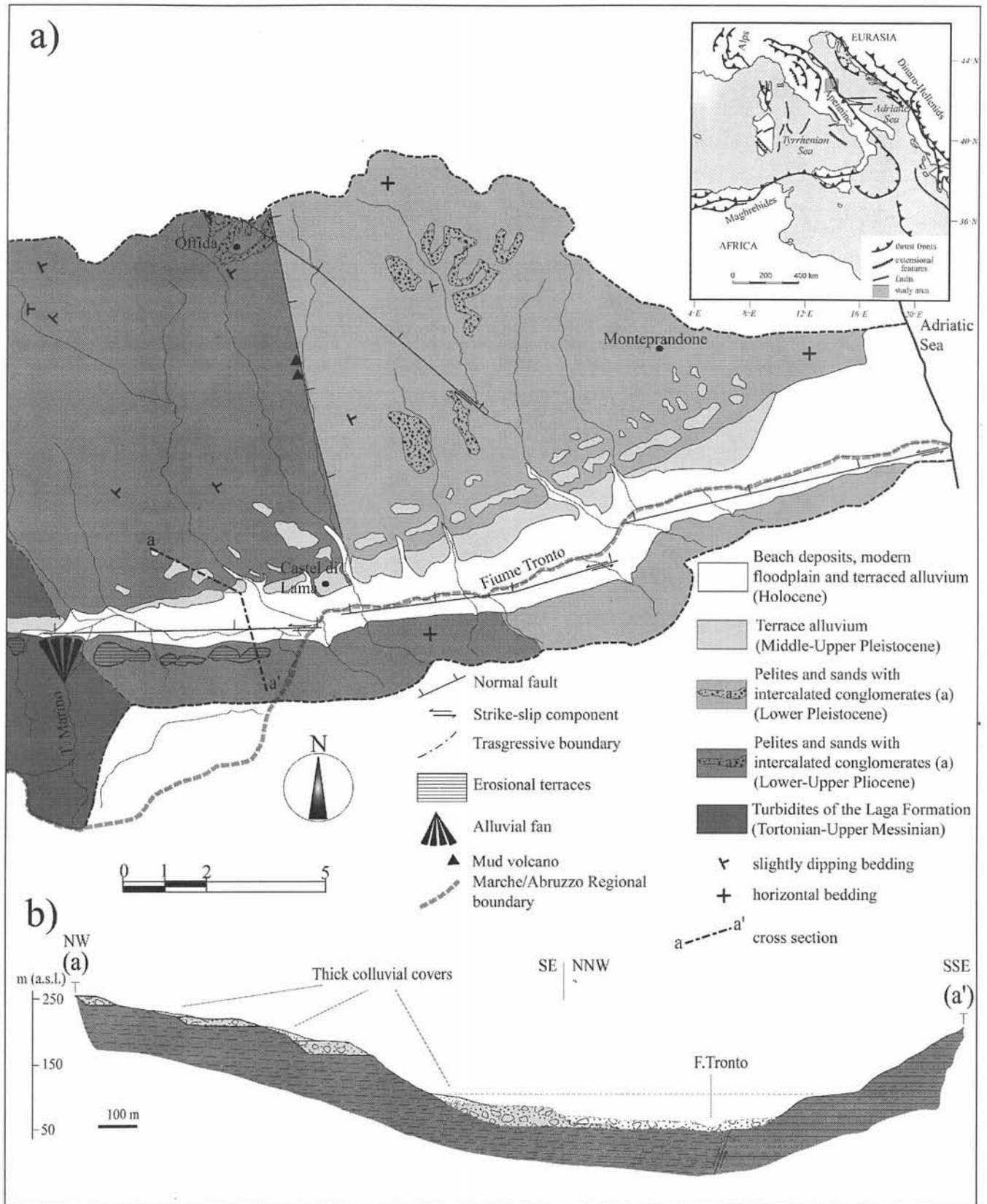


FIG. 1 - Geological sketch of the study area (a) and geological section across the Tronto Valley (b).

