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Quaternary normal faults, intramontane basins and seismicity in the Umbria-Marche-Abruzzi Apennine Ridge (Italy): contribution of neotectonic analysis to seismic hazard assessment

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ABSTRACT

In the Umbria-Marche-Abruzzi (UMA) Apennine ridge, measurements of the Quaternary amount of displacement, and the long-term slip-rates related to the extensional active faults, were carried out by geological and geomorphological analyses. This integrated study revealed that most of the major active extensional faults which bound the intramontane Quaternary basins represent the reactivation of pre- and syn-orogenic extensional structures. As a consequence, the total downthrow of the intramontane basin boundary faults must be divided amongst distinct episodes of extension; furthermore, intramontane basin locations can be strongly influenced by pre-Quaternary geological and structural assemblage. The maximum displacement / fault length (*D/L*) ratio for Quaternary normal faults shows a best fit along a curve which follows the power-law equation $D = 0.027*L^{1.071}$. We found slip-rates in the order of 0.4 mm/yr for the central Umbria-Marche Apennines (*e.g.,* Colfiorito basin boundary fault), whereas values ranging between 0.5 and 1.2 mm/yr characterize the southern Umbria-Marche and Abruzzi Apennine ridge. These values are consistent with the southward increase of the faults map length, as well as the southward widening of the intramontane Quaternary basins. Furthermore, our data are in agreement with seismological data for the study area which show the magnitude of the recent and historical major earthquakes, ranging from about M 6 to the north up to M 7 to the south.

KEY WORDS: *Neotectonics, Quaternary Normal Faults, Intramontane Basins, Seismicity, Umbria-Marche-Abruzzi (UMA) Apennine Ridge.*

RIASSUNTO

Faglie normali quaternarie, bacini intermontani e sismicità nella dorsale appenninica umbro-marchigiano-abruzzese: il contributo dell'analisi neotettonica nella valutazione della pericolosità sismica.

È stata effettuata un'analisi neotettonica quantitativa dei sistemi di faglie normali quaternarie della dorsale umbro-marchigiana-abruzzese (UMA) e dei bacini intermontani associati. La loro parametrizzazione è stata utilizzata quale contributo geologico-strutturale per la valutazione della pericolosità sismica, ottenendo dei risultati confrontabili con quelli sismologici.

Sono state prese in considerazione le faglie bordiere dei bacini di Colfiorito, di Norcia e del M. Vettore (Appennino umbro-marchigiano), di Assergi, Sulmona e del Fucino (Appennino abruzzese). L'approccio integrato dei dati geologici, strutturali e geomorfologici ha rivelato che la maggior parte delle faglie estensionali che delimitano i bacini intrappeninici quaternari rappresentano la riattivazione di faglie estensionali pre e sin-orogeniche. Pertanto, il rigetto totale è la sommatoria di distinti eventi estensionali; fa eccezione la faglia bordiera del bacino di Colfiorito dove la corrispondenza tra il rigetto geologico e quello geomorfologico suggerisce l'ipotesi di una faglia di neoformazione. L'ubicazione dei bacini montani è dunque fortemente influenzata dalla storia geologico-strutturale pre-quaternaria.

Il rapporto tra il massimo rigetto quaternario (*D*) e la lunghezza (*L*) delle faglie attive analizzate è descritto da una curva che segue una legge di potenza ($D = 0.027*L^{1.071}$) e testimonia una relazione «scala-invariante» per dette strutture. Tale relazione, inoltre, mostra una buona corrispondenza con quelle esistenti in letteratura per vari tipi e dimensioni di faglie, suggerendo che i metodi qui applicati per la valutazione del rigetto quaternario delle faglie possono essere considerati attendibili.

La valutazione del rigetto e dei tassi di movimento a lungo termine, connessi con l'attività delle faglie normali quaternarie, ha permesso di stabilire i tassi dei valori di dislocamento di circa 0.4 mm/a nell'area centrale dell'Appennino umbro-marchigiano (p.e. Colfiorito), mentre valori tra 0.5 e 1.2 mm/a caratterizzano l'area meridionale umbro-marchigiana e la dorsale abruzzese. Questi valori sono in accordo con l'aumento verso sud: *a*) della lunghezza delle faglie attive; *b*) della dimensione dei bacini intermontani; *c*) dell'intensità sismica, da M ≈6 a nord (p.e. Norcia, 1979, Colfiorito, 1997) a M≈ 7 (p.e. Avezzano, 1915) a sud (CNR-PFG, 1985; WESTAWAY, 1992; CNR-GNDT, 1996; ING-SGA, 1997; EKSTRÖM *et alii*, 1998; SELVAGGI, 1998; GRUPPO DI LAVORO CPTI, 1999).

