Active faults and inferred seismic sources in the San Vito lo Capo peninsula, northwestern Sicily, Italy

E. Tondi, D. Zampieri, G. Giunta, P. Renda, M. Alessandroni, M. Unti, A. Giorgianni and G. Cello

Geological Society, London, Special Publications 2006; v. 262; p. 365-377
doi:10.1144/GSL.SP.2006.262.01.22

Active faults and inferred seismic sources in the San Vito lo Capo peninsula, northwestern Sicily, Italy

E. TONDI[1], D. ZAMPIERI[2], G. GIUNTA[3], P. RENDA[3], M. ALESSANDRONI[3], M. UNTI[3], A. GIORGIANNI[3] & G. CELLO[1]

[1]*Dipartimento di Scienze della Terra, Università di Camerino, Via gentile III da Varano, 62032 Camerino (MC), Italy (e-mail: emanuele.tondi@unicam.it)*

[2]*Dipartimento di Geologia, Paleontologia e Geofisica, Università di Padova, Via Giotto 1, 35137 Padova, Italy*

[3]*Dipartimento di Geologia e Geodesia, Università di Palermo, Corso Tukory 131, 90134 Palermo, Italy*

Abstract: Two independent active faults, capable of generating medium-sized earthquakes in the San Vito lo Capo peninsula, northwestern Sicily (Italy) have been identified as a result of detailed field studies. In western Sicily, instrumental seismicity is low; in fact, except for the 1968 Belice earthquake (Ms = 5.4), historical records indicate that this area is relatively quiescent. Most of the seismicity is in the offshore sector of the Sicilian Maghrebian Chain, which is characterized by several medium- to low-magnitude events. The main shock of the 2002 Palermo seismic sequence (Mw = 5.9) represents the largest earthquake felt in the area in recent years. The deformation pattern characterizing the most recent faults mapped in northwestern Sicily includes a grid of high-angle faults consisting of major east–west-striking right-lateral and north–south-striking left-lateral features. This fault grid is related to a regional transcurrent right-lateral shear zone, here named the UEKA shear zone, bounded to the north by the Ustica–Eolie fault and to the south by the Kumeta–Alcantara fault. The UEKA shear zone accommodates the regional strain induced by the current stress field acting in the area, which, as emerges from both structural and seismological data, is characterized by a NW–SE-striking main compression.

The northern coast of Sicily and its Tyrrhenian offshore have been interpreted by various workers (e.g. Boccaletti *et al.* 1982; Malinverno & Ryan 1986; Dewey *et al.* 1989; Chironi *et al.* 2000) as a hinge zone between the Tyrrhenian basin (characterized by incipient oceanization processes) and the emerged portion of the Sicilian Maghrebian Chain. This hinge zone is interpreted as a regional east–west-striking right-lateral shear zone that developed from Pliocene time, while the structuring of the fold-and-thrust belt continued in southern Sicily (Boccaletti *et al.* 1982; Ghisetti & Vezzani 1984; Giunta *et al.* 2000).

As concerns seismicity, the Sicilian offshore is mainly characterized by medium- to low-magnitude events. The main shock of the 2002 Palermo seismic sequence (Mw = 5.9; CMT Catalog, Harvard Seismology, http://www.seismology.harvard.edu/) represents the largest earthquake felt in the area in recent years (Giunta *et al.* 2004). Onshore, in western Sicily, the 1968 Belice seismic sequence (Ms = 5.4 for the main shock; Anderson & Jackson 1987*b*) represents the strongest earthquake that has occurred in the area in historical times.

Several faults, in western Sicily, involve Pliocene and Early Pleistocene deposits; in the San Vito lo Capo peninsula, they cut through conglomerates of Tyrrhenian age and Holocene sediments, hence recording the effects of active tectonic processes in the area (Giunta *et al.* 2004). For this reason we focused our analyses in the San Vito Lo Capo peninsula, as it may be considered a key area for better understanding the tectonic processes acting in this sector of the peri-Tyrrhenian orogenic system, and to evaluate the seismic potential of northwestern Sicily.

Tectonic framework

The present-day structural setting of northern Sicily is the result of the Cenozoic collision between the North African continental margin and the Sardinia–Corsica block. The main tectonic units derived from the deformation of the northern margin of the African plate display a general southward vergence, and a structural style that is characterized by folds with a wavelength of a few kilometres and by thrusts that extend for tens of kilometres (Fig. 1;

From: MORATTI, G. & CHALOUAN, A. (eds) 2006. *Tectonics of the Western Mediterranean and North Africa.* Geological Society, London, Special Publications, **262**, 365–377.
0305-8719/06/$15.00

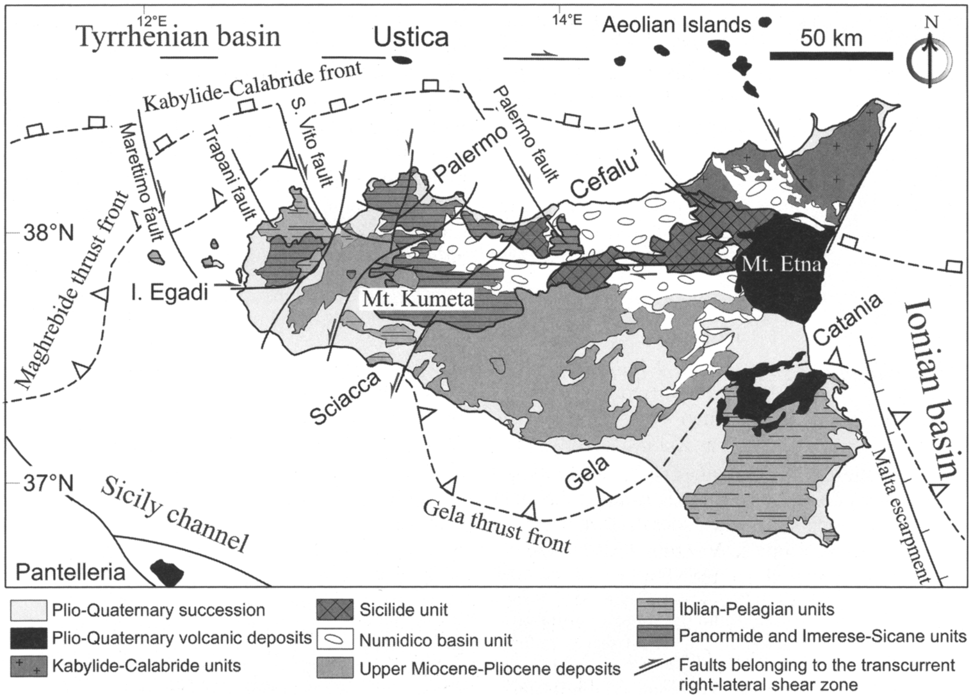

Fig. 1. Schematic geostructural map of Sicily.