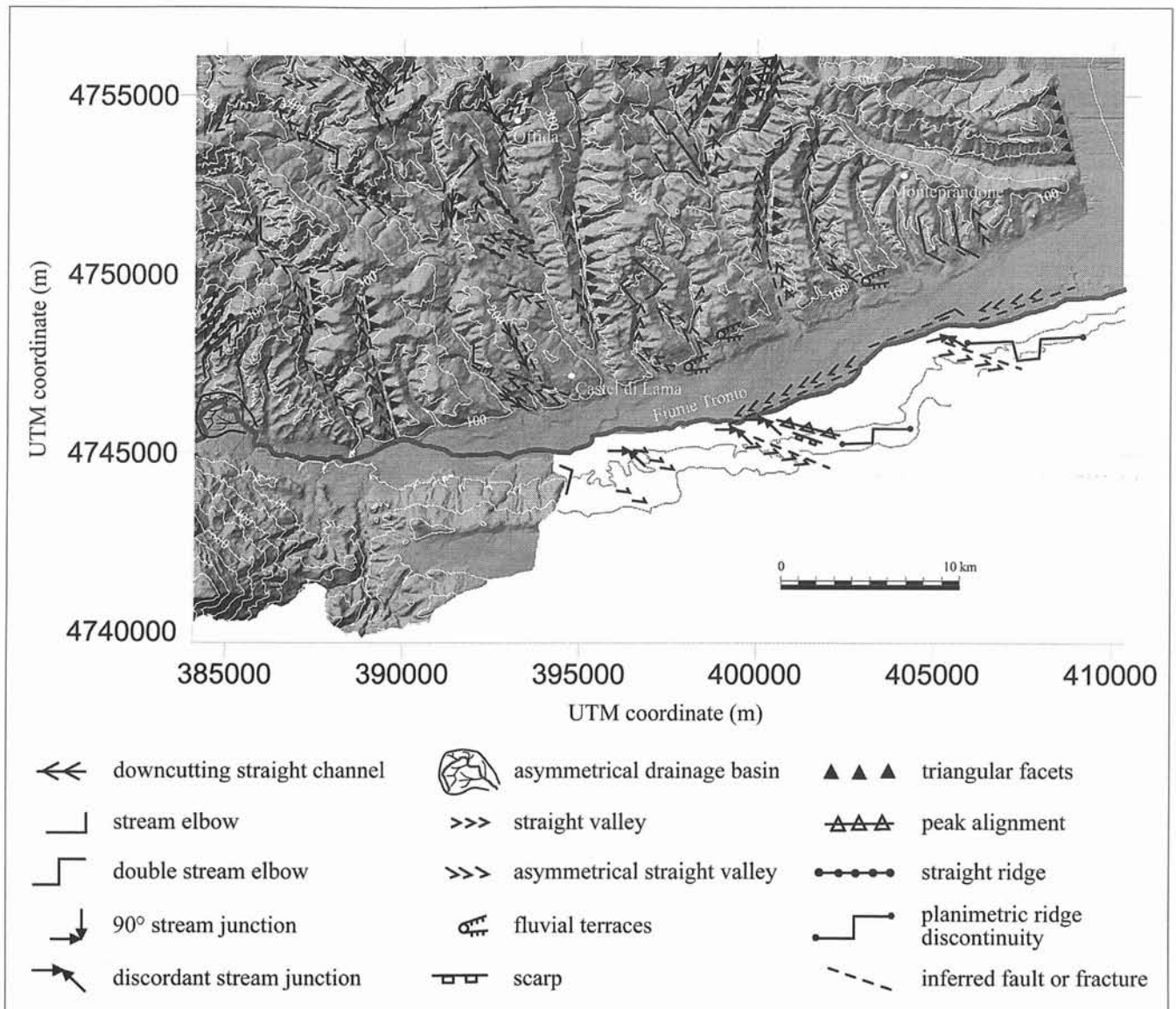


FIG. 2 - Computed DTM of the study area and morphotectonic indicators.

fault, and to the minor WNW-ESE oriented faults crossing it (fig. 2).

In fig. 4 interpretative models, location and results of the azimuthal transects of 1st and 2nd order channels are shown. Bell-shaped spectra (transects 1, 4 and 8) suggest the hypothesis of a left-lateral slip component along the Fiume Tronto inferred fault and the kinematic characterisation of some minor faults supports this observation (fig. 4d), according to the kinematic model for shear zones (Wilcox & alii, 1973). Moreover, the deformation pattern associated to this possible shear zone was already suggested by the presence of straight segments of the downstream portions of left tributaries, aligned to WNW-ESE oriented discordant stream junctions on the right slope of the valley (fig. 2).

In addition to the classical interpretative models for azimuthal transects (Belisario & alii, 1999) a new «step-like geometry» was recognized (fig. 4c). This geometry is due to a rapid change in the preferred orientation of streams, which abruptly run along the «azimuthal domain» (Ciccacci & alii, 1986) perpendicular to the fault direction. Such arrangement was interpreted as a consequence of dip-slip movements, which caused uplifted blocks to be cut by low order streams, statistically oriented along the maximum slope direction. This evidence was firstly observed across the Tronto fault, confirming the dip-slip component of displacement, already suggested by the strongly asymmetrical valley. The same geometry was detected across NNW-SSE minor faults and, for NW-SE and

