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Fault reactivation by stress pattern reorganization in the Hyblean foreland domain of SE Sicily (Italy) and seismotectonic implications

Fabrizio Cultrera [a,*], Giovanni Barreca [a], Luciano Scarfì [b], Carmelo Monaco [a]

[a] Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Università di Catania, Sezione di Scienze della Terra, Catania, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Catania, Italy

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ABSTRACT

Between the October 2011 and the July 2012, several seismic swarms occurred in the Hyblean foreland domain of SE Sicily (Italy) along the Cavagrande Canyon, one of the most impressive fluvial incisions of Sicily. Despite the low magnitude of the events (main shock with M ~3.7), they represent the biggest strain release of the Hyblean area over the last 10 years. A careful waveform analysis of the earthquakes revealed that most of them form a family of "multiplets". These findings allow us to reconstruct the attitude of the accountable fault plane by interpolating their high-precision 3D location parameters into a GIS platform. A detailed morpho-structural analysis, performed at the ideal updip projection of the modeled plane, showed that during the Middle–Late Pleistocene the epicentral area has been deformed by a belt of extensional faults, a segment of which matches well with the computer-generated surface. Despite the field evidence, computed focal solutions support contrasting strike-slip kinematics on the same fault plane, clearly indicating a dextral shearing on this pre-existing normal fault. The seismic swarms nucleated on a small rupture area along a ~10 km long, NW-SE trending fault segment, that could be able to generate M ~6 earthquakes. Following our analysis and looking at seismicity distribution in the SE portion of Hyblean area, we assess that a stress pattern reorganization occurred all over the Hyblean foreland between the Late Pleistocene and present-day. Change in the trajectory of the max stress axes (from vertical to horizontal) seems to have involved a pre-existing large-scale fault configuration with considerable seismotectonic implications.

1. Introduction

Fault reactivation under different stress conditions has been documented by several authors in various tectonic settings (Bonini et al., 2012; Koopman et al., 1987; Richard and Krantz, 1991; Viola et al., 2004). This process is commonly interpreted as the expression of a changed tectonic regime or as the result of local stress perturbation. Reactivation is a selective process which, in many cases, reworks pre-existing zones of rheological and mechanical weakness (Holdsworth et al., 2001) since it is mechanically easier than forming a new fault (Scholz, 1998). Previously faulted zone can also influence the kinematic pattern and the strain accumulation with associated seismicity depending on the geometric relations between re-oriented stress and trend of inherited faults. In particular, when the trend of the pre-existing faults is nearly perpendicular or oblique to the orientations of maximum horizontal stress, high-angle dip-slip faults are prone to be reactivated as strike-slip mode rather than reverse one (Davis and Reynolds, 1984; Letouzey et al., 1990). Moreover, analog sandbox experiments showed that reactivation in strike-slip mode of pre-existing faults can occur at depth without surface expressions (Richard and Krantz, 1991).

The Hyblean Plateau is a highly fractured carbonate block of SE Sicily (southern Italy) which experienced several deformation phases during Neogene–Quaternary times (Grasso and Lentini, 1982). The main tectonic features consist of extensional fault systems, widespread all over the Hyblean area, which mainly nucleated in response to foreland-bulging dynamics within a larger geodynamic scenario dominated by the long-living convergence between Nubia and Eurasia plates (Dewey et al., 1989; Faccenna et al., 2001). These NE-SW oriented faults generally occur at the edges of the Hyblean Plateau block, whereas other fault systems, mainly NW-SE trending, dissect its internal portion. As suggested by the occurrence of several destructive seismic events and sequences in historical times (e.g., the 1169 and 1693 earthquakes, MCS intensities of XI with estimated magnitudes of about 7 or higher; Boschi et al., 2000) faulting is still active, even though the lack of coseismic ruptures at surface (or not found yet) and other clues that typically develop in a seismic landscape (sensu Michetti, 2005) makes the location of the seismogenic sources for these large earthquakes problematic.

