Quaternary reverse surface faulting in Mallorca Island (Baleares, Spain): Relationships with historical seismicity

Rupturas superficiales cuaternarias de carácter inverso en la Isla de Mallorca (Baleares, España): Relaciones con la Sismicidad histórica

P. G. Silva(*), F. M. González Hernández(**), J. L. Goy(**), C. Zazo(***) and N. A. Mörner(****).

(*) Depto. Geología, Universidad de Salamanca, E.U. Politécnica de Ávila. 05003-Avila (Spain). pgsilva@gugu.usual.es
(**) Depto. Geología, Universidad de Salamanca, Fac. Ciencias. 37008- Salamanca (Spain)
(***) Depto. Geología, Museo Nac. CC. Naturales (CSIC), Gutierrez Abascal, 2. 28006-Madrid (Spain)
(****) Dept. Paleogeophysica & Geodynamics, University of Stockholm. S-10691 Stockholm (Sweden).

RESUMEN

Se analiza una falla inversa que afecta a depósitos cuaternarios de relleno de la Dolina de Portol, situada en la zona epicentral del terremoto de Palma de 1851 (VIII MSK). La falla presenta un desplazamiento inverso acumulado de 5,58m, provocando un desplazamiento máximo de la superficie del terreno de 0,88 m que da lugar a un escarpe de falla inverso y afecta a construcciones humanas. Este evento aparentemente compresivo, se explica como un fenómeno subsidiario ligado a los procesos extensionales, tipo roll-over, que dominan la evolución de la zona antiformal que separa las cuencas sedimentarias de Palma e Inca. Las deformaciones observadas aparentemente se produjeron durante el mencionado terremoto de 1851.

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Geological and Structural setting

Mallorca Island constitutes the more important emerged segment of the so called Balearic Promontory, which constitutes the Northeastern prolongation of the external zones of the Betic Cordillera (East Spain) into the Mediterranean sea (Fontoboté et al., 1990). The overall structure of the island comprises a set of NE-SW trending basins and ranges developed during a period of tectonic extension active since at least the Late Miocene. The structure of all the ranges is compressional. They were built up in addition to folds by a pile of thrust sheets hundreds of meters thick during the Paleogene-Early Miocene betic nappe emplacement (Gelabert *et al.*, 1992). The Serra de Tramuntana to the Northwest and the Serras de Llevant to the Southeast constitute the main reliefs. In contrast, the basins respond to half-grabens developed along the detached horizons of ancient NE-SW thrust planes, driven by a broad NW-SE trending extensional stress field active until the more recent Quaternary times (Alvaro *et al.*, 1984 ; Benedicto *et al.*, 1993). The more important sedimentary basins (Palma, Inca, and Alcudia) are developed at the toe of the Serra the Tramuntana, generating a Neogene-Quaternary sedimentary through of more than 80km length, 10-6km wide and more than 0,7 km deep, limited by the main NE-SW normal fault of the island, the Sencelles Fault (Fig. 1).

In spite of the prevailing NW-SE extensional setting, anomalous NW-SE trending compressional features has been reported in the complex tectonic threshold separating the Palma Bay and the Inca basins (Benedicto *et al.*, 1993; Del Olmo *et al.*, 1991, Silva *et al.*, 1997). This work deals with the analysis of the reverse surface faulting event recorded in the SW corner of the Inca basin affecting to quaternary deposits near the village of El Portol (Goy *et al.*, 1991).

Reverse Faulting at the Portol Doline

The Portol Doline is located between to large NW-SE trending antiforms (Marratxí and Sta. Eugenia) whose constitute the borderland zone of the Palma and the Inca basins. Pliocene and Early Pleistocene calcarenitic deposits of littoral and eolian origin (Del Olmo *et al.*, 1994) are involved in these two main structures. In particular, at Marratxí, the present anticline-like pattern of these calcarenitic outcrops responds to the geometric hiteraction of Plio-Pleistocene eolian sedimentation gently dipping SW (depositional slope) towards the Palma Bay at the South "limb" with the previous Late Pliocene littoral deposits folded in a monoclinal style by rollover-type extensional structures located at the North "limb" (Silva *et al.*, 1997). A similar situation can be inferred for the more complex Antiform of Sta. Eugenia. Aside of the probable extensional origin of these complex antiform structures, within the Portol Doline reverse surface faulting occurs affecting to the younger Quaternary doline filling, as reported by Goy *et al.* (1991).