Sono state ricostruite 3 principali tipologie di bacino: 1) bacini connessi a faglie bordiere caratterizzate da un basso valore dello *slip-rate* 0,2-0,5 mm/a (p.e. Colfiorito) che si presentano totalmente o parzialmente erosi, a drenaggio esterno e con substrato affiorante nel blocco di tetto alla base della scarpata di faglia; 2) bacini delimitati da faglie con *slip-rate* maggiori 0.6-1.0 mm/a (p.e. Norcia, Sulmona), anch'essi esoreici, ma con depositi di maggior spessore che ricoprono il blocco di tetto della faglia; 3) bacini delimitati da faglie con *slip-rate* > 1 mm/a (p.e. Fucino) dove il drenaggio è endoreico e lo spessore dei depositi può superare i 1000 m.

Detta tipologia è strettamente connessa al rapporto tra il tasso di sollevamento, valutato a circa 1.0 mm/a e lo *slip-rate* delle faglie. Per valori confrontabili (*slip-rate* ≈ tasso di sollevamento), il rigetto della faglia corrisponde allo spessore del cuneo di crescita dei sedimenti nel bacino, come evidenziato attraverso i dati di sottosuolo per il bacino del Fucino.

TERMINI CHIAVE: *Neotettonica, Faglie Normali Quaternarie, Bacini intermontani, Sismicità, Dorsale Appenninica Umbro-Marchigiano-Abruzzese.*

INTRODUCTION

Extensional faults affecting the Neogene thrust system of the Central Apennine (fig. 1) show geological and morphotectonic evidence of Quaternary activity (BARCHI *et alii*, 2000 and references therein). The ongoing extensional tectonics of the Central Apennines is confirmed by widespread seismicity and historical earthquakes of moderate magnitude M≤7 (*e.g.,* CNR-PFG, 1985; CNR-GNDT, 1996; ING-SGA, 1997; GRUPPO DI LAVORO CPTI, 1999). Neotectonic analysis for active faults systems is crucial, because its time span is greater than the seismological and paleoseismological records, while comparison of the

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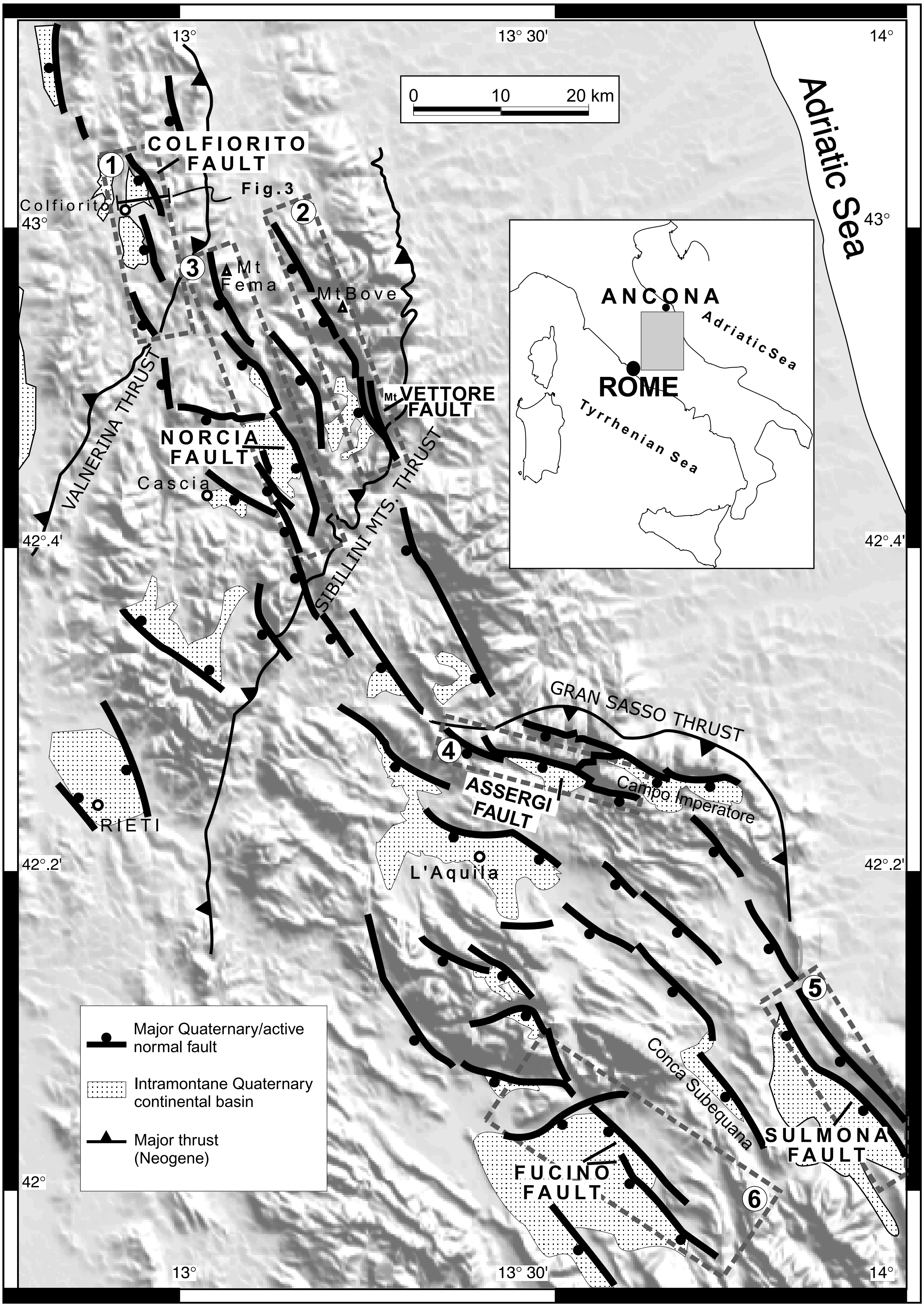