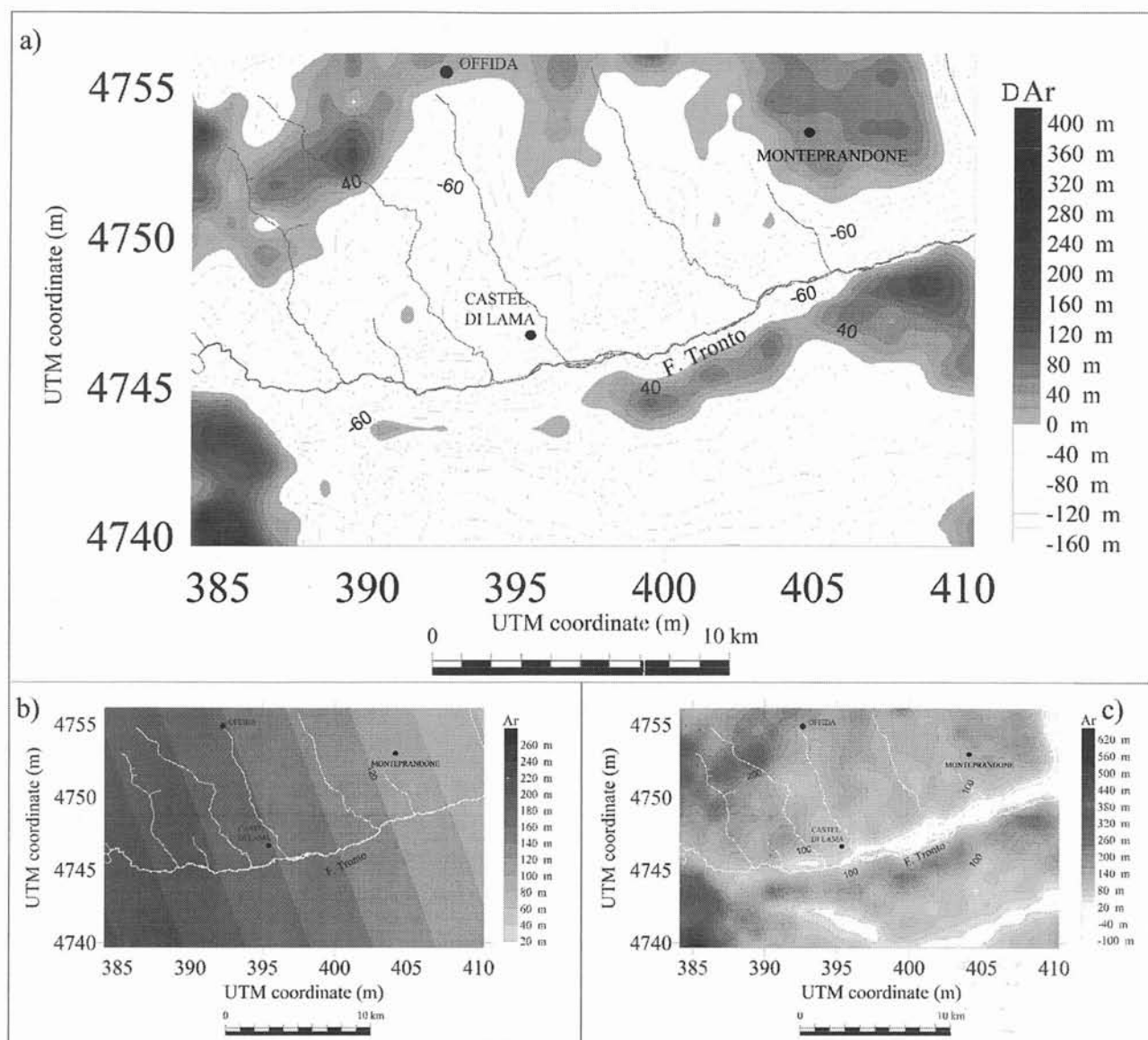


FIG. 3 - Amplitude of relief geostatistical analysis; the residual map (a) was obtained by subtracting the regional trend of A, (b) from the original dataset grid (c).

SW-NE oriented ones; in all these cases it is associated to «valley-shaped» and «bell-shaped» spectra as well, suggesting the presence of both dip- and strike-slip offsets along these fault zones. However, this preliminary outcome does not provide information about the mechanism (oblique-slip or strain partitioning), which accompanies these two offset components.

THE TRONTO VALLEY FLUVIAL TERRACES

The first studies on the rivers draining the peri-adriatic region of Central Italy focused on the classification and description of fluvial terraces; four orders of terraces were

recognized and related to glacial and inter-glacial stages (Lipparini, 1939; Villa, 1942). This linear correlation was successively considered inadequate to explain the terraces formation that occurred, more precisely, as response to alternating aggradational and erosive phases of rivers, associated to Quaternary climatic oscillations and to regional uplift (Nesci & Savelli, 1986; Bisci & Dramis, 1991). During the main glacial periods of the Middle-Upper Pleistocene increasing solid discharge, induced by strong weathering, led to aggradation. On the contrary, during more temperate climatic periods, increasing erosional power of rivers led to fluvial deepening, in a first time simply by load decrease, but successively under the control of regional uplift (Nesci & Savelli, 1986; Coltorti & *alii*, 1991).