The present-day doline has a near-circular shape in plant view with a mean diameter of 0.4 km, inset in a major karstic landform, a polje-type depression elongated in NW-SE orientation developed on

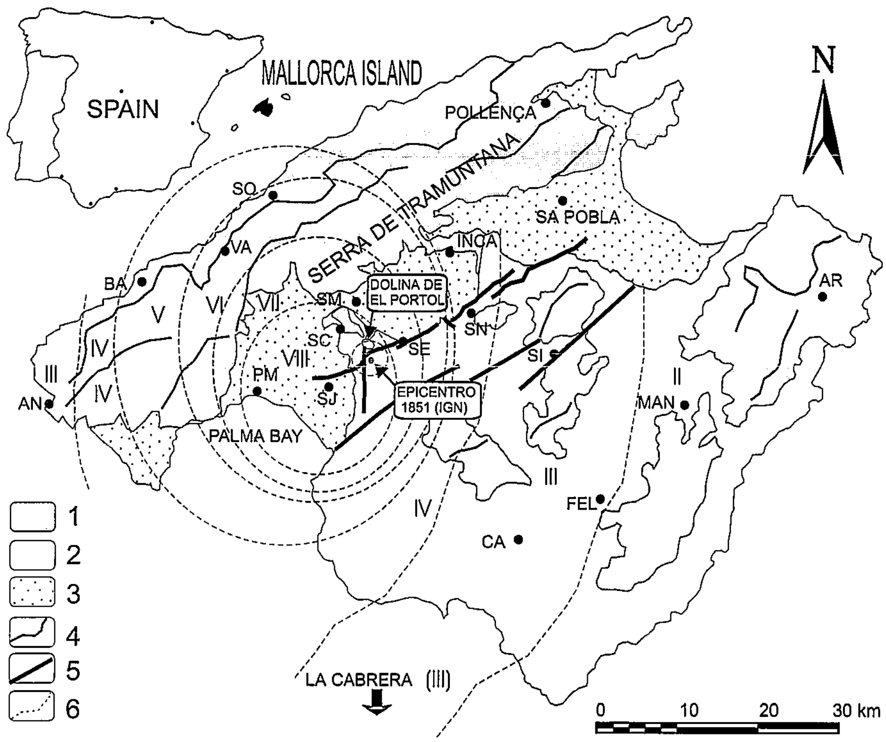

Fig. 1. Location of the Portol Doline in relation to the Geological framework of the Mallorca Island and main zones affected by the 1851 Palma Earthquake. 1. Neogene-Quaternary Basins; 2- Pliocene Calcarenites (Fm. St. Jordi); 3-Mesozoic outcrops (relief). 4- Main betic structural trend (thrust planes); 5) Main neotectonic normal faults; 6) Isoseismal lines of the 1851 Palma Earthquake (MSK Intensity).

Fig.1. Localización de la Dolina de Portol en relación a la geología general de la Isla de Mallorca y a las zonas afectadas por el Terremoto de Palma de 1851. 1- Cuencas neogeno-Cuaternarias; 2- Calcarenitas pliocenas (Fm. ST. Jordi); 3- Afloramientos Mesozoicos (Relieves); 4- Principales orientaciones structurales béticas (cabalgamientoa); 5- Principales fallas normales neotectónicas; 6- Isosistas correpondientes al Terremoto de Palma de 1851 (Intensidad MSK).

the Pliocene calcarenitic substratum. The doline is mainly filled by distal alluvial deposits coming from the antiformal relieves surrounding the polje borders and reworked decalcification clays (terra rossas). The development of reddish gley paleosoils and discrete calcareous palustrine levels are a characteristic feature in the whole sedimentary sequence.

Reverse faulting is evidenced in the walls of a quarry located in the southern sector of the Doline, open since the 30's decade for local pottery clay supply. Doline filling (up to 20m thick) is comprised by a sequence of six different fine-grained distal alluvial inputs separated by reddish and/or brown paleosoils holding well-developed gley features on thick Bt clayey horizons (0.2-0.6m) at the uppermost part of each unit. The occurrence of basal gravel lags in the different alluvial inputs, eroding and disrupting the underlying Bt horizons, is also common. The basal deposits of the doline sequence are constituted by a thick unit (>5m) of red sticky clays (terra rossa) which directly rest on the upper Pliocene littoral calcarenites. Large unweathered blocks of the calcarenites occur within this basal unit. The whole overlying quaternary sequence is tilted 25 to 20° towards the Southwest, holding a broad N30-40°E strata orientation.