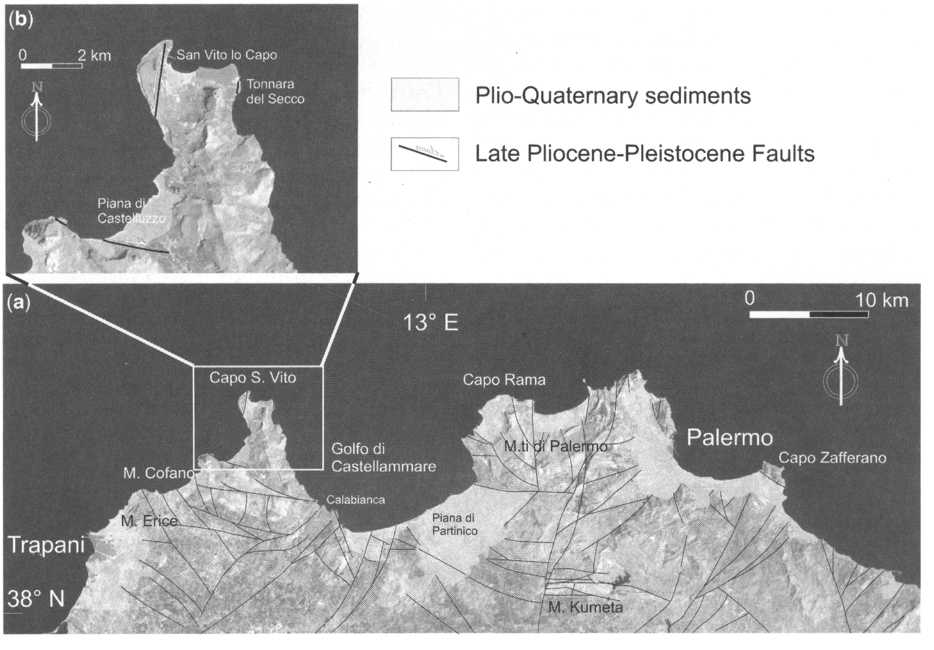

Fig. 2. (**a**) Plio-Quaternary faults of northwestern Sicily; (**b**) active fault zones in the San Vito lo Capo peninsula.

Ogniben 1960; Scandone *et al.* 1974; Catalano *et al.* 1979; Catalano & D'Argenio 1982). The main stages in the Neogene deformation history of the area include (Giunta *et al.* 2000): (1) thrust tectonic events, from the Early Miocene; (2) extensional tectonics and crustal thinning processes, from the Late Miocene; (3) strike-slip tectonic activity, often reactivating inherited structures, during the Plio-Pleistocene evolution of the northern Sicily–southern Tyrrhenian hinge zone (Boccaletti *et al.* 1982; Finetti & Del Ben 1986).

According to some workers, strike-slip tectonics, in the area separating the southern Tyrrhenian Sea from northern Sicily, started in Pliocene time, when the UEKA shear zone was first established. The latter extends offshore for more than 400 km from the island of Ustica to the Aeolian Islands (the Ustica–Eolie Line of Boccaletti *et al.* 1982), and onland, for more than 300 km, from the Trapani mountains to Mt. Etna, including the so-called Kumeta–Alcantara Line (Ghisetti & Vezzani 1984). Lower-rank structures related to the Ustica–Eolie and Kumeta–Alcantara lines comprise the NW–SE-striking faults of Marettimo, Trapani, San Vito and Palermo (Nigro *et al.* 2000; Gueguen *et al.* 2002). Taken as a whole, these structures were interpreted as a right-lateral duplex: the Southern Tyrrhenian Strike-Slip Duplex (Renda *et al.* 2000).

Related to these faults, some minor shear zones are well exposed at several localities (Fig. 2a; Giunta *et al.* 2004). Based on their geometric and kinematic characteristics, these have been grouped into three major sets: (1) an ESE-striking mainly right-lateral to transtensive fault set; (2) a north–south-striking left-lateral to transtensive fault set; (3) a NE–SW-striking set including faults with left-lateral transpressive and reverse kinematics. Some of these high-angle faults involve Pliocene and Early Pleistocene deposits; at San Vito lo Capo peninsula, in particular, two fault zones (trending roughly ESE and NNE) cut through both conglomerates, of Tyrrhenian age, and Holocene sediments (Fig. 2b).

Seismicity

The seismicity pattern recorded in the southern Tyrrhenian Sea since 1988 is shown in Figure 3a. As may be seen in Figure 3b (see also Giunta *et al.* 2004), the distribution of the hypocentres reveals the presence of two seismogenic zones. The first is located in the eastern portion of the southern Tyrrhenian Sea, where about 480 events are concentrated around a NE-dipping plane with a slope angle of 58° down to a depth of about 400 km. This distribution has been associated with the Wadati–Benioff plane of the Ionian lithospheric slab dipping beneath the Calabrian Arc (Gasparini *et al.* 1982; Anderson & Jackson 1987*a*).

The second seismogenic zone extends parallel to the northern coast of Sicily and is generally located within the upper crust. The 2002 Palermo seismic sequence is located within this belt (Fig. 3c). The hypocentral distribution of about 540 earthquakes recorded from 6 September to 15 October 2002 shows a NE–SW trend and a NW-dipping seismic belt (Fig. 3d; Giunta *et al.* 2004). The focal solutions of the main shock ($Mw = 5.9$) display NE–SW-striking nodal planes with compressive mechanisms (CMT Catalog, Harvard Seismology, http://www.seismology.harvard.edu/). As may be seen in Figure 3c, some 60 earthquakes cluster at about 55 km west from the main shock.

On land, in western Sicily, instrumental seismicity is very low and the 1968 Belice earthquake sequence, characterized by six main shocks with a magnitude of 5–5.4 (Anderson & Jackson 1987*b*), represents the strongest seismic event recorded in historical times (CPTI Gruppo di Lavoro 1999). There is some controversy about the seismogenic structure responsible for the 1968 Belice seismic sequence. Monaco *et al.* (1996) discussed the possibility that the seismic source might be a blind steeply north-dipping reverse fault, whereas Michetti *et al.* (1995) recognized surface faulting evidence interpreted in terms of strike-slip tectonics associated with a NW–SE-striking right-lateral fault.

Active faults in the San Vito lo Capo peninsula

The San Vito lo Capo peninsula, located at the western end of the northern coast of Sicily, extends in a roughly north–south direction into the southern Tyrrhenian Sea (see Fig. 2). This area represents the westernmost and the most external sector of the Sicilian orogenic belt, which is composed mainly of south-verging folds and thrusts. Here, deformed Mesozoic to Tertiary platform carbonates evolve upwards into deep-water marls, limestones and siliciclastic deposits. These, in turn, are unconformably overlain by terrigenous deposits of Plio-Pleistocene age that crop out widely in the coastal plain of Castelluzzo (Piana di Castelluzzo; Fig. 4). These latter deposits consist of carbonate grainstones overlain by shales and sands. Along the coast, small outcrops of Tyrrhenian conglomerates and bio-calcarenites are well exposed (see Fig. 4).