Apart from the well-known extensional tectonics, oblique deformation has also been documented in the Hyblean Plateau and particularly

* Corresponding author. Fax: +39 0957195728.
E-mail address: fcultrera@unict.it (F. Cultrera).

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at its western sector (Ghisetti and Vezzani, 1980; Grasso and Reuther, 1988), where reactivation in strike-slip mode of pre-existing normal faults system has been evidenced (Monaco et al., 2003). Recent seismological and geodetic studies (Musumeci et al., 2014) indicate that the entire Hyblean Plateau is currently undergoing prevailing strike-slip deformation. This kinematic pattern has been interpreted by the authors as the result of foreland segmentation dynamics even though the geological expression of these ongoing processes and correlation between seismicity and the accountable tectonic structures has not been satisfactorily explored.

Starting from the analysis of low-magnitude seismic swarms recently occurred in the southern portion of the Hyblean Plateau (the 2011–2012 Cavagrande seismic sequence), we firstly provide a GIS-aided method to model the attitude of the responsible fault surface (or the geometry of the asperity where rupture nucleated) by managing high-precision locations of a family of multiplet earthquakes, i.e. a group of events with similar waveforms detected within a considered seismic cluster. Results have been after matched with a detailed morpho-structural analysis at the ideal updip projection of the modeled plane. The comparison between seismological and field data allows us to capture the instrumental and the morpho-structural signatures of recent stress pattern configuration along this sector of the Hyblean Plateau and to identify a seismogenic structure resulting from tectonic reactivation.

2. Geodynamic setting

2.1. General outlines

The Hyblean Plateau (hereinafter the HP) is an isolated carbonate “promontory” in the central Mediterranean region which represents the emergent fragment of a larger foreland domain, the Pelagian Block (Burollet et al., 1978; Ben-Avraham and Grasso, 1991, Fig. 1A). This is a 25–30 km thick continental crustal portion of the African margin (Cassinis, 1983; Dewey et al., 1989; Scarascia et al., 1994), extending from the Sahel region of Tunisia to the eastern Sicily, where it is interrupted by the Malta Escarpment, a regional tectonic boundary that separates the Pelagian Block from the Ionian Basin (Nicolich et al., 2000; Torelli et al., 1998, Fig.1A). As revealed by the long-time collected field and sub-surface data, the HP is formed by ~10 km thick Mesozoic–Cenozoic carbonate sequences with several intercalations of volcanic products (Grasso et al., 2004; Patacca et al., 1979). Exposed rocks consist of Cretaceous to Miocene shallow to open-shelf series outcropping in the eastern and western sector, respectively (Grasso and Lentini, 1984, Fig. 1B). Top-sequences are made up of Quaternary sediments, generally preserved within fault-bounded structural depressions at the edges of the HP, and lava flow units mostly outcropping at its northern border (Grasso and Lentini, 1984).

The deformation history of the HP has been conditioned by its crustal feature (Barreca, 2014) and by the foreland role that it played within the larger geodynamic scenario dominated by the NW-SE convergence between Nubia and Eurasia plates (Dewey et al., 1989; Faccenna et al., 2001). During the Neogene, the progressive tectonic shortening has involved the northern portion of the Pelagian Block, giving rise to a NE-SW trending, foreland-verging fold and thrust system (the Sicilian Collision Zone, SCZ in Fig. 1B). During this phase, thrust sheets piled at the north-western margin of the underthrusted Hyblean foreland, causing tectonic overload and consequent foreland-bulging of the HP (Billi et al., 2006). This process developed since the middle Miocene time (Grasso and Pedley, 1990) and has reached its acme (probably) during the late Miocene–early Pliocene when deep-thrusting of previously flexured foreland units occurred in the inner part of the SCZ (Catalano et al., 2013). Bulging produced the large bending of the HP, with the consequent development of a gentle NE-SW trending hinge zone (roughly parallel with the trend of the SCZ), accompanied by extensional tectonics along coaxial outer-arc fault systems (Grasso et al., 1995) and by the nucleation of pervasive fracture systems with orthogonal trends (NW-SE and NE-SW respectively, see Billi et al., 2006).

