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MULTIDISCIPLINARY METHODS OF INVESTIGATION FOR A SINGLE FAULT

CONTENTS

ABSTRACT

We use different methods of investigation (field geology, structural analysis, geomorphology, seismic reflection profiles and seismological data) to study the same fault (Gubbio normal fault in central Italy). The availability of different data-sources gives us the opportunity of comparing different approaches, hence evaluating points of consensus and/or controversy in fault analysis. From our integrated analysis we define a well focussed image of the geometry and kinematics of the Gubbio fault and the related Quaternary basin, while the seismogenic role of the fault is still ambiguous.

KEY WORDS: Normal faults, earthquakes, seismic profiles, seismotectonics

1. INTRODUCTION

Different, widely shared, methods of investigation can be used in fault analysis: surface geology is more concerned with sudden changes in lithology associated with fault activity and describes the fault plane characteristics and the fault rocks in terms of geometric and kinematic analysis. Geomorphology studies irregularities in slopes and anomalies in the drainage network linked with faulting. Seismic reflection data display a prominent reflector on a seismic profile and/or interruption and displacement of seismic markers. Seismology is more focused on the assessment of seismic energy release associated with earthquakes as well as on the geometry and distribution properties of aftershock sequences. These methods of investigation are different and provide different pictures of a same fault.

Comparison and integration of these different methods, however, is not a trivial matter. Here we discuss this problem in detail in order to emphasise the importance of a multidisciplinary approach for the study of active faults. To this aim, we refer to the Gubbio normal Fault, GuF, located in the northern Apennines of central Italy. This fault gives us the opportunity of comparing different available data sets from different sources: surface geology, structural analysis, geomorphology, seismic reflection profiles and seismology. On the basis of data comparison we propose a discussion about the possibility of integrating different data sources into a coherent image of the GuF.

2. GEOLOGICAL SETTING

The Gubbio fault (GuF) is a 22 km long normal fault which borders a Quaternary basin and pertains to the active faults alignment of the Umbria Fault System (UFS – BARCHI, 2002) in Central Italy. To this fault, both historical (I_{max}=VIII, BOSCHI *et alii*, 1997) and instrumental seismicity (i.e. 1984 Ms=5.2, HAESSLER *et alii*, 1988) are associated. The fault downthrows the backlimb of a prevoiusly formed NE verging anticline (BARNABA, 1958; DE FEYTER & MENICHETTI, 1986; MENICHETTI & MINELLI, 1991) emplaced during upper Serravallian-lower Tortonian (fig.1a). At the surface, the GuF hangingwall consists of the Gubbio basin, elongated for about 22 km the NW-SE direction. The basin has a maximum width of about 4 km (MENICHETTI, 1992; PUCCI *et alii*, 2003) in correspondance with the town of Gubbio and is infilled with early Pleistocene (i.e. late Villafranchian) fluvio-lacustrine deposits (ESU & GIROTTI, 1991).

3. STRUCTURAL DATA

The Gubbio fault strikes about N135° and dips towards SW at dips in the range 50°-70° at the surface (fig.1b). Structural analysis of the Gubbio fault shows that the associated deformation zone (up to 150 m wide) consists of synthetic and subordinate antithetic splays showing Andersonian dips, 52°-78°, and a slightly bimodal strike direction (azimuth 120°-140°) with a nearly pure dip-slip extensional kinematics (fig.1b). Striated fault planes were analysed in 16 structural stations, homogenously distributed within the study area; inversion of slip data was computed by a standard inversion technique (DAISY, Salvini, 1998), and the results allowed us to define a constant stress tensor with a vertical $\sigma1$ and a SW-NE oriented $\sigma3$, in accordance with regional studies of this sector of the Apennines (e.g. LAVECCHIA *et alii*, 1994; BONCIO *et alii*, 1996; BONCIO *et alii*, 2000).