Fig. 1 - Simplified structural map of the Umbria-Marche-Abruzzi (UMA) Apennine ridge. Boxes (1-6): studied fault systems. – *Schema strutturale della dorsale appenninica umbro-marchigiano-abruzzese. I rettangoli racchiudono i sistemi di faglie quaternarie analizzate in questo lavoro.*

quantitative data yielded by these three methods gives a more detailed insight of seismogenic faults behavior.

The integrated analysis of geologic and geomorphic data in the UMA Apennine ridge was used to evaluate the Quaternary fault displacement. In particular, recognition of a «planation surface» (modeled during the end of Lower Pliocene: COLTORTI & PIERUCCINI, 2000), which is then offset by the Quaternary faults, was useful in evaluating the amount of geomorphological downthrow. For most of these major active normal/transtensive faults, in fact, the displacement amount of the planation surface is generally less with respect to the geological downthrow, confirming that they must be directly related to pre-existing normal faults reactivated during Quaternary extension (PIZZI & SCISCIANI, 2000). Pre-orogenic extensional structures are the well-documented Jurassic normal faults (*e.g.*, CENTAMORE *et alii*, 1986 and references therein) related to the Tethyan rifting phase (pre-orogenic structures), or younger, Cretaceous (*e.g.*, WINTER & TAPPONIER, 1991 and references therein); whereas syn-orogenic structures, mostly Miocene, have been related to flexure of the foreland (*e.g.*, CALAMITA *et alii*, 1998 and references therein).

For several active faults of the UMA Apennine ridge (fig. 1) we parameterized their: *a*) Quaternary amount of displacement; *b*) map length; and *c*) the geometry of the related intramontane basins. Since evaluation of fault displacement permits the investigation of quantitative neotectonic relationships such as the maximum fault displacement (*D*) *vs.* fault length (*L*) (*e.g.*, WALSH & WATTERSON, 1988; COWIE & SCHOLZ, 1992; SCHLISCHE & ANDERS, 1996) the obtained amount of (*D*) was compared with the map length of the active faults (*L*) in order to test data consistency and to reconstruct the regression of faults map length on earthquake magnitude.

QUATERNARY FAULT DISPLACEMENT

Neotectonic quantitative analyses allowed us to evaluate the Quaternary maximum amount of displacement which can be closely related to the extensional active faults. In particular, we analyzed the Mt. Vettore, Norcia and Colfiorito (Umbro-Marchean Apennines), and the Assergi, Sulmona and Fucino (Abruzzi Apennines) fault systems. They are characterized by a NNW-SSE average trend, and have normal to transtensive behavior (CALAMITA *et alii*, 1997 and references therein). Extensional fault segments have a map length up to 20-25 km and are arranged in distinct fault systems, which have a maximum length of about 30-40 km and are spaced approximately every 10-15 km. Normal faults kinematics is in good agreement with the focal mechanism solutions of the Central Apennines earthquakes which indicate a T-axis mainly oriented NE-SW (*e.g.*, FREPOLI & AMATO, 1997).