More recently, regional and fault-related uplift, accompanied by sea level changing, caused episodic emersions of the HP, as testified by the occurrence of several orders of Pleistocene marine terraces (Bianca et al., 1999 and reference therein) culminating with a large (~480 ky old, according to Bianca et al., 1999) wave-cut summit surface, presently exposed on the eastern part of the HP.

2.2. Tectonic setting of the Hyblean Plateau

In contrast with the deformation expected by the foreland-bulging dynamics (outer-arc extensional fracturing, parallel to the NE-SW oriented hinge zone, see above), the HP exhibits a network of variously oriented fault systems, mostly extensional and subordinately strike-slip. Eastwards, the HP ends with the Malta Escarpment system (Fig. 1A and B), a ~NNW-SSE trending normal to oblique fault belt partially reactivating the ancient (Mesozoic) boundary between the HP and the adjacent Ionian Basin (Casero et al., 1984; Fabbri et al., 1982; Scandone et al., 1981). Quaternary activity of this fault belt is testified by the occurrence of coaxial on-land graben structures (e.g., the Augusta structural depressions, Fig. 1B), filled by Late Quaternary marine sediments (Bianca et al., 1999). The northern edge of the HP is controlled by a NE-SW trending extensional fault belt (the Monterosso–Agnone Fault System, MAFS in Fig. 1B) which has accommodated its northward bending beneath the front of the SCZ (Grasso and Pedley, 1990). Faulting gives rise to the setting of NE-SW oriented structural highs and depressions (e.g., the Scordia-Lentini Graben and the S. Demetrio High, Fig. 1B). The western border of HP is deformed by a system of NE-SW oriented extensional faults array, the Comiso-Chiaramonte Fault Belt (Ghisetti and Vezzani, 1980; Grasso et al., 2000, Fig. 1B) through which the Hyblean successions have been downfaulted by about 4000 m (Cogan et al., 1989). Similarly to the northern border, the southern sector of the HP is dissected by a NE-SW oriented normal fault system which includes the Pozzallo–Ispica–Rosolini Fault Belt and the ~20 km long Avola Fault (Bianca et al., 1999; Grasso et al., 1992; Monaco and Tortorici, 2000). Apart from the NE-SW trending bounding faults, resulting from regional bulging process (Grasso et al., 2000), the HP is also internally deformed by ~N-S and NW-SE trending tectonic structures. The western portion is transversally sliced by a ~70 km long, roughly N-S oriented, shear zone, known as the Scicli–Ragusa Fault System (SRFS, Ghisetti and Vezzani, 1980; Grasso and Reuther, 1988, see Fig. 1B), which offsets in right-lateral mode the bulging-related NE-SW structures. The NW-SE striking faults exclusively occur in the eastern part of HP within a rectangular-shaped deformation zone, confined between the Monterosso–Agnone Fault System to the north (MAFS in Fig. 1B) and the Pozzallo–Avola Fault System (PAFS in Fig. 1B), to the south. With respect to the fault systems that affect the northern edge, whose recent tectonic activity is demonstrated by displaced late Quaternary sediments, active deformation along the southern ones remains doubtful (see Bianca et al., 1999).

2.3. Seismotectonics

The Hyblean Plateau is one of the most seismically hazardous regions of Italy since it has been struck by large earthquakes in historical times such as the February 4, 1169 and the January 11, 1693 events. The latter is commonly reported as the strongest seismic event of the Italian Peninsula (Io = X/XI MCS and Mw 7.4 according to CPTI04 reference catalogue, see Fig. 2A for the inferred epicentral locations), causing more than 54,000 casualties and extensive damages in the whole Eastern Sicily (Bianca et al., 1999; Visini et al., 2009 and reference therein). The location of its seismogenic source is a topic still widely debated: normal-oblique faults located along the Ionian offshore (e.g., Argnani et al., 2012; Bianca et al., 1999; Gutscher et al., 2006; Piatanesi and Tinti, 1998; Visini et al., 2009) and/or compressional structures located