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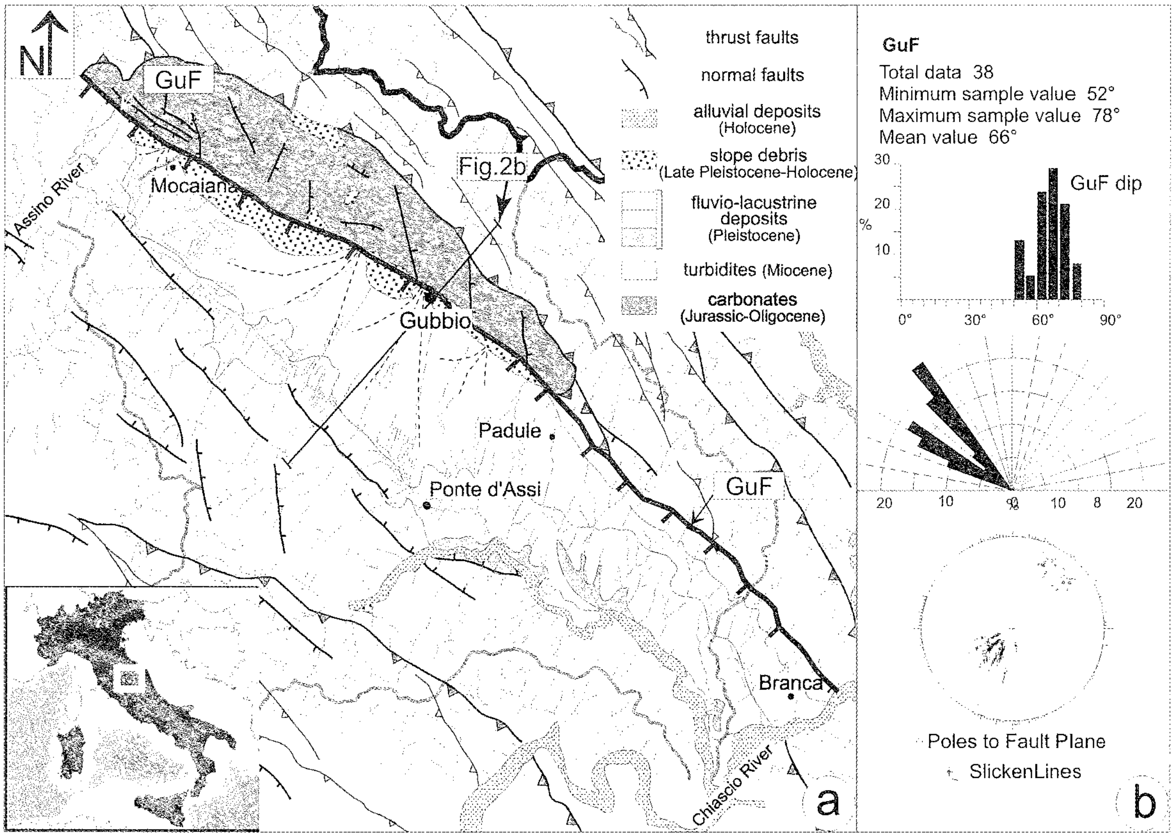

Fig. 1 - (a) Simplified map of the Gubbio area modified after, Moretti & Perno (1968), MENICHETTI (1992), showing the drainage network of the Gubbio basin and its watershed. (b) Gubbio normal fault dip histogram (top), strike and stereoplot (Schmidt equal area projection, lower hemisphere).

4. GEOMORPHOLOGY

A set of topographic profiles through the Gubbio basin shows that the basin floor lies at about 400 m a.s.l., whereas the eastern and western ranges reach elevations of about 950 and 650 m a.s.l. respectively (PUCCI *et alii*, 2003). This strong topographyc expression (~450m) strictly reflects the fault Quaternary activity which affected the drainage pattern of the area, producing deep transversal gorges perpendicular to the basin (fig.2a). Concerning indicators of recent activity of the fault, however, the drainage pattern of the two flanks, described in detail in COLLETTINI et alii (2003) shows that it is difficult to identify clear recent geomorphological evidence of the GuF in the eastern flank of the Gubbio basin, probably due to the prevalence of erosional processes on tectonics.

5. SEISMIC REFLECTION PROFILES

A network of 6 good quality seismic profiles (e.g. Fig.2d) allowed to reconstruct the geometry of the fault at depth (MIRABELLA, 2002). Depth conversion of the seismic profiles show that the fault geometry is steep in its shallow portion, ~45° for the first 4 km, and gently dipping at depth, ~20° at 5-6 km. The deeper portion of the fault reactivates a thrust of the previous compressional phase, which formed the Gubbio anticline. The profiles also show that the GuF is antithetic to and detached on a regional NE-dipping low-angle normal fault, the Altotiberina fault (ATF; BARCHI *et alii*, 1999; BONCIO *et alii*, 2000) which bounds the westernmost Tiber basin at the surface.