We show here two case examples (Mt. Vettore and Colfiorito faults: figs. 2 and 3) where the morphotectonic approach can been applied to define the geomorphologic downthrow (*i.e.*, the amount of cumulative Quaternary displacement). For these two faults, in fact, the dimen-

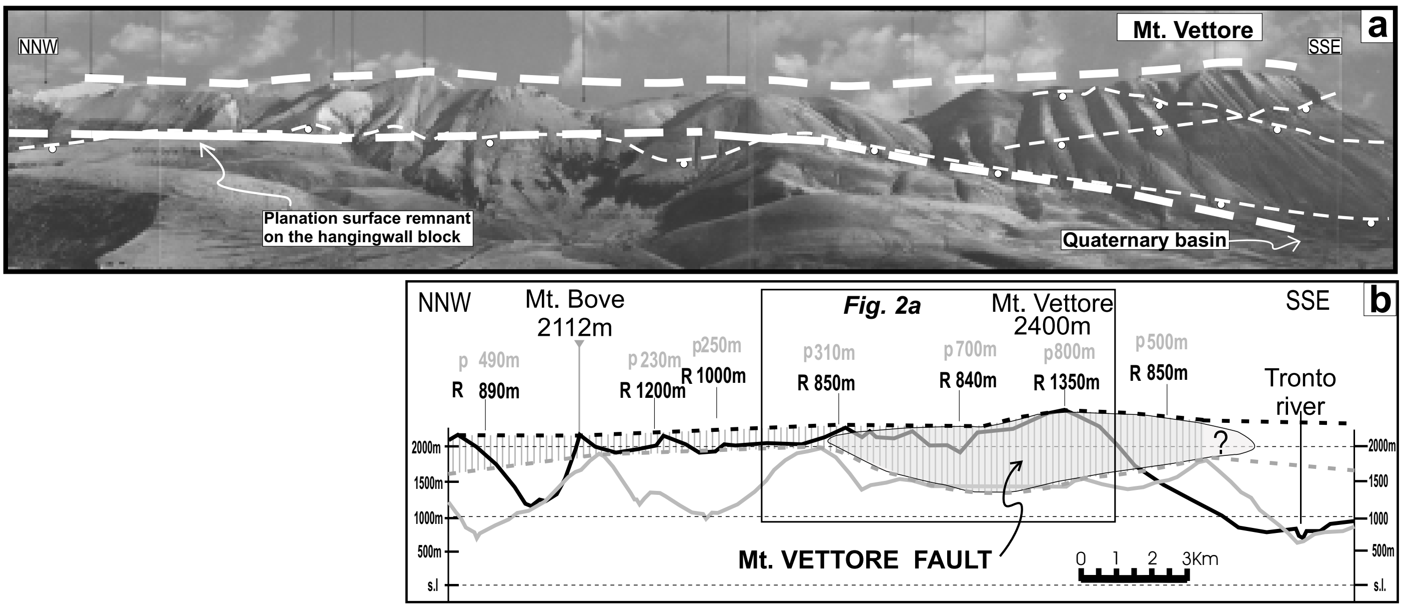

Fig. 2 - The Mt. Vettore fault system (box 2 in fig. 1). *a*) View of the Mt. Vettore normal faults (narrow broken line). The wide broken lines mark the traces of the reconstructed planation surface on the carbonate bedrock both on the footwall and the hangingwall blocks. *b*) Topographic profiles along the Mt. Vettore fault system (black solid line: hangingwall block; gray solid line: footwall block). Dashed area is delimited by the traces (black and gray broken lines) of planation surface remnants interpolation (which occurs within a 5 km wide transect) and represents the offset of the planation surface «Δp» (Quaternary downthrow). «R» = geological downthrow, obtained from geologic cross sections (modified from PIZZI & SCISCIANI, 2000).

– *Sistema di faglia di M. Vettore (per l'ubicazione vedere fig. 1).* a) *Panoramica delle faglie del M. Vettore (linea a tratteggio sottile) mostrante l'andamento della superficie di planazione nei blocchi di tetto e di letto (linea a tratteggio spessa).* b) *Profili topografici longitudinali lungo il sistema di faglie di M. Vettore (linea nera: blocco di letto; linea grigia: blocco di letto). L'area a tratteggio verticale è delimitata da linee che rappresentano l'interpolazione dei lembi di superficie di planazione (presenti lungo un transetto largo 5 km) ed esprime l'entità del rigetto della superficie di planazione «Δp» (rigetto quaternario). «R»: rigetto geologico calcolato lungo profili geologici trasversali (modificato da PIZZI & SCISCIANI, 2000).*