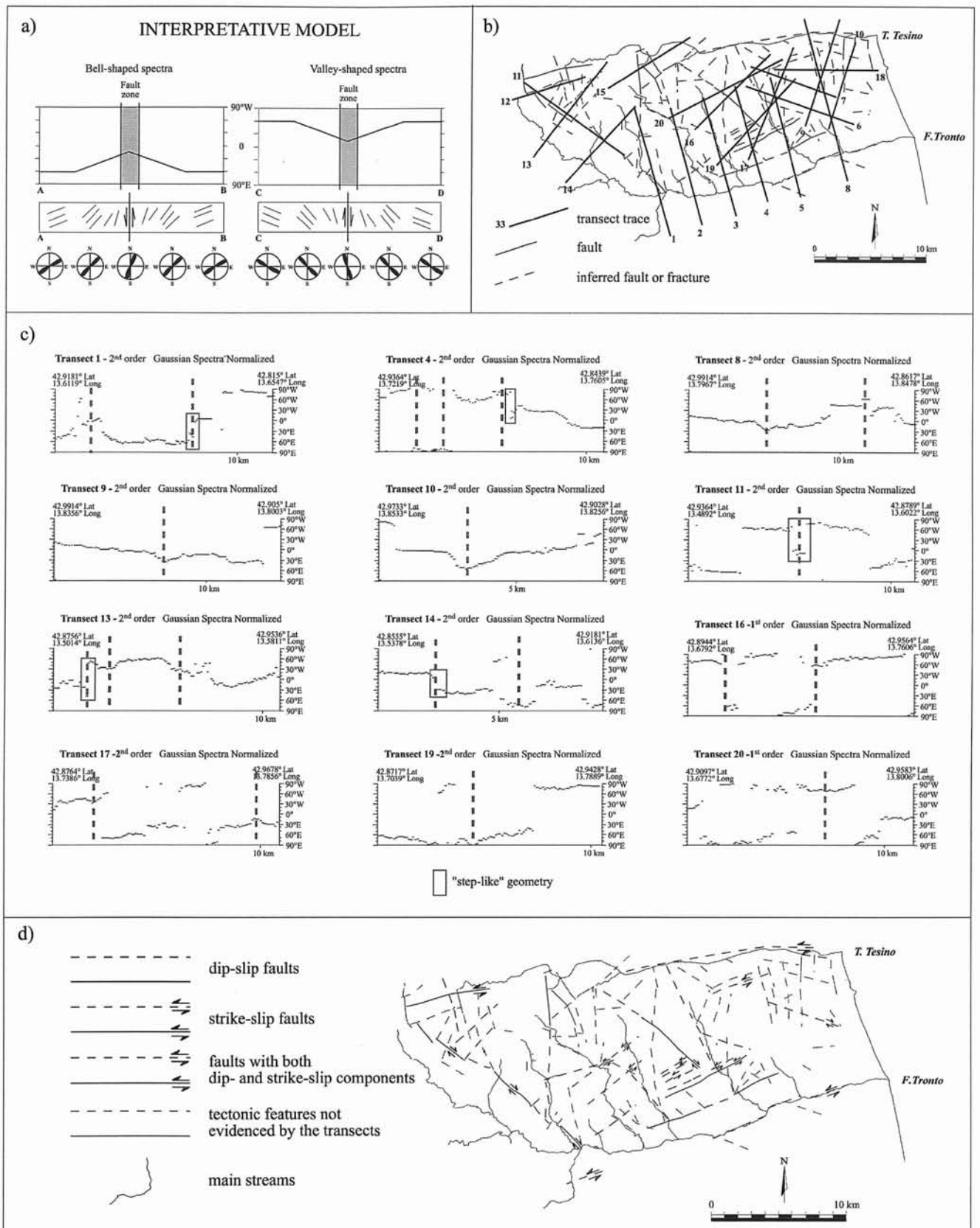


FIG. 4 - Azimuthal transects. Interpretative model (a) and location of transects (b) are indicated, along with the most significant output diagrams (c) and final results (d).

In particular, the early glacial stages as well as the interglacials were characterized by fluvial entrenching and extensive terracement of previous valley fills (Nesci & Savelli, 1990); repeated aggradation episodes did occur along the trunk-valleys (Coltorti, 1991; Nesci & *alii*, 1995), but they superimposed to an overall down-cutting tendency (Nesci & Savelli, 1991a, 1991b). During the interglacials only the river mouth areas and the downstream-valley reaches experimented thick and extensive aggradation, mainly connected to sea-level rise (Nesci & *alii*, 1995). On the contrary, the aggradational upward growing of the alluvial plain levels (i.e. the primitive, undeformed, terrace level) - although repeatedly interrupted by cut-and-fill episodes (Calderoni & *alii*, 1991) - seem to continue during almost the whole second half of the glacial stages with both fluvial and alluvial-fan deposits (Nesci & *alii*, 1995).

Although the classification (succession) of the Middle Pleistocene-Holocene terraced units is confirmed in the Marche and Abruzzi regions (Fanucci & *alii*, 1991), the terrace sequence of the Fiume Tronto is more difficult to determine, because of the strong tectonic influence on the

terraces formation acknowledged since the earliest studies (Lipparini, 1939).

To improve the comprehension of terraces development and to test a methodological approach for morpho-tectonic studies, the quantitative topographic analysis of the Tronto terraces has been performed.

Quantitative topographic analysis

The geostatistical analysis was preceded by detailed stratigraphic, sedimentological and morphological field surveys of the alluvial bodies. Once recognized the terrace top surfaces, their elevations were sampled (850 points) using a portable GPS with 5 m resolution. Five «levels» of terraces, at most, was recognised, not necessarily coinciding to five different «orders». These levels were marked by progressive letters (A, B, C, ...) from the *talweg* upward (fig. 5); the lowest one (level A), probably corresponding to the Holocene terrace, was not sampled because of the wide anthropogenic modifications.

With the exception of level A, the alluvial terraces are present only on the left valley slope, while on the right one only a level of erosional terrace is present (figs. 1b and 6).