Reverse faulting is recorded by the offset of a singular calcareous palustrine level, of 0.4-06m thick outcropping at the NW wall of the quarry. This can be considered as an artificial fault trench of 32,7m long and 2,3 to 11,8m depth (Fig. 2), which leads the determination of good quality fault plane parameters. Fault throw measured from the palustrine guide-level is of 2,56m, but the apparent total reverse slip of the up-thrusted segment measured along the fault plane is of 5,20m. The fault strikes in a N140-130°E trend, subparallel to the monoclinal fold axis of the adjacent Marratxí Antiform, and dip towards the SW (N250-240°E). Anyway, fault dip it is no uniform, and shows a variable angle which decreases upwards along the fault plane, from 55° to 23°. In this overall fault plane concave geometry, some discrete steps inducing sharp changes of dip angle, which give place to the development of dip-slip restraining and releasing bends. In detail, the palustrine guide-level is strongly disrupted in the upthrown SW block, displaying a deformational style similar to those showed by fold-limb faults, and in particular to the coseismic low-angle pressure ridges developed along some sectors of the Spitak fault during the 1987 Armenian earthquake (Philip *et al.*, 1992). In addition, several sets of subsidiary normal and reverse faults, also dipping towards the SW, but oblique to the main fault (N150-170°E), occur showing centimetric scale offsets (< 0.1m) accommodating the fault-induced dislocation at the up-thrusted block. The whole faulted sequence is truncated by a thin alluvial veneer mainly constituted by sandy clays, of 0.4 to 0.6m thick, which unconformably rests on the underlying tilted sequence (Fig.2). The top of this last unit constitutes the present ground surface and supports a weakly developed brown soil, which is also dislocated by the main fault plane.

The fault consists in a fault gouge of about 4-12 cm thick in which the clayey sediments has been strongly stressed into a, firm and sheared, but locally brecciated, state. Slickenside surfaces occur frequently within the deformed clays in subsidiary s-shears, but also on the footwall surface of the main fault plane, displaying striations and pressure cutans ranging from 90 to 122° SE pitch. These kinematic criteria, make possible to determine the net oblique slip of the fault recorded by the calcareous guide-level, resulting a maximum estimated value of 5,58m. Conventional structural analysis of striations and pressure cutans developed on the fault gouge has been performed using the computer program Stereonet.02. This integrated analysis gives a consistent SW-NE orientation for the compressive stress with N210-220°E average orientations holding a 87% conficence level (Fig.2).

Surface Faulting features

Ground surface dislocation is recorded by the occurrence of a reverse fault scarp facing to the NE, opposite to the SW fault dip, which range from 0,88-0,20m high along the upthrusted block (Fig. 2). In detail fault scarp morphology can be classified as a protruded scarp (Gordon and Lewis, 1980) in which the firmer palustrine guide level is bent, brecciated, and collapsed onto the ancient ground surface. Presently, the scarp front is partially buried, a co-