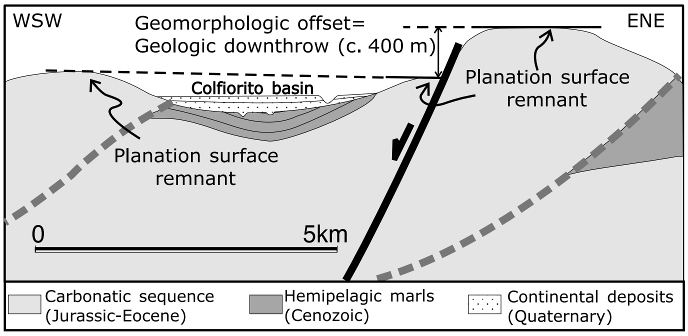

Fig. 3 - Schematic geologic cross section through the Colfiorito basin showing the Quaternary fault displacement evaluated by planation surface data. Location on fig. 1.
– *Sezione geologica schematica attraverso il bacino di Colfiorito mostrante il rigetto quaternario della faglia valutato dalla dislocazione della superficie di planazione. Vedere fig. 1 per l'ubicazione.*

sion of the related Quaternary basin (5-8 km long) is quite small with respect to fault length.

In the Mt. Vettore fault system, which represents the easternmost active extensional fault zones of the southern Umbro-Marchean Apennine ridge (fig. 1), remnants of the planated surface have been recognized in the carbonate bedrock (BLUMETTI & DRAMIS, 1992; COLTORTI & FARABOLLINI, 1995). Morphotectonic analysis allowed us to reconstruct the former location of the displaced planation surface both on the footwall and the hangingwall blocks (fig. 2a). In the topographic profiles (fig. 2b) drawn along the footwall and the hangingwall blocks of the Mt. Vettore fault, the offset of the planation surface due to the Mt. Vettore fault provides a measurement of the post-planation maximum displacement (Δp), which is in the order of 700-800 m.

The Colfiorito basin developed above a syncline where Cenozoic marls crop out. In the hangingwall block, the planation surface remnants are found close to the fault trace (fig. 3). The Colfiorito fault provided a case study of a newly-formed fault which shows the same amount (c.a. 400 m) of geological and geomorphological displacement, suggesting that fault activity is entirely attributable to Quaternary extension.

The presence of a wider tectonic basin (*e.g.*, the Sulmona and Fucino basins), however, prevented the recognition of the planation surface (in the hangingwall block of the boundary fault) over long distances. In the Fucino fault system, the extent of Quaternary displacement of the eastern boundary fault can be evaluated from seismic reflection data (CAVINATO *et alii*, 1999; PALTRINIERI, unpublished data). Pre-Quaternary fault activity has been documented for this fault system (BONCIO *et alii*, 1998). However, a reflective interval attributed to Pliocene?-Early Pleistocene sediments is recognizable on the hangingwall (below the «growth wedge» of deposits due to Quaternary fault activity) and on the footwall. Therefore, the Quaternary downthrow of the fault can be estimated to be in the order of 1200 m.

With regard to the Sulmona fault, we evaluated the map length as being in the order of 20 km, whereas unavailable subsurface data prevented us from determining the amount of Quaternary fault displacement.

Table 1 lists the data which were used for the active faults parameterization.

TABLE 1

Geometric and kinematic parameters of the studied Quaternary/active faults.
– *Parametri geometrici e cinematici delle faglie quaternarie ed attive analizzate.*

Quaternary/ active normal fault	Map length (km)	Fault dip at surface	Main kinematics	Maximum Quaternary displacement (m)
Colfiorito	8	50°-60° SW	NE extension	400
M. Vettore	13	45°-70° SW	NE extension	700-800
Norcia	15	50°-60° SW	NE extension	800-900
Assergi	17	45°-60° SSW	NNE extension	1000
Sulmona	20-21	50°-70° SW	NE extension	?
Fucino	23	50°-70° SW	NE extension	c. 1200

DISPLACEMENT/LENGTH SCALING RELATIONSHIP FOR ACTIVE FAULTS

Several studies have documented a systematic increase in maximum finite displacement along faults with respect to their length (*e.g.*, WALSH & WATTERSON, 1988; COWIE & SCHOLZ, 1992). The length of active fault segments within the analyzed fault systems was evaluated with regard to their map length, constrained by geologic and morphotectonic data, as well as the length of the related intramontane basin.

In the bi-log diagram of fig. 4, the maximum finite Quaternary displacement (*D*) plotted *vs.* the fault segment length (*L*) is represented by the power-law equation $D = 0.027 * L^{1.071}$ which suggests a «self-similar» behavior for the analyzed active faults. This equation is well within the range of those scale invariant relations found by other researchers, who obtained *L* exponent ranges between 1.0 and 2.0 (*e.g.*, WALSH & WATTERSON, 1988; COWIE & SCHOLZ, 1992; DAVISON, 1994).

The bi-log diagram of fig. 4 was used to evaluate the maximum finite Quaternary displacement of the Sulmona fault considering its map length, which is approximately 20 km. The obtained Quaternary offset is in the order of 1000 to 1100 m, whereas the amount of geological downthrow has been evaluated to be 1500 to 2000 m according to CALAMITA & PIZZI (in press), suggesting that the Sulmona fault also reactivates a pre-existing normal fault.