6. SEISMOLOGICAL DATA

Three seismic sequences have been recorded in the Central Apennines in the last two decades: Norcia 1979 Mw=5.8, Gubbio 1984 Mw=5.6 and Colfiorito 1997-1998 Mw<6.0 (DESCHAMPS *et alii*, 1984; HAESSLER *et alii*, 1988; WESTAWAY *et alii*, 1989; AMATO *et alii*, 1998). A relocation (COLLETTINI e tal., 2003) of ~300 aftershocks (M<3.5), recorded within a week at a temporary, local network of 9 stations during the 1984 Gubbio sequence with the "double-difference" relocation algorithm (WALDHAUSER & ELLSWORTH, 2000) produced 215 relocated events (fig.2c), with mean RMS of 0.04 s and formal horizontal and vertical errors of 200m and 400m respectively. Though the general shape of the seismicity on the map is very similar to that presented by HAESSLER *et alii*, (1988) and the elongation of the seismicity is the N130° direction, the distribution is shallower and does not unambiguously define a fault plane. The focal mechanism solution associated to the mainshock is very controversial too; three different focal mechanism solutions are available for the same mainshock: 1) a body wave focal mechanism (HAESSLER *et alii*, 1988), 2) a CMT solution (DZIEWONSKI *et alii*, 1985), and 3) a revised body wave focal mechanism (WESTAWAY *et alii*, 1989). The last two solutions show NW-SE trending focal planes that are consistent