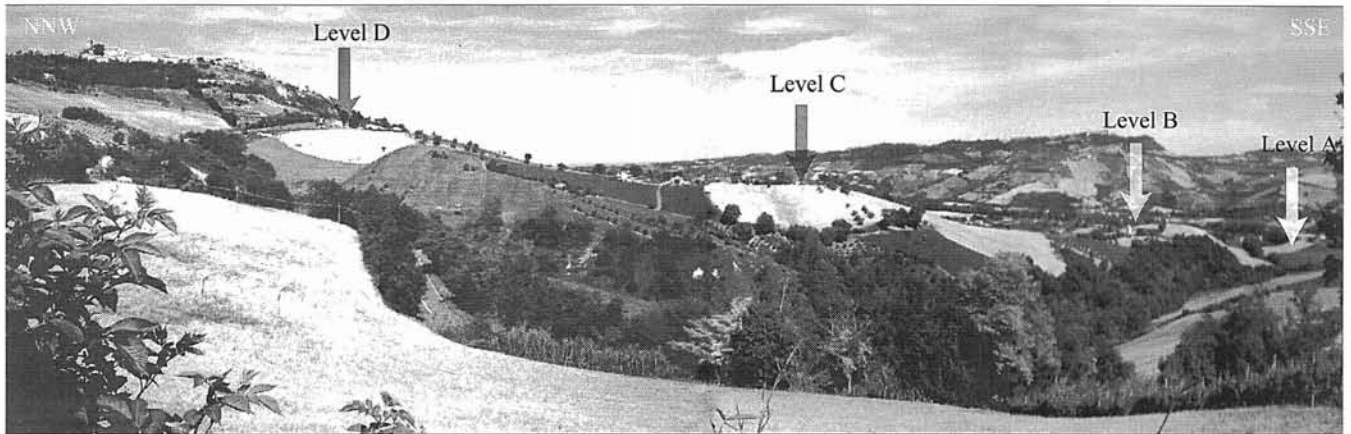
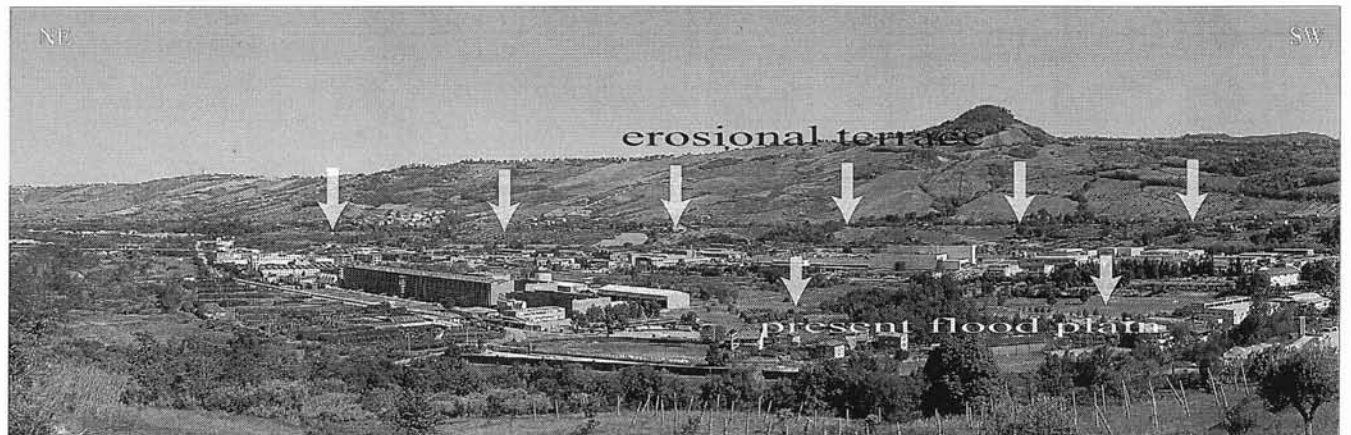


FIG. 5 - Levels of terrace surfaces on the left slope of the Tronto valley.



* FIG. 6 - View of the Tronto valley with the erosional terrace on the right slope.

This asymmetrical distribution can be explained with south-southeastward migration of the main river due to the Tronto fault downthrown block tilting. Moreover the right tributaries of Fiume Tronto deeply cut their valleys on the upthrown block, especially in the westernmost portion of the slope. Here, the powerful head-ward erosion of the Torrente Marino (fig. 1) shifted the Tronto divide southward; consequently the enhanced solid discharge could have led to the formation of the large alluvial fan shown in fig. 7.

All the alluvial bodies show similar lithological and sedimentological features, independently from their elevation: at the base, heterometric, polygenic (carbonate and sandstone clasts) and grain-supported gravels (3-6 m thick) with silty matrix are present; the gravel bed is overlain by a silty deposit of variable thickness (3-4 m for higher terrace levels, 8-20 m for lower ones) with no evidence of sedimentary structures (fig. 8). Comparing qualitatively the composition of gravel clasts at different heights, a progressive decrease in the abundance of carbonate clasts is registered upward; this testifies for lithological changes within the Apenninic stratigraphical sequence, cut by the Fiume Tronto during its progressive deepening. Finally, very large blocks have been observed just within the alluvial deposits of the topographically higher levels of terraces (fig. 9).

Collected topographic data, processed as a whole by the kriging method (Cressie, 1990, and references therein),

provided the «overall topography map» of all the terraces (fig. 10a). Successively, a «residual contour map» was derived, indicating the relative elevations of terrace remnants upon the present *talweg*. Finally, to better evidence the longitudinal shape of terrace levels, their elevations were projected on the XZ plane (fig. 10c).

The general trend of the flattish surfaces indicates that not all the levels can be considered as different orders of terraces; nevertheless, the continuity of levels B and C indicates their possible correspondence to T_3 and T_2 terrace orders by Nesci & Savelli (1991a). The interpolation among the remnants of the different levels evidences the presence of «converging» terraces (Castiglioni, 1934). In fact, both the «overall topography map» and the «residual map», show high gradients between levels B and C, and C and D, in the westernmost portion of the area; on the contrary, moving towards the Tronto mouth the difference in elevation between levels B and C tends to disappear. This convergence confirms the influence of the regional uplift on the terrace development.

The interpretation of the longitudinal trends of levels D and E is more difficult. Nevertheless some observations are of interest.

In the eastern portion of the projection of fig. 10c (i.e. to the East of the UTM coordinate 400,000), level D seems to be shifted downward respect to the same level in the western portion; with the exception of the area