THE RELATION OF FAULT LENGTH TO EARTHQUAKE MAGNITUDE

Surface rupture length of an active fault can be related to earthquake magnitude by means of the relationships found in WELLS and COPPERSMITH (1994). We applied these relationships to the studied active faults (fig. 5a) and assumed that the length of the fault segment

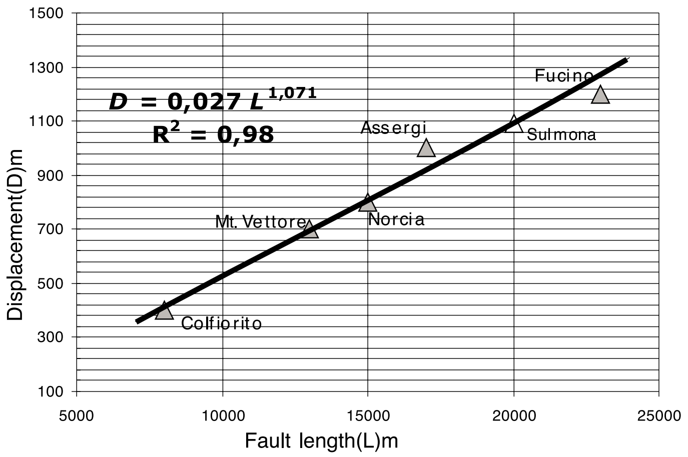

Fig. 4 - Log maximum finite displacement (D) *vs.* log fault-strike length (L) for the analyzed active faults (see text for explanation).
– *Diagramma bilogaritmico rigetto massimo finito (D)/lunghezza (L) relativo alle faglie attive esaminate.*

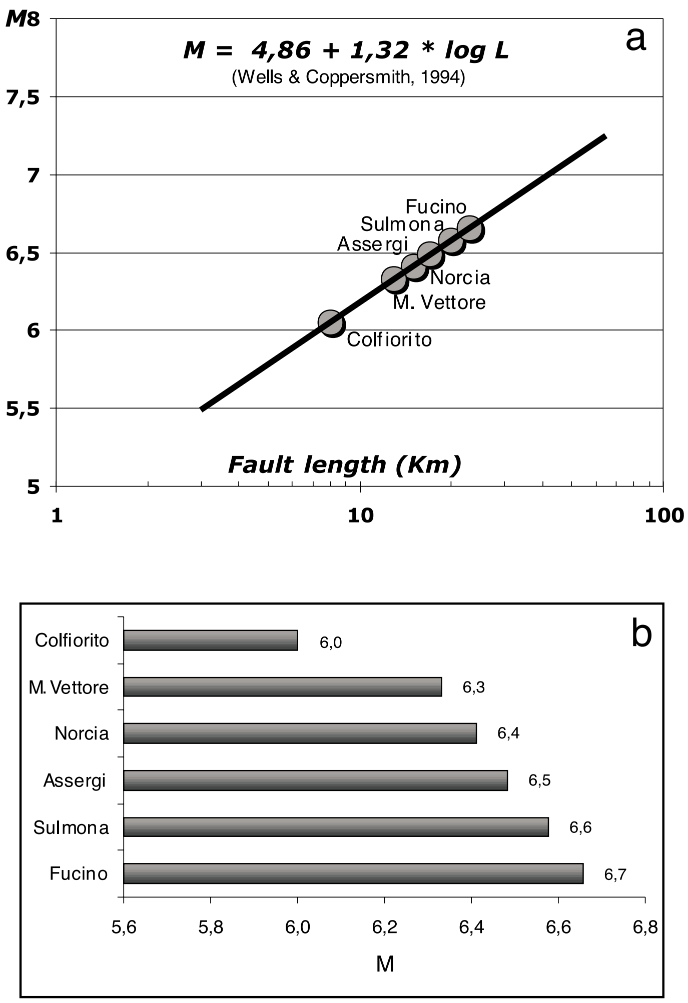

Fig. 5 - *a*) Fault map length vs. magnitude according to the WELLS & COPPERSMITH (1994) relationship (see text for explanation). *b*) obtained magnitude values (note the increase in magnitude toward the south).
– a) *Diagramma lunghezza faglia/magnitudo, ottenuto utilizzando la relazione di* WELLS & COPPERSMITH *(1994) per le faglie normali.* b) *valori della magnitudo ricavati (notare l'aumento dei valori verso sud).*

was equivalent to the surface rupture length following the «n» th earthquake of that characteristic magnitude according to SCHWARTZ *et alii* (1981), WESNOUSKY (1983) and WALSH & WATTERSON (1992).