At San Vito lo Capo peninsula we analysed in detail the two main active faults shown in the map of Figure 4. The NNE-striking fault (here named the Faro fault) is exposed, for a length of about 3 km, in the Mesozoic carbonates cropping out in

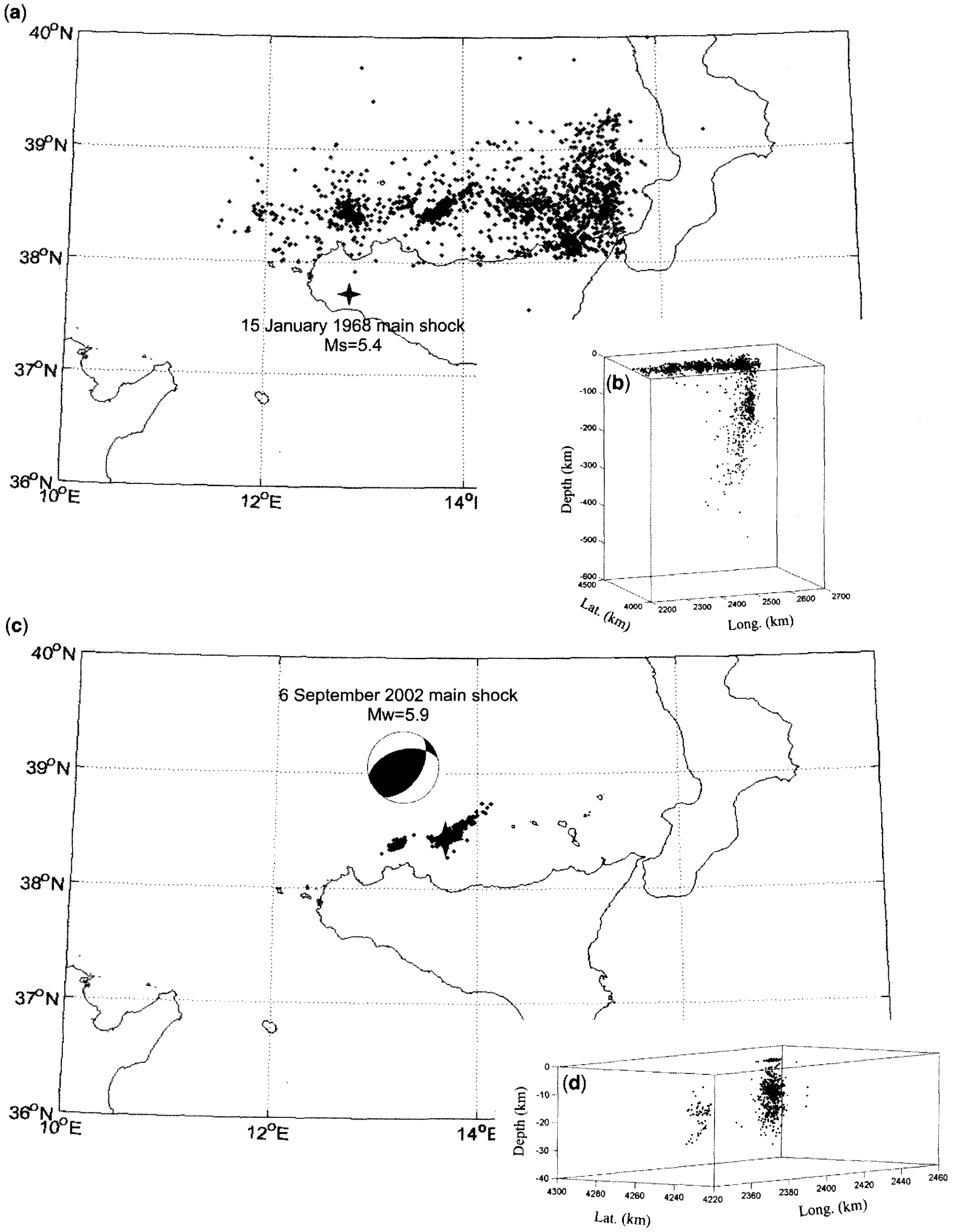

Fig. 3. Distribution of epicentres (**a**) and hypocentres (**b**) of the 2100 earthquakes occurring in the southern Tyrrhenian Sea and northern Sicily between 1988 and 15 October 2002. The epicentre location of the main shock (Ms = 5.4) of the 1968 Belice seismic sequence is also shown. (**d**) Distribution of epicentres (**c**) and hypocentres of the *c*. 540 earthquakes belonging to the Palermo seismic sequence, recorded from 6 September to 15 October 2002 (after Giunta *et al.* 2004). The epicentre and hypocentre location of the main shock (Mw = 5.9) is marked by a star.

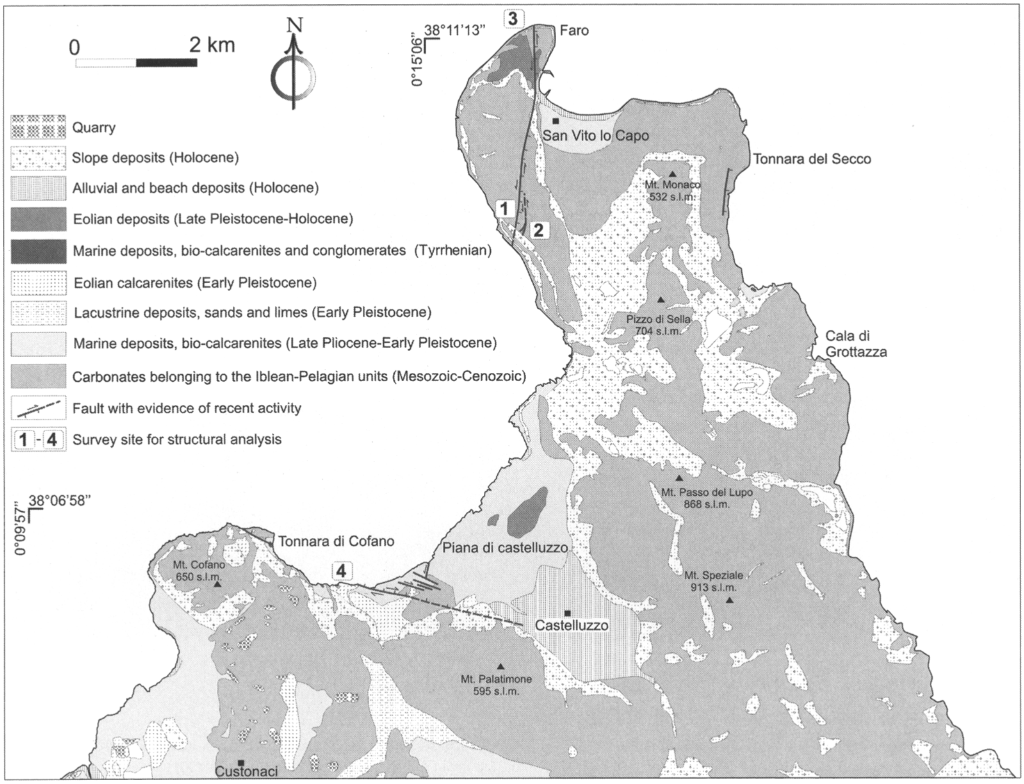

Fig. 4. Geological map of the Plio-Pleistocene deposits cropping out in the San Vito lo Capo peninsula (Abate *et al.* 1993).

the surroundings of the San Vito lo Capo village. Here, we observed striated fault surfaces showing left-lateral strike-slip kinematics, and a few morphotectonic features characterizing NE-striking lower-rank positive flower structures (Fig. 5a and d). Evidence for recent tectonic activity of the Faro fault is given by a continuous 20 m high fault scarp cutting a flat erosional surface that is interpreted to be an Early Pleistocene marine terrace (Fig. 5c; Abate *et al.* 1998). Furthermore, about 3 km north of the marine cliff shown in Figure 5a, at Faro, the fault runs across Late Pleistocene to Holocene aeolian deposits (see Fig. 4). The latter deposits are also cut by lower-rank (metre-scale) faults related to the main NNE trend (Fig. 5d).