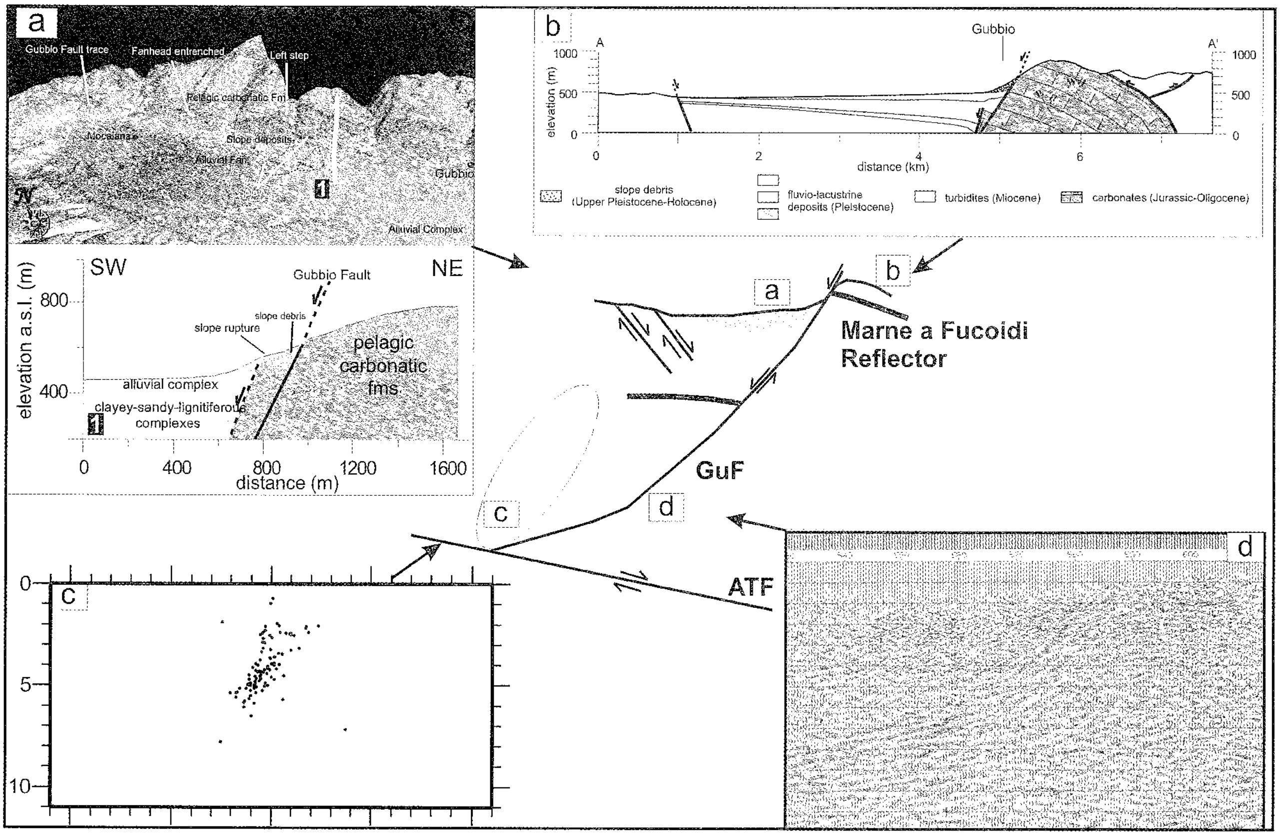

Fig. 2. (a) DEM (resolution=5m) of the northern portion of the Gubbio basin and cross section through the basin showing the geometry of the basin infillment; (b) Geological cross-section through the GuF (trace in fig.1); (c) Cross section through the relocated seismic sequence of the 1984 earthquake (after COLLETTINI *et alii*, 2003); (d) Seismic image of the GuF up to about 1 s (twt).

with the strike of the GuF and of the active faults of the region.

7. DISCUSSION AND CONCLUSIONS

Comparison of different methods of investigation (fig.2) shows a great consistency for the geometry and kinematics of the Gubbio normal fault. Though the seismogenic role in terms of maximum expected magnitude is still controversial.

Surface geological data (fig.2b) , structural analisys and geomorphology (fig. 1b) define a coherent image of the GuF concerning the fault extensional kinematics, length (22 km) and orientation (N135°) which strickly correspond to the length and orientation of the Quaternary basin; the steeply dipping fault plane measured at the surface, 52°-78° can be easily merged with the seismic image (fig 2d) of the shallower portion of the fault trace, dipping about 45° in the first 4 km and at about 20° at depth <6km providing a listric geometry. The strong asymmetry of the basin, infilled with syntectonic sediments (fig.2a), is clearly related to the activity of the SW-dipping GuF. The stress tensor obtained from the inversion of the striated fault planes, is constant within the Gubbio area and is consistent with the orientation of both the GuF and the geological stress tensor derived from other Quaternary faults in the region (e.g. LAVECCHIA *et alii*, 1994; BONCIO *et alii*, 1996).

For what concerns the seismogenic role of the GuF, the available dataset is more controversial. In fact there is little geological and geomorphological evidence of very recent activity of the fault and no surface breaks were observed during the 1984 seismic crisis. On the other hand, some evidence supporting a seismogenic role of the GuF can be derived, in particular: 1) The GuF is part of the active alignment of the northern Apennines and shows the same geometrical and geological characters of the active faults in the area (SW-dipping, basin-bounding normal fault). 2) The stress tensor obtained from the inversion of the striated fault planes is constant within the Gubbio area and is consistent with both the orientation of the GuF and the active stress tensor of the UFS (e.g. BONCIO *et alii*, 1996; MONTONE *et alii*, 1999). 3)Two of the three different focal mechanisms available for the mainshock have strikes which are consistent with the direction of the fault and also with the aftershock distribution. In conclusion we emphasise that the state knowledge on the dimensional properties of the GuF is well constrained, on the other hand the role of the GuF as an earthquake source in central Italy still needs to be better focussed.

ACKNOWLEDGMENTS

Research leading to this paper was supported by MIUR01 UR Perugia and Regione Umbria. We would like to thank ENI-AGIP, particularly S. Merlini, who provided the data set of seismic reflection profiles.

REFERENCES

AMATO A., AZZARA R., CHIARABBA C., CIMINI G.B., COCCO M., DI BONA M., MARGHERITI L., MAZZA S., MELE F., SELVAGGI G., BASILI A., BOSCHI E., COURBOULEX F., DESCHAMPS A., GAFFET S., BITTARELLI G., CHIARALUCE L., PICCININI D., RIPEPE M. (1998) - *The 1997 Umbria-Marche, Italy, earthquake sequence: a first look at the main shocks and aftershocks*. Geophysical Research Letters, **25**, 2861-2864.

BARCHI M. R., PAOLACCI S., PAUSELLI C., PIALLI G., MERLINI S. (1999) - *Geometria delle deformazioni estensionali recenti nel bacino dell'Alta Val Tiberina fra S. Giustino Umbro e Perugia: Evidenze geofisiche e considerazioni geologiche*. Bollettino Società Geologica Italiana, **118**, 617-625.

BARCHI M.R. (2002) - *Lithological and structural controls on the seismogenesis of the Umbria region: observations from seismic reflection profiles*. Bollettino Società Geologica Italiana, Volume Speciale n.**1**, 855-864.