The values we obtained (fig. 5b) are compatible with the southward increase in coseismic extension rate (SELVAGGI, 1998 and references therein), as well as in earthquake magnitude, from approximately M 6.0 in the north (*e.g.*, Colfiorito, 1997) to approximately M 7 in the area to the south (*e.g.*, Avezzano, 1915), estimated for recent and historical earthquakes (*e.g.*, CNR-PFG, 1985; WESTAWAY, 1992; CNR-GNDT, 1996; ING-SGA, 1997; EKSTRÖM *et alii*, 1998; GRUPPO DI LAVORO CPTI, 1999).

LONG-TERM SLIP-RATES, REGIONAL UPLIFT RATE AND BASINS MORPHOLOGY

Long-term (Quaternary) slip-rates were estimated assuming that the beginning of the Quaternary faults activity was ca. 1.0-1.2 Ma BP, which is the age of the oldest continental deposits in the tectonic depressions of the UMA Apennine ridge (COLTORTI *et alii*, 1998; CALAMITA *et alii*, 2000). This assumption is likely correct for some basins (*i.e.*, Colfiorito) due to the many independent chronostratigraphic elements available and their association with the fault activity. However, it is more difficult to establish in the Norcia, Mt. Vettore, Sulmona, and Fucino basins where the age of the basal deposits is still unknown. The timing of activity for faults like the Assergi fault system is more difficult to establish because of extensive erosion and the absence of Middle Pleistocene deposits within the basin.

However, long-term slip-rates clearly increase progressively southeastward (fig. 6) and give comparable results with some of the co-seismic slip-rates evaluated for historical earthquakes or deduced from paleoseismological analysis (BARCHI *et alii*, 2000 and references therein). This suggests that the seismic potential of the seismogenic faults remained nearly constant during their Quaternary activity.

The compatibility of the displacements and relative slip-rates of the Quaternary faults analyzed with the dimensions and typology of the associated intramontane basins was verified.

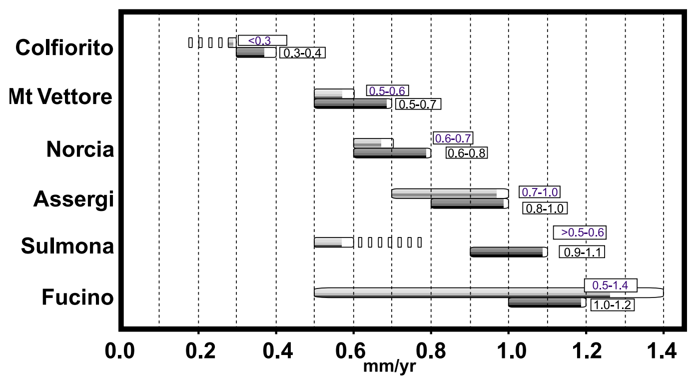

Fig. 6 - Comparison between the evaluated long-term (Quaternary) slip-rates and the seismological/paleoseismological values available in the literature (BARCHI *et alii*, 2000 and references therein).
– *Confronto tra i valori degli slip-rate a lungo termine (quaternari) e quelli disponibili dalla bibliografia (*BARCHI *et alii, 2000 cum biblio) mediante dati sismologici e paleosismologici.*

The size and morphology of the tectonic continental basins, in fact, are due to the dynamic interaction between the deepening of the hydrographic network, the regional uplift rates, and the slip-rates of the faults, as well as to the sedimentation rate. To a lesser extent they are influenced by local factors such as footwall and hangingwall lithology, and the spacing between sub-parallel fault systems (*i.e.*, Assergi and Aquila; Media Valle Aterno/Conca Subequana and Sulmona; Celano/Ovindoli/Mts. d'Ocre and Fucino).

Comparing our results on the Quaternary activity of the studied faults (long term slip-rates) and considering the mean regional uplift rate during the Quaternary of ca. 1 mm/yr, as we deduced from available literature (*e.g.*, BASILI, 1999; CALAMITA *et alii*, 1999) we hypothesize that the typology of the basins is associated mostly with the dynamic interaction of slip-rate *vs* uplift-rate. These two factors operate independently from the evolution of the drainage network. Three main basin/infilling relationships can be observed (fig. 7). The first case (figs. 3 and 7a) is found in basins that are partially (in some cases totally) eroded. The bedrock of the hangingwall crops out also along or at the base of the fault escarpment. These basins are usually associated with faults having minimal slip-rates in the order of 0.2-0.5 mm/yr (*i.e.*, Colfiorito basin); the Assergi basin, which could be included in this group but which is characterized by a master fault with slip-rates of ca. 0.7-1 mm/yr seems to suggest the intervention of local factors such as the high relief energy of the surrounding area (higher erosional power of the local streams) related to the proximity of the lower L'Aquila basin. In the second case, faults delimit well-developed basins but there is also clear evidence of erosional processes and external drainage (fig. 7b). This second type of basin usually corresponds to faults with a slip-rate in the order of 0.6-1.0 mm/yr (*i.e.*, Norcia and Sulmona basins). In the third relationship (fig. 7c), the basins are well-developed, usually with an endorheic drainage which is mostly affected by depositional processes and usually corresponds to faults with slip-rates > 1 mm/yr (*i.e.*, the Fucino basin).