The southern margin of the Piana di Castelluzzo is bordered by an ESE-striking fault (here named the Castelluzzo fault), which is exposed for about 2 km in Early Pleistocene marine sediments (see Fig. 4). The morphological evidence of the Castelluzzo fault is given by a fresh-looking fault scarp (about 15 m high; Fig. 6). At several localities, along the coast, we observed striated surfaces indicating prevalent right-lateral kinematics (Fig. 6b). In the fault footwall, lower-rank features (meso-faults and shear fractures) cut through Tyrrhenian conglomerates (Fig. 7).

In the Piana di Castelluzzo, Early Pleistocene bio-calcarenites cropping out along the coast are also affected by several minor faults (Fig. 8). There, we produced a detailed map (at 1:25 scale) by combining field data and image analysis of a photo mosaic composed of digital photographs taken from a helicopter. The marine flat surface is pervasively affected by individual deformation bands and zones of deformation bands with overprinted stylolites, sheared stylolites and slip surfaces (Fig. 9). Individual deformation bands are known to represent the smallest structures, caused by faulting in high-porosity, poorly cemented sandstones (Aydin & Johnson 1978; Antonellini *et al.* 1994) as well as in porous carbonate grainstones (Tondi *et al.* 2006). They consist of broken and compacted grains defining roughly planar features that record small amounts of displacement, typically from a few centimetres to <1 mm. Larger

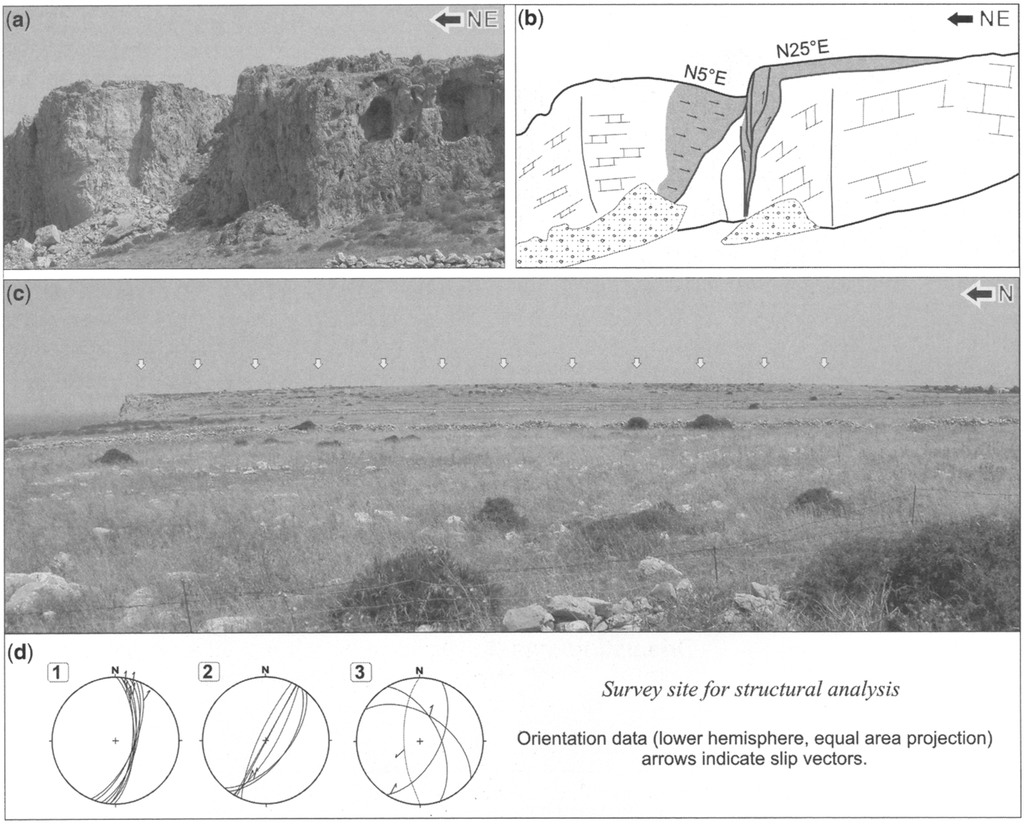

Fig. 5. (**a**) Surface evidence of active faulting associated with the NNE-striking Faro fault. (**b**) Line drawing from the digital image of the marine cliff shown in (a). (**c**) The 20 m high fault scarp, associated with the Faro fault, cutting a flat erosional surface of Early Pleistocene age. (**d**) Fault orientation and kinematic data (see Fig. 4 for locations).

amounts of displacement can be accommodated by wider zones of multiple, composite, deformation bands (Engelder 1974; Aydin & Johnson 1978; Antonellini *et al.* 1994). In the Piana di Castelluzzo, deformation bands are generally shear bands (Aydin *et al.* 2006), mostly trending ESE (Fig. 10). Sheared stylolites are associated with all sets of shear bands. The geometry of step-over zones and 'horse-tail' terminations (Figs 11 and 12) indicates a right-lateral strike-slip character for most of them (striking east–west and ESE) and left-lateral strike-slip kinematics for those (subordinate) trending NNW and north–south. The NW-striking set is often characterized by oblique-normal kinematics, whereas all sets of shear bands and related sheared stylolites show cross-cutting relationships that suggest that they sheared at the same time (see Fig. 8).

In the Piana di Castelluzzo, several mesofaults also affect the Dendropoma coastal reef platform, which is made of worm populations still growing at present in the temperate climate of northwestern Sicily (Fig. 13; Antonioli *et al.* 1999). The fault-controlled reef therefore records clear evidence of the very recent activity of these structures.

The information collected in the study area also suggests that the geometry of the stress field responsible for the overall deformation pattern observed in this sector of northwestern Sicily is characterized by a direction of maximum compression oriented roughly NW. In fact, as shown in Figure 14, the most abundant features exposed in the Piana di Castelluzzo may be interpreted as R shears related to a roughly east–west-striking fault driven by a NW-oriented compression.

As concerns chronology, our observations indicate that deformation bands are the oldest structures formed in the Piana di Castelluzzo area, from Early Pleistocene time, whereas sheared stylolites and mesofaults affecting the Dendropoma reef