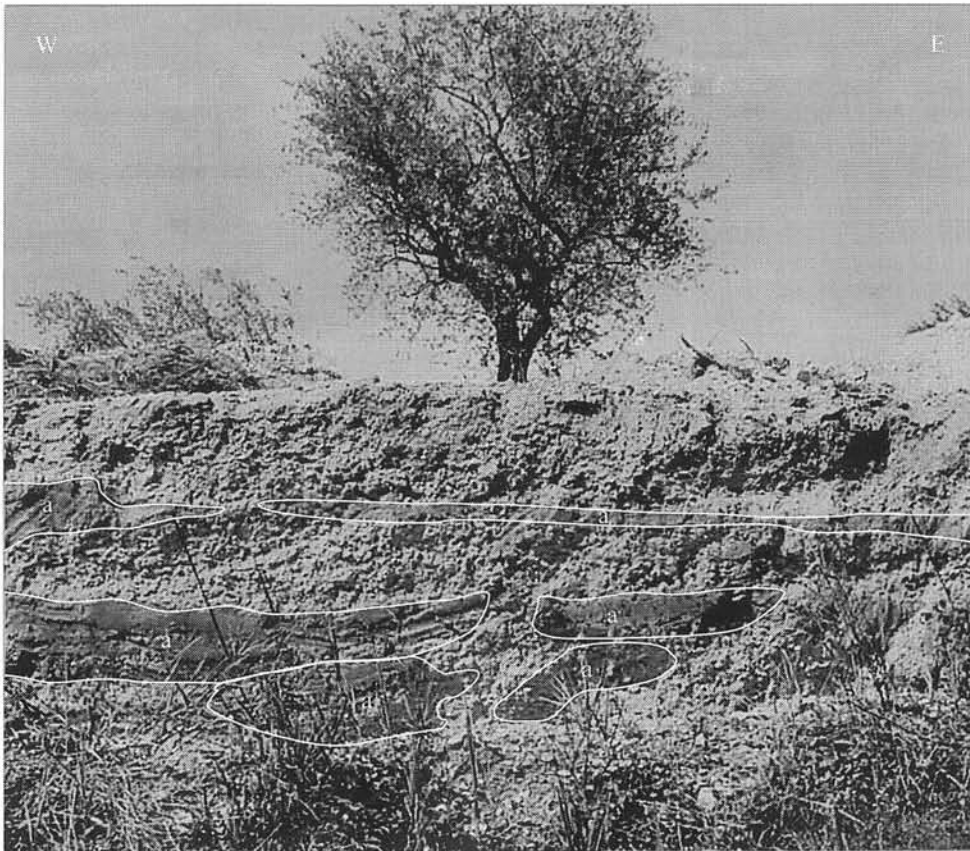


FIG. 7 - Torrente Marino alluvial fan deposit, made up of gravels with intercalated sandy beds and lenses (a).

FIG. 8 - Typical terrace section.



FIG. 9 - Example of large block at the base of the terrace body at higher levels.

close to the river mouth, where an increase in elevation is recorded.

Level E is rather discontinuous; where observable, however, it seems to keep parallel to level D. Moreover, the longitudinal trend of these two levels shows some similarity, as if they were the same level shifted in height. Although preliminary this observation is in accordance with the results of previous morphotectonic analysis that indicate the existence, in this area, of faults, approximately WSW-ENE oriented, with dip-slip components as shown by the step-like geometry of some azimuthal transects (fig. 4, transect 4 and 8). Then, the comparison of results suggests that level D and E can be really a single depositional body, corresponding to T_1 terrace (probably referable to T_{1b} in the sequence of Nesci & Savelli, 1991a) displaced by a normal fault of about 20 m (fig. 10c). This consideration is in accordance with Coltorti & *alii* (1991). The inferred fault is probably a conjugate plane of the major Tronto fault (figs. 1 and 10b). In the eastern portion of the projection in fig. 10c the effects of this fault are outlined also by the general downward shift of all terrace levels which probably lie on the downthrown block, while the remnants in the westernmost part of the slope are on the up-thrown one.

A field evidence given by a counter slope (fig. 11) suggests the presence of a minor normal fault to the West of Castel di Lama Town (fig. 10b) which could have displaced the T_1 terrace, giving rise to back tilting of the downthrown block. Thus, probably, the westernmost remnants of level C surface may belong to the T_1 terrace and not to the T_2 one.