BARNABA P.F. (1958) - *Geologia dei Monti di Gubbio*. Bollettino Società Geologica Italiana, **77(3)**, 39-70.

BONCIO P., BROZZETTI F., LAVECCHIA G., (1996) - *State of stress in the Northern Umbria-Marche Apennines (Central Italy): inferences from microearthquake and fault kinematic analyses*. Annales Tectonicae, **10 (1-2)**, 80-97.

BONCIO P., BROZZETTI F., LAVECCHIA G. (2000) - *Architecture and seismotectonics of a regional low-angle normal fault zone in Central Italy*. Tectonics, **19 (6)**, 1038-1055.

BOSCHI E., GUIDOBONI E., FERRARI G., VALENSISE G., GASPERINI P. (1997) - *CFTI, Catalogo dei Forti Terremoti Italiani dal 461 a.C. al 1990*. Istituto Nazionale di Geofisica, Storia Geofisica Ambiente, Bologna, 644 pp.

COLLETTINI C., BARCHI M.R., CHIARALUCE L., MIRABELLA F., PUCCI S. (2003) - *The Gubbio fault: can different methods give pictures of the same object*. Journal of Geodynamics, **36**, 51-66.

DEFEYTER A.J. & MENICHETTI M. (1986) - *Back thrusting in forelimbs of rootless anticlines, with examples from the Umbro-Marchean Apennines, (Italy)*. Memorie Società Geologica Italiana, **35**, 357-370.

DESCHAMPS A., IANNACCONE G., SCARPA R. (1984) - *The umbrian earthquake (Italy) of 19 september 1979*. Annales Geophysicae, **2(1)**, 29-36.

DZIEWONSKI A. M., FRANZEN J. E., WOODHOUSE J. H. (1985) - *Centroid-moment tensor solutions for April-June, 1984*. Physics Earth Planetary International, **37**, 87-96.

ESU D. & GIROTTI O. (1991) - *Late Pliocene and Pleistocene assemblages of continental molluscs in Italy; a survey*. Il Quaternario, **4 (1a)**, 137-150.

HAESSLER H., GAULON R., RIVERA L., CONSOLE R., FRONGNEUX M., GASPARINI G., MARTEL L., PATAU G., SICILIANO M., CISTERNAS A. (1988) - *The Perugia (Italy) earthquake of 29, April 1984: a microearthquake survey*. Bulletin Seismological Society of America, **78**, 1948-1964.

LAVECCHIA G., BROZZETTI F., BARCHI M. R., MENICHETTI M., KELLER J. V. A. (1994) - *Seismotectonic zoning in east-central Italy deduced from an analysis of the Neogene to present deformations and related stress fields*. Geological Society of America Bulletin, **106**, 1107-1120.

MENICHETTI M. & MINELLI G. (1991) - *Extensional tectonics and seismogenesis in Umbria (Central Italy) the Gubbio area*. Bollettino Società Geologica Italiana, **110**, 857-880.

MENICHETTI M., (1992) - *Evoluzione tettonico-sedimentaria della valle di Gubbio*. Studi Geologici Camerti, Vol. Spec. **1992/1**, 155-163.

MIRABELLA F., (2002) - *Seismogenesis of the Umbria-Marche region (Central Italy): geometry and kinematics of the active faults and mechanical behaviour of the involved rocks*. PhD thesis, University of Perugia (Italy), 172 p.

MONTONE P., AMATO A., PONDRELLI S. (1999) - *Active stress map of Italy*. Journal of Geophysical Research, **104**, 25595-25610.

MORETTI A., PERNO U. (1968) - *Carta geologica d'Italia 1:100.000* (2nd ed.) - sheet 123 Assisi, Italian Geological Survay.

PUCCI S., DE MARTINI P. M., PANTOSTI D., VALENSISE G. (2003) - *Geomorphology of the Gubbio basin (Central Italy): understandingthe active tectonics and earthquake potential*. Annals of Geophysics (in press).

SALVINI, F. (1998) - DAISY 2.1 Software. Rome.

WALDHAUSER F. & ELLSWORTH W. L., (2000) - *A double-difference earthquake location algorithm: Method and application to the northern Hayward Fault*. California. Bulletin Seismological Society of America, **90**, 1353-1368.

WESTAWAY R., GAWTHORPE R., TOZZI M. (1989) - *Seismological and field observations of the 1984 Lazio-Abruzzo earthquakes: implications for the active tectonics of Italy*. Geophysical Journal International, **98**, 489-514.