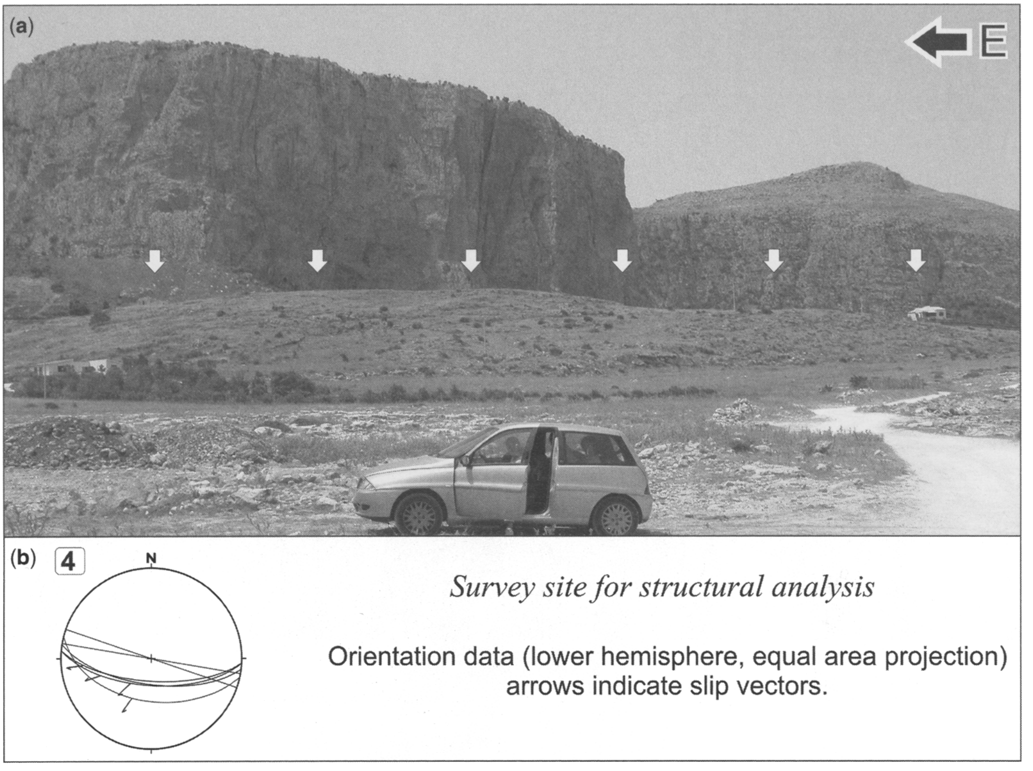

Fig. 6. (**a**) The 15 m high fault scarp in Early Pleistocene marine deposits associated with the Castelluzzo fault. (**b**) Fault orientation and kinematic data (see Fig. 4 for locations).

(characterized by distinctive slip surfaces, visible gauge, and the same kinematics of the deformation bands) developed later. This also suggests that the geometry of the stress field acting in the area has not changed from Early Pleistocene time to the present.

Discussion and conclusions

Detailed analyses of macro- and mesostructural features exposed in the San Vito lo Capo peninsula, in northwestern Sicily, show that the overall deformation pattern in the area may be interpreted in terms of strike-slip tectonics driven by a current

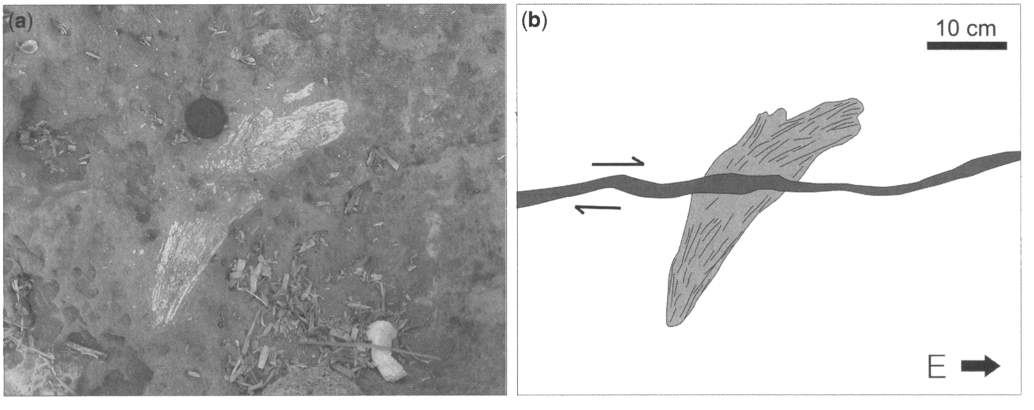

Fig. 7. Remains of macrofauna of Tyrrhenian age cut by an east-striking right-lateral shear fracture: (**a**) photograph; (**b**) schematic drawing.

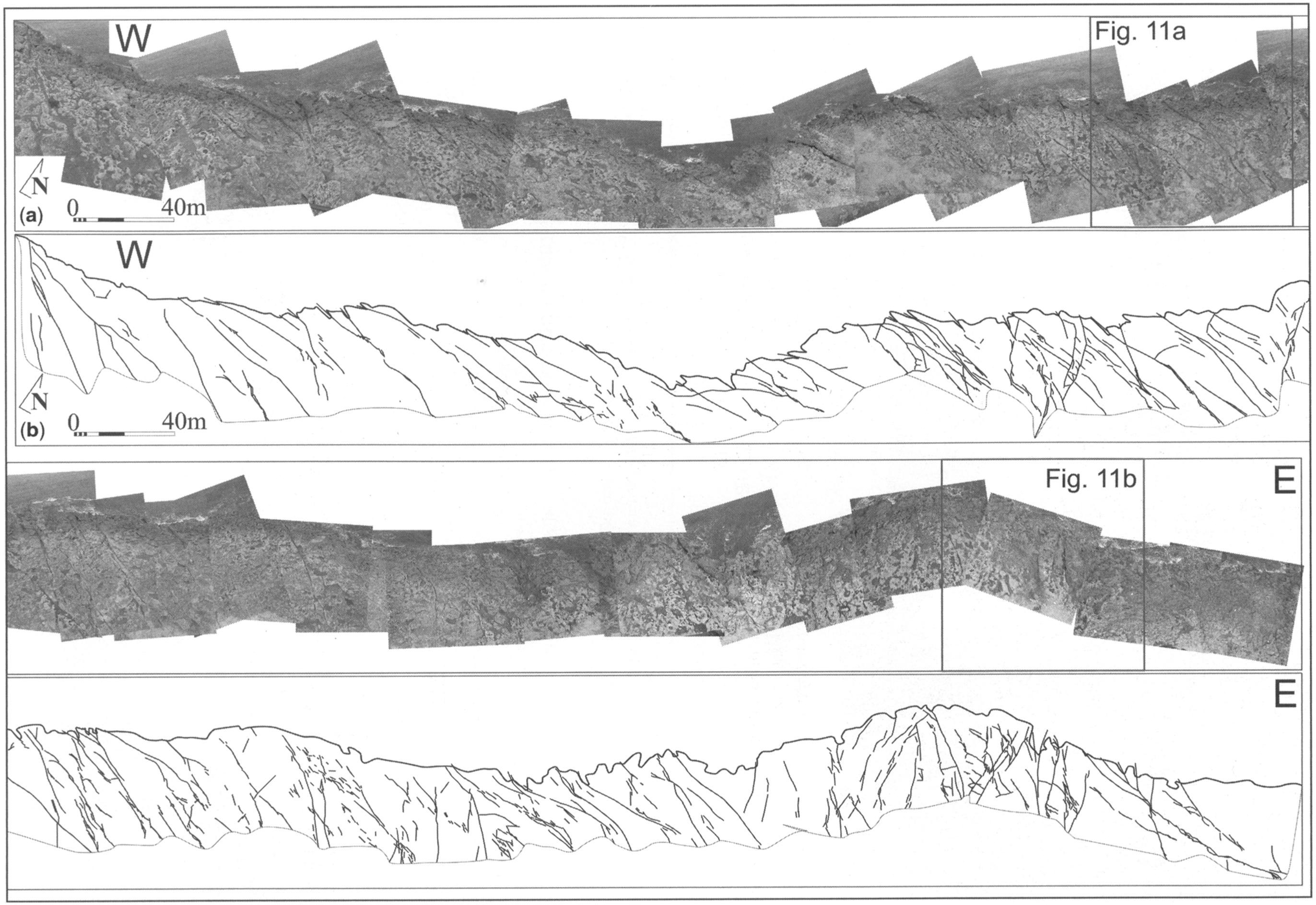

Fig. 8. Detailed map of lower-rank structures exposed in a >1 km long outcrop located along the coast of Piana di Castelluzzo. The analysed images were digitally acquired by flying at a height of about 50 m above sea level. (**a**) Photograph and (**b**) map.