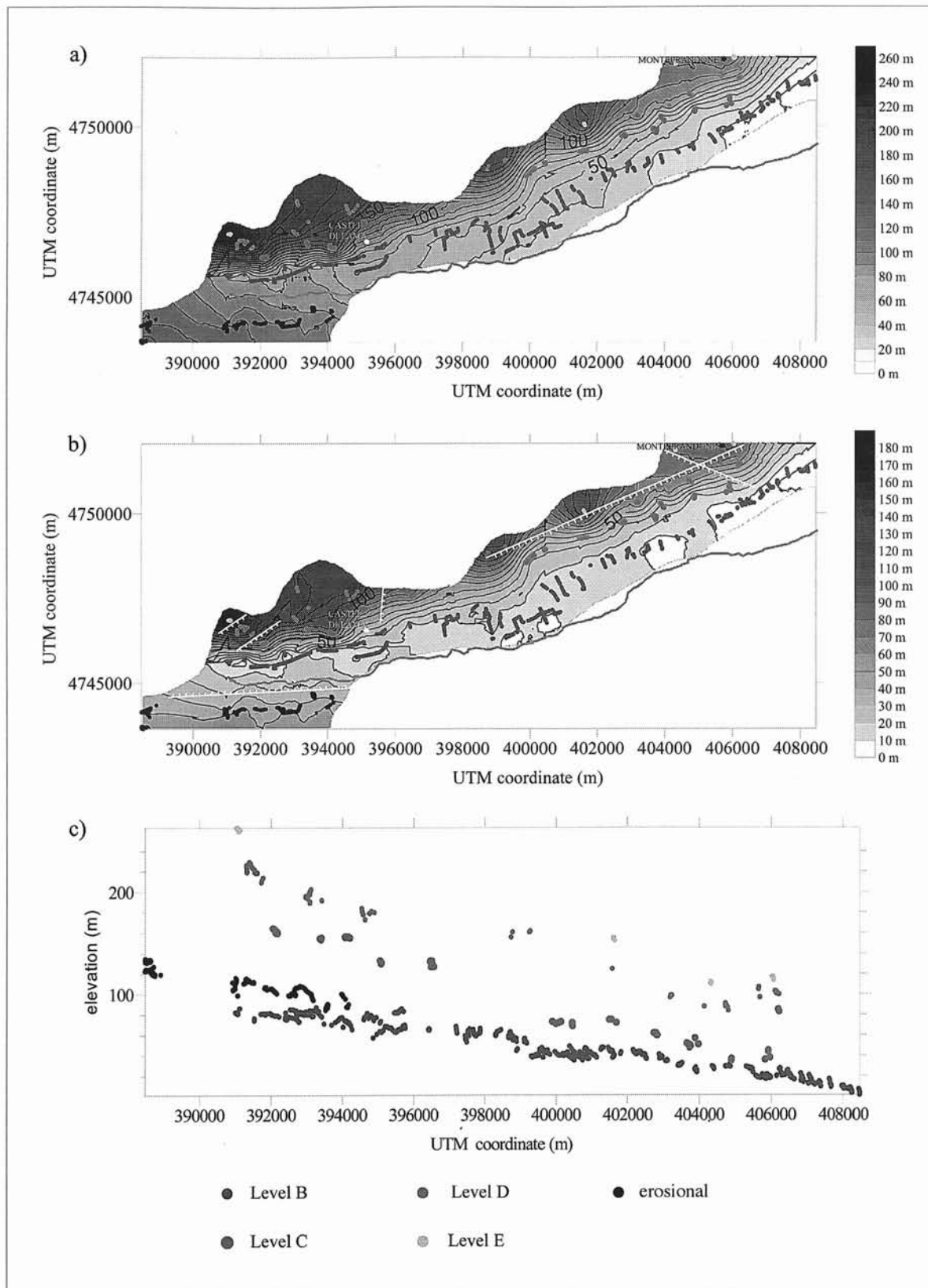


FIG. 10 - Geostatistical topographic analysis of the Tronto basin fluvial terraces; a) «overall topography» map of all terraces. The location of the different levels helps the interpretation of the terraces chronology; b) residual topography, given by the elevations of the surfaces on the *talweg*, and inferred faults dislocating the terraces; c) projection of the terraces absolute elevations on the XZ plane: the projection gives the longitudinal trend of terrace levels.

FIG. 11 - Counterslope to the West of Castel di Lama town, suggesting the presence of a WSW-ENE dip-slip fault. Between the upthrown (Ut) and the downthrown (Dt) the bedrock crop out, outlined by the vegetation.



To the East of Castel di Lama town an altimetric anomaly indicates that the T_2 and T_3 terraces seem to be lowered eastward, of about 20 and 10 meters respectively, by a normal fault transverse to the valley (fig. 10b); this fault might correspond to the N-S trending one indicated in fig. 1, along which active mud volcanoes were detected. Another altimetric anomaly is clearly evidenced by the longitudinal trend of levels C, D and E near the mouth. In fact, they undergo an increase in elevation, which is incompatible with the fluvial dynamics and probably due to the activity of a WNW-ESE trending normal fault near Montepreandone. Thus, all the terrace remnants to the

West of this fault probably belongs to T_{1b} WSW-ENE faulted terrace, while the highest level detectable in the profile might represent a little remnant of the oldest fluvial terrace of the Tronto river (i.e. T_{1a} , Nesci & Savelli, 1991a).

The distribution of elevation points on the remnant surfaces of terraces, as indicated by the contour map of figure 10a, suggests also that lower orders are more tilted towards the present flood plain than the higher ones, confirming the hypothesis of south-south-eastward tilting of the left slope due to the Tronto fault dip-slip kinematic component (fig. 12). The erosional, rock-cut terrace on the right valley side is about 25-30 m higher than the upper Pleistocene

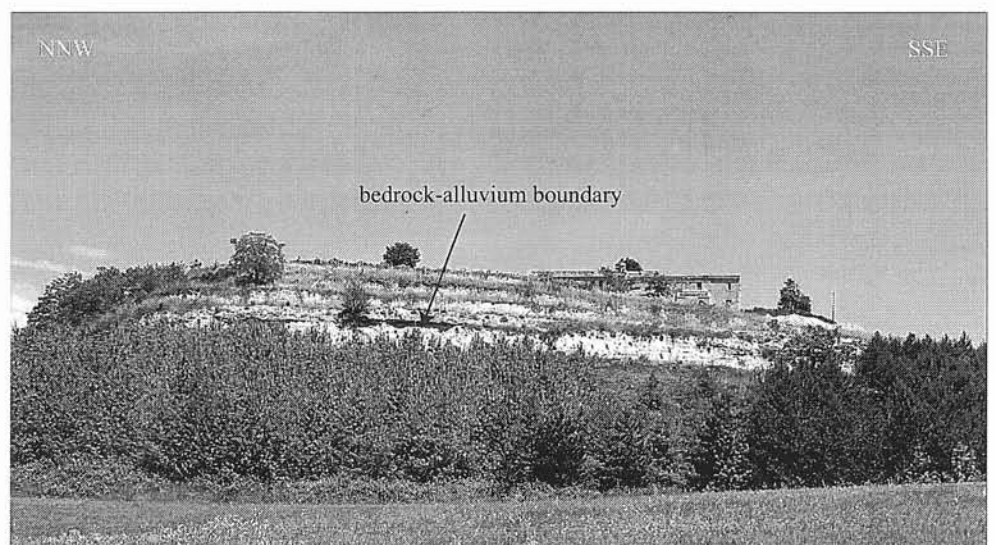


FIG. 12 - Bedrock and terrace deposit slightly tilted towards the SSE confirm the presence of the Tronto fault with a normal kinematic component lowering and tilting the left slope of the valley.

terrace alluvium top-surface (T_3) on the opposit valley flank (fig. 7). Supposing that the primitive rock-cut surface was a prosecution of the top-surface of the T_3 alluvium, their vertical offset (about 25-30 m) might be ascribed to the dip-slip displacement along the major fault. Since a slightly remoulding of the T_3 alluvium top-surface - with formation of unpaired minor terraces - cannot be ruled out, the offset could be fairly lesser than the above. Nevertheless, a certain amount of fault-related terrace offset between the two valley sides is to be confirmed on the basis of integrated quantitative and qualitative geomorphologic analysis.