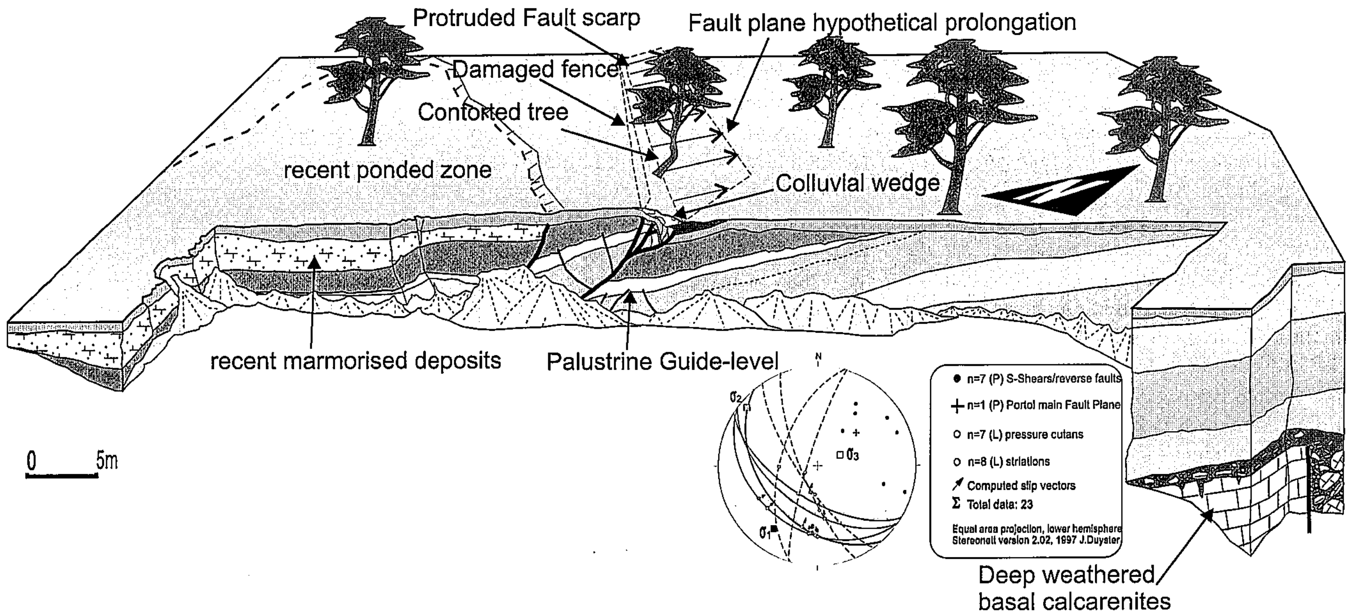

Fig. 2. Block-diagram showing main deformational features displayed at the Portol doline reverse fault and stereoplot (lower hemisphere projection) of structural elements used for the determination of the intervening main stress axis. In white the palustrine guide level. Scaled grey strata represent the different alluvial inputs involved in the doline filling. At the right corner, basal deep-weathered calcarenit outcrop.

Fig. 2. Bloque-diagrama mostrando los principales estructuras de deformación asociadas a la falla Inversa de la Dolina de Portol y Projección estereográfica (según hemisferio inferior) de los elementos structurales utilizados para la determinación de los ejes principales de esfuerzos involucrados. En blanco el nivel-guia palustre. En escala de grises los diferentes aportes aluviales involucrados en el relleno de la dolina. En la esquina inferior derecha el afloramiento basal calcarenítico altamente meteorizado.

lluvial wedge of 27° mean slope connects the upthrown and downthrown blocks of the fault. This includes large calcarenitic blocks (40x20cm) of an ancient severely damaged fence. The fault scarp crest strikes in an N158-163°E orientation similar to those showed by the subsidiary reverse faults located in the upthrusted block, but the fault scarp toe strikes following the mean orientation of the main fault (N140°E). Eventually, further to the NW, these two fault geomorphic elements tend to converge inducing a progressive decrease in fault scarp height form 0,88 to 0,20m (Fig. 2). Eventually, the fault scarp dies out abruptly in a transverse stone-fence, 197 m away from the quarry-wall, which obviously not corresponds to the original true fault scarp termination. Simple trigonometric relationships based on the present geometry of the different involved fault planes led to estimate an original fault scarp-length of about 535m towards the NW. To the SE the south wall of the quarry, opposite to the fault outcrop is presently covered by a slag-heap, but levelling of the ground surface southwards of the present quarry shows a mean dislocation of 1,20m. This seems to suggest the occurrence of a former prolongation of the fault scarp over the 120m separating the quarry from the polje border. In any case reverse surface faulting seems to be confined to the softer sediments of the doline (c.a 900m).

Age of probable faulting events: Paleoseismic activity and Historical seismicity

Paleomagnetic surveys carried out in the quaternary sequence of the doline (Goy *et al.*, 1991) throw a constant normal polarity in all the different sedimentary units. In this way, the whole paleomagnetic sequence has been ascribed to the normal polarity Bruhnes epoch (<0.78 Ma) indicating that reverse faulting took place during, or after middle Pleistocene times as reported by Goy et al. (1991). The absence of more than one guide-level make difficult to unravel a precise fault history, but the present outcrop led to infer a complex multi-event history. The contrasting values of displacement showed by fault throw (2,56m) and the present ground faulting dislocation (0.88m), seem to indicate the occurrence of at least to different events. A first major middle to late Pleistocene event (or events) during which, at least 1,68m of fault throw was accumulated. A second, more recent event, during which a maximum ground dislocation of 0,88m, was generated as the present fault scarp records.

Two main features seem to evidence the recent historical character of the paleoseismic activity along this reverse fault. (1) An ancient stone-fence that ran along the fault scarp strike is seriously damaged (Fig. 2) and large calcarenitic fence blocks are included in the fault scarp-related colluvial wedge. (2) Some of the ancient and unproductive almond trees placed onto the fault scarp are strongly tilted towards the NE reaching inclinations up to 40°. In all the cases tree trunk inclinations took place during early growing stages, since abrupt basal trunk reorientation to vertical trunk trends are observed. This fact leads the occurrence of strongly contorted trees only along the present fault scarp (Fig. 2). Local reports from the quarry owners led to know that this zone of the doline has been traditionally used for local pottery clay extraction since the late 19th Century, and few to none surface modification has been introduced at the northern sector of the present quarry since that times. These damaged surface-elements suggest that the last deformational event took place before earlier quarry excavations, during the late 19th Century, data which agree with the events recorded in the Seismic Catalogue of Spain (IGN, 1996).