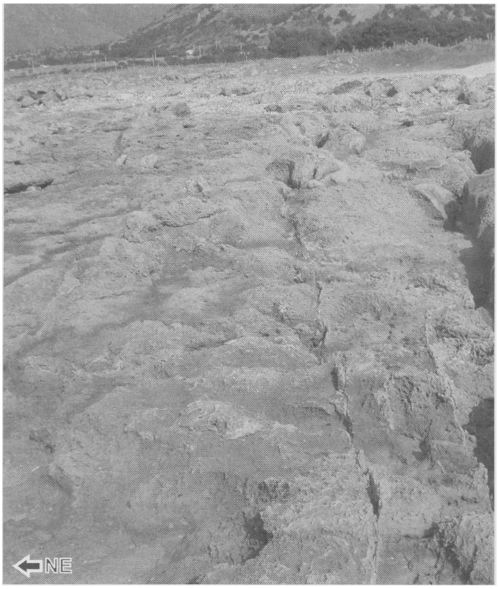

Fig. 9. East–West- and NW-striking deformation bands, in the Piana di Castelluzzo, easily recognized because of their increased resistance to weathering with respect to the host-rock.

stress field geometry characterized by a NW-oriented maximum compression. The stress field acting in the area appears to be directly controlled by the convergence between the African and European plates. The present-day Africa motion along NNW–SSE- to NW–SE-directed vectors is substantiated by geological, seismological, VLBI (very long baseline interferometry) and global positioning system data (Ward 1998; Zarraoa *et al.* 1994; Cello *et al.* 1997; Di Bucci & Mazzoli 2003; Goes *et al.* 2004; Tondi *et al.* 2005).

In the San Vito lo Capo peninsula, we identified two main active faults: the Faro and Castelluzzo faults. Both faults are marked by 15–20 m high fault scarps cutting marine deposits of Early Pleistocene age.

Integrating the values of the vertical component of motion (derived from the height of the fault scarps) and data from mesostructural analysis (which shows a mean pitch value of about 10° for the faults mapped in the area) we computed the cumulative displacement across both faults as some 90–120 m. Consequently, slip on both faults must have occurred at a rate of about 0.05 mm a^{-1} since the Pleistocene. Furthermore, the notion that empirical expressions relating fault length and displacement (Cowie & Scholz 1992; Schlische *et al.* 1996; Tondi & Cello 2003) may provide good estimates for their dimensional properties allowed us to suggest that the cumulative length of each fault is in the range of about 10 km.

Frequency Data, Gaussian
Total Data: 943

GAUSSIAN PARAMETERS					
#	%	Nor. H.	Max H.	Azimuth	sd
1	22.9	100.0	23.25	-75.0°	6.2°
2	21.3	88.6	20.60	-88.2°	6.5°
3	16.2	49.5	11.50	-60.7°	8.8°
4	26.9	36.2	8.41	-39.3°	20.0°
5	7.8	25.9	6.02	74.0°	8.1°

Min Value Fit = 0.3999954

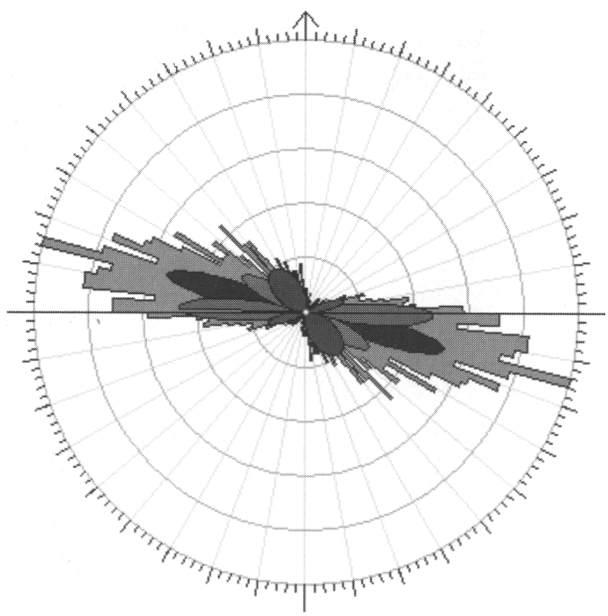

Fig. 10. Orientation data for the structures exposed in the Piana di Castelluzzo outcrop.

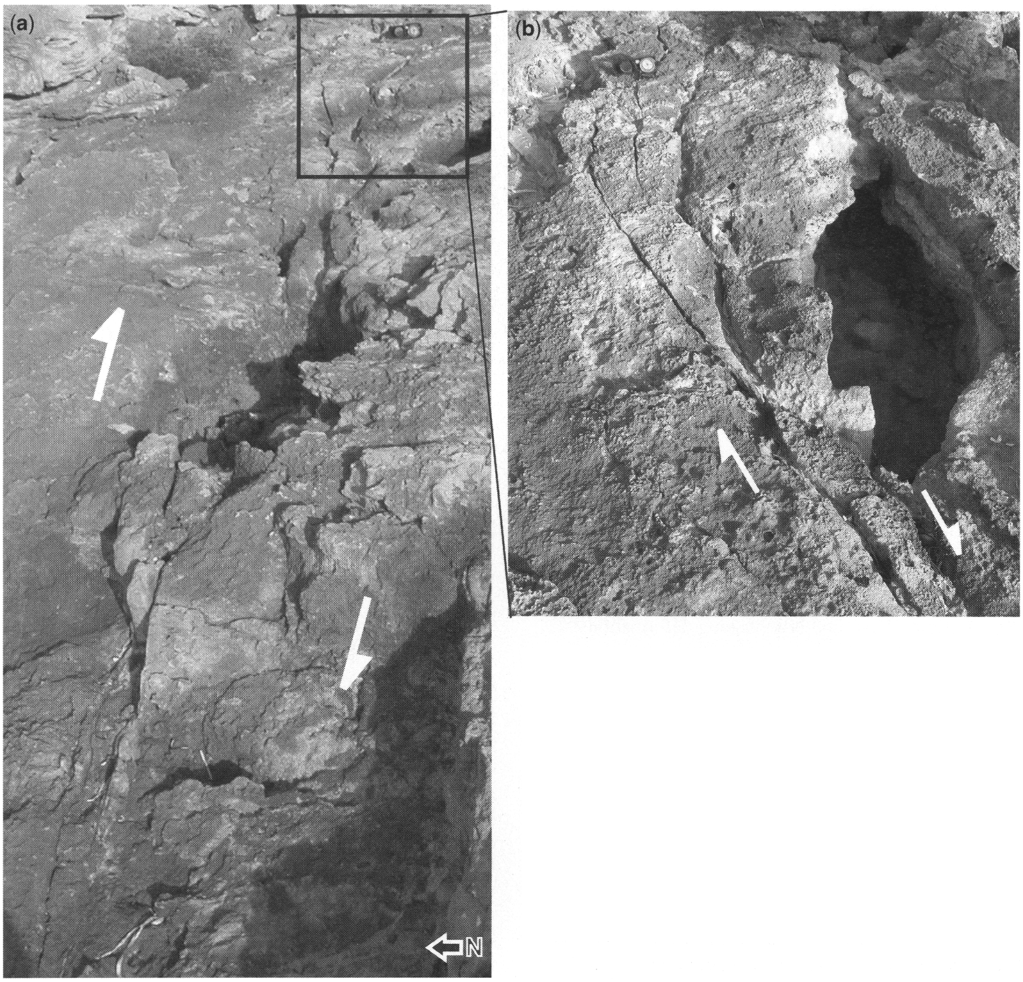

Fig. 11. Detail of Figure 8 showing: (**a**) east–west-striking mature mesofaults with right-lateral kinematics, and (**b**) NNW-striking sheared stylolites with left-lateral sense of motion.