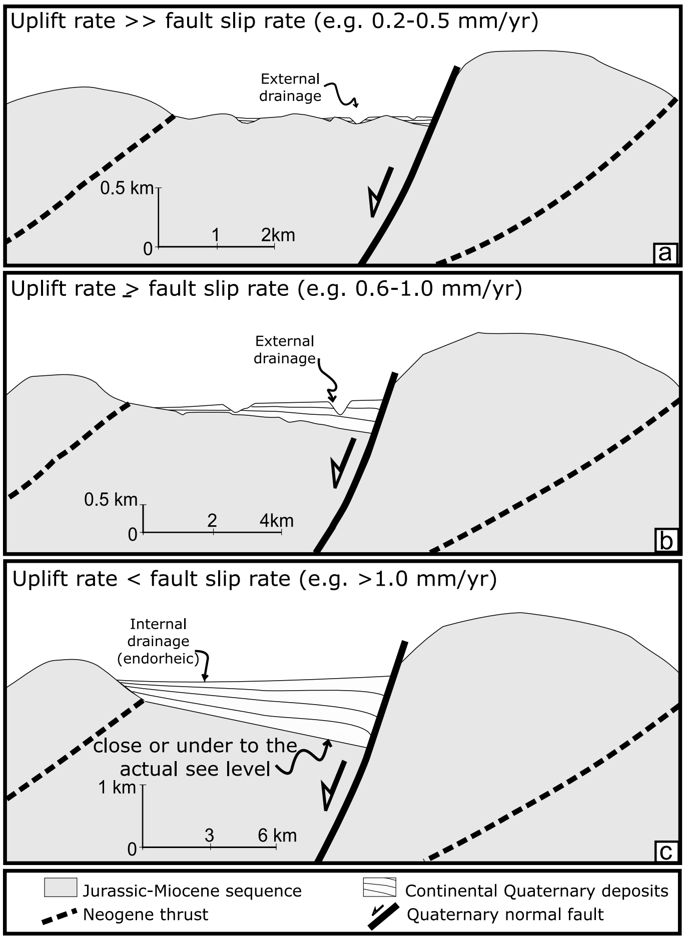

Fig. 7 - Three simplified typologies of intramontane basins defined by different slip-rates vs. regional uplift-rate.
– *Tre principali tipologie di bacini intermontani riconosciute nell'area studiata e definite da differenti rapporti tra gli slip-rate delle faglie ed il tasso di sollevamento regionale.*

CONCLUSIONS

A quantitative neotectonic analysis was carried out for the Quaternary normal faults and related intramontane basins in the UMA Apennine ridge (Italy). The parameterization of the fault data allowed us to make a contribution to seismic hazard assessment. In fact, the results are in good agreement with the seismological data, which shows the relevance of the geological and morphotectonic approach.

The integrated analysis revealed that most of the major Quaternary, and still active, normal faults represent the reactivation of pre- and syn-orogenic extensional structures. The Quaternary amount of maximum displacement (D) for the intramontane basins boundary faults was separated from the total geologic downthrow and compared with the map length (L) of the faults. The D/L ratio for these active normal faults shows a best fit along a curve which follows the power-law equation $D = 0.027*L^{1.071}$. The good correlation between this equation and that already described in the literature for other fault systems, suggests that our method of evaluating the maximum Quaternary displacement is reasonable for the studied faults and may also be applied in similar morphotectonic settings.

Assuming that the beginning of the ongoing extensional tectonic regime in the UMA Apennine ridge began at 1.0-1.2 My BP, then we estimate long-term slip-rates in the order of 0.4 mm/yr for the faults of the central Umbria-Marche Apennines (*e.g.*, Colfiorito fault) and, values between 0.5 and 1.2 mm/yr for the southern Umbria-Marche and the Abruzzi Apennine ridge.

These values are consistent with the southward increase in length of the faults, as well as the southward widening of the intramontane Quaternary basins. Furthermore, we suggest that this pattern of length and widening is in agreement with the increase of earthquake magnitude for the area from about M 6 to the north up to M 7 to the south, as well as the coseismic extension rate.

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