CONCLUSIONS

Results obtained confirmed the reliability of the quantitative geomorphic approach to the study of morphological records of neotectonic significance.

In particular, the methodological outcomes of this work demonstrate that fluvial terraces can be geostatistically treated with success, as already confirmed for other

landscape features (relief, drainage patterns). In fact, the application of geostatistical methods to the study of fluvial terraces can help the unbiased interpretation of their evolutionary sequence, thus increasing their importance as neotectonic indicators. In this perspective, since they represent timelines capable of timing the tectonic deformations, the geostatistical topographic analysis of river terraces can provides important constraints to morphotectonic reconstructions.

Locally, four orders of pre-Holocene alluvial terraces were recognized on the left slope of the Tronto drainage basin, while on the right one a single erosional terrace was observed (fig. 13). Their topographic arrangement is influenced by the ENE-ward dipping regional uplift and confirms the activity of a WSW-ENE major fault, run by the Fiume Tronto. Associated to this fault, a conjugate one and two minor N-S and WNW-ESE trending active faults were detected that displace the different orders of terraces by estimated amounts. Once the absolute ages of terraces will be known, it will be possible to calculate exactly the slip rates of the identified faults.

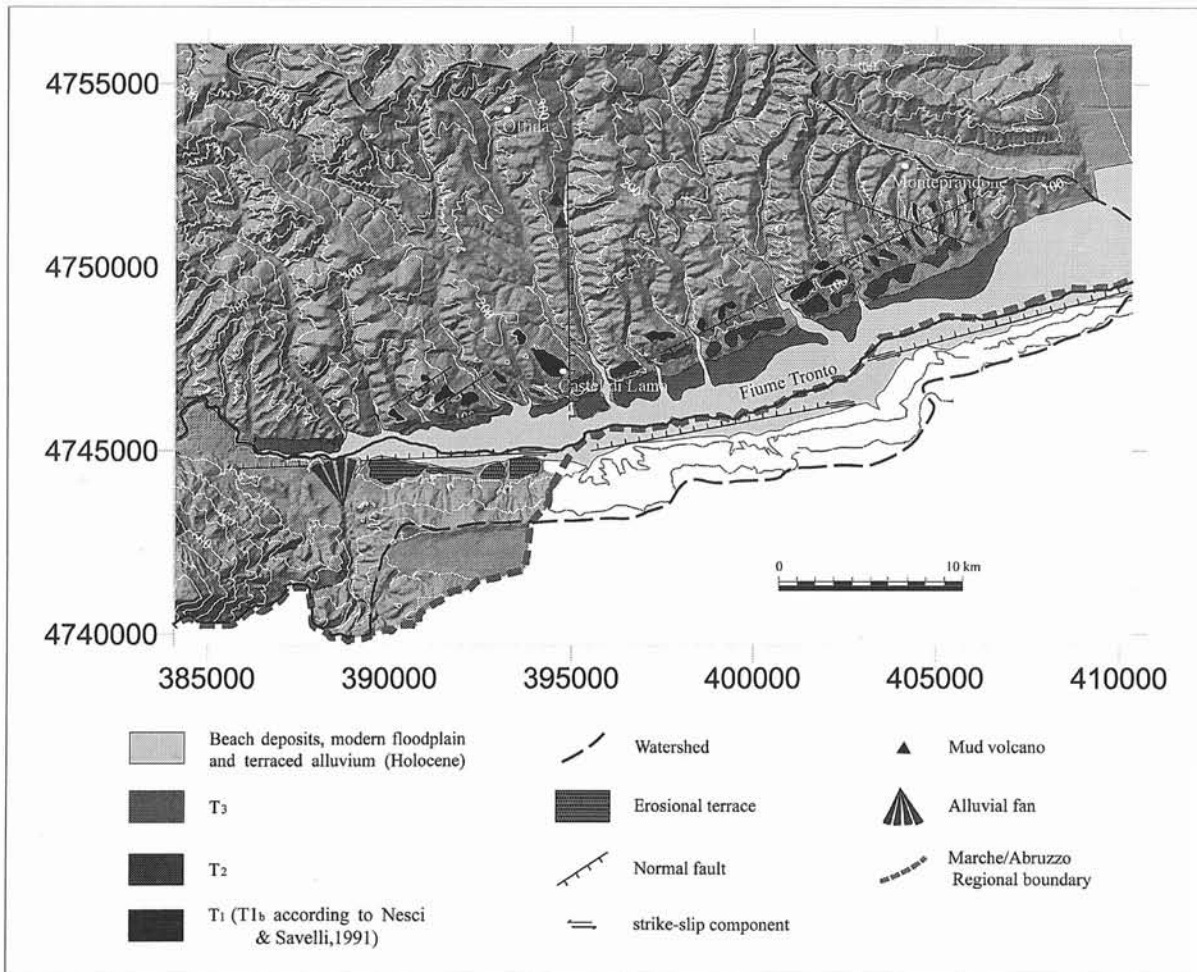


FIG. 13 - Morphotectonic reconstruction of the low Tronto valley.

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