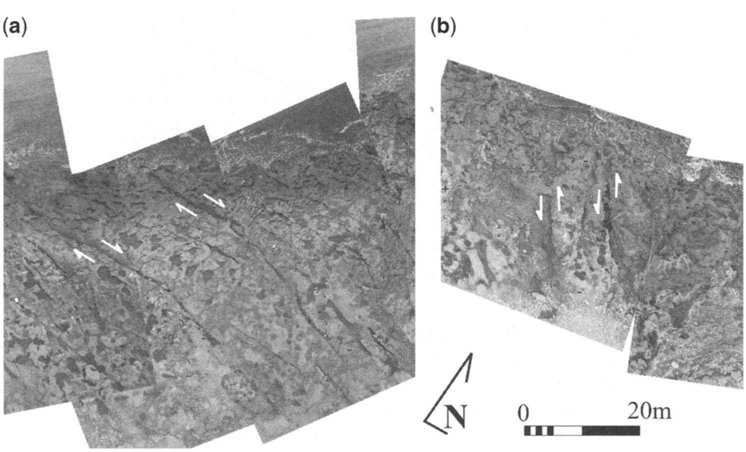

Fig. 12. (**a**) Left-stepping geometry of ESE-striking sheared stylolites; (**b**) 'horse-tail' termination showing right-lateral kinematics.

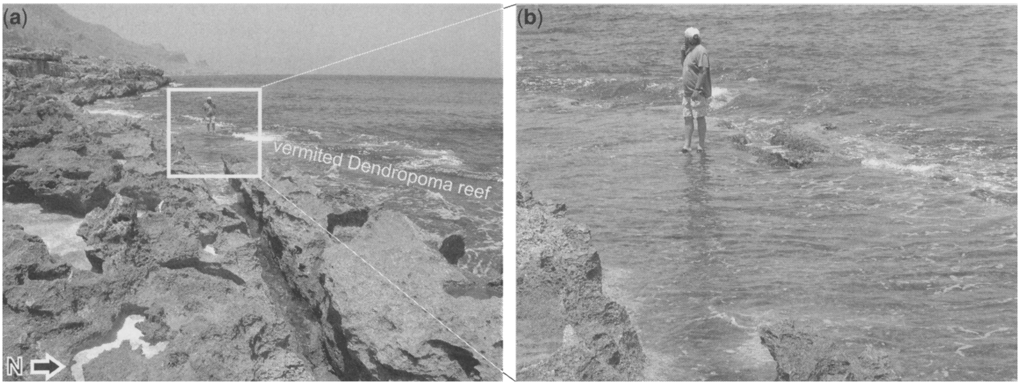

Fig. 13. (**a, b**) Fault-controlled morphology of the Dendropoma reef platform.

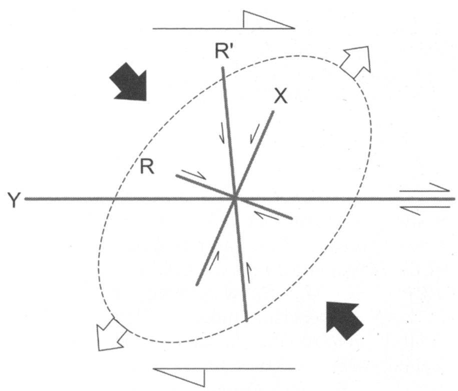

Fig. 14. Two-dimensional geometry of the stress field acting in northwestern Sicily, and structural interpretation of the structures mapped in the Piana di Castelluzzo.

Based on this estimate, we also computed the maximum expected moment magnitude for both faults from the relationship

$$\mathrm{Mo} = \mu A \delta u \qquad (1)$$

where Mo is the seismic or geological momentum, A is the fault surface area, μ is the rigidity modulus (3×10^{11} dyn cm^{-2}) and δu is the last slip increment on the fault.

We calculated A from the inferred fault length, by assuming that its width is equal to the thickness of the seismogenic layer (about 10 km; as may be averaged from the hypocentre distributions shown in Fig. 3).

From (1), it follows that the moment magnitude is (Kanamori 1977)

$$\mathrm{Mw} = (\log \mathrm{Mo}/1.5) - 10.73. \qquad (2)$$

Considering each seismogenic structure individually, and a mean coseismic displacement of the order of 0.5 m (Wells & Coppersmith 1994), we propose that the maximum expected moment magnitude for each fault is about 6.0. This result suggests therefore that, in western Sicily, as well as the Belice region, the San Vito lo Capo peninsula may also be considered as a seismic source area for medium-sized earthquakes.

This work was supported by the Universities of Camerino and Palermo (research funds to E. Tondi, G. Giunta, P. Renda and M. Unti), and by the MIUR, Cofin 2002 (research funds to G. Cello and D. Zampieri).

References

Abate, B., Di Maggio, C., Incandela, A. & Renda, P. 1993. *Carta Geologica dei Monti di Capo San Vito*. Dipartimento di Geologia e Geodesia dell'Università di Palermo.

Abate, B., Incandela, A., Nigro, F. & Renda P. 1998. Plio-Pleistocene strike-slip tectonics in the Trapani Mts. (NW Sicily). *Bollettino della Società Geologica Italiana*, **117**, 555–567.

Anderson, H. & Jackson, J. 1987*a*. The deep seismicity of the Tyrrhenian Sea. *Geophysical Journal of the Royal Astronomical Society*, **91**, 613–637.

Anderson, H. & Jackson, J. 1987*b*. Active tectonics of the Adriatic Region. *Geophysical Journal of the Royal Astronomical Society*, **91**, 937–983.

Antonellini, M. A., Aydin, A. & Pollard, D. D. 1994. Microstructure of deformation bands in porous sandstones at Arches National Park, Utah. *Journal of Structural Geology*, **16**, 941–959.

ANTONIOLI, F., CHEMELLO, R., IMPROTA, S. & RAGGIO, S. 1999. Dendropoma lower intertidal reef formations and their paleoclimatological significance, NW Sicily. *Marine Geology*, **161**, 155–170.

AYDIN, A. & JOHNSON, A. M. 1978. Development of faults as zones of deformation bands and as slip surfaces in sandstone. *Pure and Applied Geophysics*, **116**, 931–942.

AYDIN, A., BORJA, R. I. & EICHHUBL, P. 2006. Geological and mathematical framework for failure modes in granular rock. *Journal of Structural Geology*, **28**, 83–98.