In spite of the low degree and moderate character of the seismic activity in the Balearic Islands, a major MSK Intensity VIII historical event took place in 1851 (Galbis, 1934; IGN, 1996), from which nice epoch reports are available (Bouvy, 1851, 1853; Pujó, 1851). Ground motion was felt in a zone of about 497 km², with a mean width of 13 km (Pujó, 1851), within the polygonal area defined by the localities of Soller, Valldemossa and Banyalbufar to the Northwest, and Majorca City, El Arenal and Sencelles to the Southeast. This distribution of ground shaking broadly coincides with the geometry of the Palma and Inca sedimentary basins plus the adjacent mountainous sector of the Tramuntana range. The Location of the Macroseismal epicentre listed in the present Spanish Catalogue (2°48'E-39°36'N; IGN, 1996) is close to the Portol Doline. Even, taking into account the imprecision of this kind of determinations, all the ancient reports of Bouvy (1851; 1853) and Pujó (1851) agree that the Macroseismal zone (VIII MSK) of this historical event was located between the Villages of Marratxí and Sta. Eugenia, including the Portol Doline area, 11km NE of Mallorca City and 4-5 km NW of the IGN earthquake location. This zone, broadly coincides with the SW deflected prolongation of the Sencelles Fault along the Palma Bay Basin border. This structure is the main NE-SW extensional fault of the island, with an accumulated throw of 750m over the last 12 Ma (Benedicto *et al.*, 1991) which, as previously suggested by Del Olmo *et al.* (1988), could be the seismogenic fault of the 1851 event.

In the Macroseismal zone most of the villages, such as Marratxí, Sta. Eugenia, and the former mainly unpopulated districts of Sa Cabaneta and Portol were partially but severely damaged. Away from this zone, strong ground motion were mainly felt to the SW, in those villages located in the soft-sedimentary filling of the Palma Bay, specially in Sant Jordi and Mallorca City (Pujó, 1851), but also in Sta. Maria del Camí, located in the adjacent Inca Basin,(El Heraldo, La Esperanza y Diario Constitucional de Palma, 1851). In all these sites seismic shacking was presumably amplified by ground conditions (soft sediments, high water table, etc..). From the available descriptions seismic shaking at these zones ranged from VII-VIII MSK Intensity (Fig.1), trigering moderate damage on buildings, much of the towers and cupolas of the churches fallen down in Mallorca, including the Cathedral (Bouvy, 1851). In those localities located in the Tramuntana ranges (Soller, Valldemosa and Banyalbufar) ground shacking promoted discrete to moderate rock-falls, and some pendulum clocks stopped (La Esperanza; Diario Constitucional de Palma, 1851), ranging from V to IV MSK Intensity (Fig. 1). During the aftershock sequence a main event, of at least Intensity VI (7/6/1851), destroyed most of the previously severely damaged buildings inducing the total collapse of the Sant Marsal church at Marratxí (Pujó, 1851) and relevant ground failures in the macroseismal zone. A preliminary interpretation suggests that the reported surface faulting at the Portol doline could be probably generated during the 1851 seismic period.

Conclusions

As recently reported by Silva *et al.* (1997), apparent compressive Plio-Quaternary features of Mallorca Island can be reasonably interpreted within the NW-SE extensional framework recorded in the island since the Paleogene. As mentioned above, North limbs of the Marratxí and Sta. Eugenia antiforms, seem to be developed in response to roll-over type processes active along the lateral ramps of the ancient betic thrust planes presently outcropping in the Serra de Tramuntana. Similar processes along the deflected termination of the Marratxí antiform northern limb, in which the polje depression is installed, can also explain the reverse surface faulting at the Portol doline. In this sense, reverse faulting can be interpreted as a local and subsidiary event in relation to rollover, near-surface, collapse along the southern NW-SE trending polje border. Extensional collapse could generate the development of local, near surface, sympathetic reverse faults, and antithetic normal faults in the softer and plastic doline filling by relative rotation, triggering the recorded subsidiary SW-NE compressional stress. In this way, the case study can not be considered as true surface faulting, but as secondary and/or sympathetic coseismic surface rupture indirectly related to the seismogenetic fault. The last deformational event can be reasonably correlated with the 1851 Mallorca Earthquake (VIII MSK). In any case this preliminary interpretation needs to be properly tested, and specific fault trenching studies are planned to be developed at this zone in the framework of new research projects.

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