BOCCALETTI, M., CONEDERA, C., DAINELLI, P. & GOCEV, P. 1982. The recent (Miocene–Quaternary) rhegmatic system of western Mediterranean region. A new model of ensialic geodynamic evolution in a context of plastic/rigid deformation. *Journal of Petroleum Geology*, **5**, 31–49.

CATALANO, R. & D'ARGENIO, B. 1982. Schema geologico della Sicilia. *In*: CATALANO, R. & D'ARGENIO, B. (eds) *Guida alla Geologia della Sicilia Occidentale*. Guide Geologiche Regionali, Memorie della Società Geologica Italiana, Supplemento A, **24**, 9–41.

CATALANO, R., D'ARGENIO, B., MONTANARI, L. ET AL. 1979. Contributo alla conoscenza della struttura della Sicilia Occidentale: Il profilo Palermo–Sciacca. *Bollettino della Società Geologica Italiana*, **19**, 485–493.

CELLO, G., MAZZOLI, S., TONDI, E. & TURCO, E. 1997. Active tectonics in the Central Apennines and possible implications for seismic hazard analysis in peninsular Italy. *Tectonophysics*, **272**, 43–68.

CHIRONI, C., DE LUCA, L., GUERRA, I., LUZIO, D., MORETTI, A., VITALE, M. & Sea Land Group 2000. Crustal structures of the Southern Tyrrhenian Sea and the Sicily Channel on the basis of the M25, M26, M28, M39 WARR profiles. *Bollettino della Società Geologica Italiana*, **119**, 189–203.

COWIE, P. A. & SCHOLZ, C. H., 1992. Displacement–length scaling relationship for faults: data synthesis and discussion. *Journal of Structural Geology*, **14**, 1149–1156.

CPTI GRUPPO DI LAVORO 1999. *Catalogo Parametrico dei Terremoti Italiani*. ING, GNDT, SGA, SSN, Bologna.

DEWEY, J. F., HELMAN, M. L., TURCO, E., HUTTON, D. H. W. & KNOTT, S. D. 1989. Kinematics of the Western Mediterranean. *In*: COWARD, M. P., DIETRICH, D. & PARK, R. G. (eds) *Alpine Tectonics. Gelogical Society, London, Special Publications*, **45**, 265–283.

DI BUCCI, D. & MAZZOLI, S. 2003. The October–November 2002 Molise seismic sequence (southern Italy): an expression of Adria intraplate deformation. *Journal of the Geological Society, London*, **160**, 503–506.

ENGELDER, T. 1974. Cataclasis and the generation of fault gouge. *Geological Society of America Bulletin*, **85**, 1515–1522.

FINETTI, I. & DEL BEN, A. 1986. Geophysical study of the Tyrrhenian opening. *Bollettino di Geofisica Teorica ed Applicata*, **28**, 75–155.

GASPARINI, C., IANNACCONE, G., SCANDONE, P. & SCARPA, R. 1982. Seismotectonics of the Calabrian Arc. *Tectonophysics*, **82**, 267–286.

GHISETTI, F. & VEZZANI, L. 1984. Thin-skinned deformation in Western Sicily. *Bollettino della Società Geologica Italiana*, **103**, 129–157.

GIUNTA, G., NIGRO, F., RENDA, P. & GIORGIANNI, A. 2000. The Sicilian–Maghrebides Tyrrhenian Margin: a neotectonic evolutionary model. *Bollettino della Società Geologica Italiana*, **119**, 553–565.

GIUNTA, G., LUZIO, D., TONDI, E. ET AL. 2004. The Palermo (Sicily) seismic cluster of September 2002, in the seismotectonic framework of the Tyrrhenian Sea–Sicily border area. *Annals of Geophysics*, **47**(6), 1755–1770.

GOES, S., GIARDINI, D., JENNY, S., HOLLENSTEIN, C., KAHLE, H.-G. & GEIGER, A. 2004. A recent tectonic reorganization in the south–central Mediterranean. *Earth and Planetary Science Letters*, **226**, 335–345.

GUEGUEN, E., TAVARNELLI, E., RENDA, P. & TRAMUTOLI, M. 2002. The geodynamics of the southern Tyrrhenian Sea margin as revealed by intregrated geological, geophysical and geodetic data. *Bollettino della Società Geologica Italiana, Volume Speciale* **1**, 77–85.

KANAMORI, H. 1977. The energy release in great earthquakes. *Journal of Geophysical Research*, **82**, 2981–2987.

MALINVERNO, A. & RYAN, W. B. F. 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as results of arc migration driven by sinking of the lithosphere. *Tectonics*, **5**, 227–245.

MICHETTI, A. M., BRUNAMONTE, F. & SERVA, L. 1995. Paleoseismological evidence in the epicentral area of the January 1968 earthquakes, Belice, southwestern Sicily. *In*: SERVA, L. & SLEMMONS, D. B. (eds) *Perspectives in Paleoseismology*, **6**, 127–139, Peanut Butter Publishing, Seattle.

MONACO, C., MAZZOLI, S. & TORTORICI, L. 1996. Active thrust tectonics in western Sicily (southern Italy): the 1968 Belice earthquake sequence. *Terra Nova*, **8**, 372–381.

NIGRO, F., RENDA, P. & ARISCO, G. 2000. Tettonica recente nella Sicilia nord-occidentale e nelle Isole Egadi. *Bollettino della Società Geologica Italiana*, **119**, 307–319.

OGNIBEN, L. 1960. Nota illustrativa dello schema geologico della Sicilia nord-orientale. *Rivista Mineraria Siciliana*, **64–65**, 184–212.

RENDA, P., TAVARNELLI, E., TRAMUTOLI, M. & GUEGUEN, E. 2000. Neogene deformations of Northern Sicily, and their implications for the geodynamics of the Southern Tyrrhenian Sea margin. *Memorie della Società Geologica Italiana*, **55**, 53–59.

SCANDONE, P., GIUNTA, G. & LIGUORI, V. 1974. The connection between Apulia and Sahara continental margins in the Southern Apennines and in Sicily. *Memorie della Società Geologica Italiana*, **13**, 317–323.

SCHLISCHE, R. W., YOUNG, S. S., ACKERMANN, R. V. & GUPTA, A. 1996. Geometry and scaling relations of a population of very small rift-related normal faults. *Geology*, **24**, 683–686.

TONDI, E. & CELLO, G. 2003. Spatiotemporal evolution of the central Apennines fault system (Italy). *Journal of Geodynamics*, **36**, 113–128.

TONDI, E., PICCARDI, L., CACON, S., KONTNY, B. & CELLO G. 2005. Structural and time constraints for dextral shear along the seismogenic Mattinata Fault (Gargano, southern Italy). *Journal of Geodynamics* **40**, 134–152.

TONDI, E., ANTONELLINI, M., AYDIN, A., MARCHEGIANI, L. & CELLO, G. 2006. Interaction of deformation bands and stylolites in fault development in carbonate grainstones of the Majella Mountain, Italy. *Journal of Structural Geology*, **28**, 376–391.

WARD, S. N. 1998. On the consistency of earthquake moment release and space geodetic strain rates: Europe. *Geophysical Journal International*, **135**, 1011–1018.

WELLS, D. L. & COPPERSMITH, K. J. 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of Seismological Society of America*, **84**, 974–1002.

ZARRAOA, N., RIUS, A., Sardón, E. & Ryan, J. W. 1994. Relative motions in Europe studied with a geodetic VLBI network. *Geophysical Journal International*, **117**, 763–768.