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Criteria to distinguish neotectonic from other active faults: Examples from the Central Pyrenees

Criterios para distinguir fallas neotectónicas de otras fallas activas: Ejemplos de los Pirineos Centrales

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Abstract

In several settings, such us the high mountain environment or the karstic terrains, active faults might be the result of non-tectonic processes. Neotectonic and non-tectonic processes causing faulting can be grouped under the term "active deformation". To characterize the seismogenic potential of a fault and, thus, its association to seismic hazard, it is necessary to determine the causes of its activity. However, the nature of the deformation along a faults is, often, not obvious. To deal with this problem, a number of criteria have been reviewed and proposed in order to constitute a working-guide to determine the origin of faulting. Two examples of the Maladeta massif (Spanish Central Pyrenees) illustrate how very different processes can generate similar scarp-forms and how one single fault-scarp might be the result of the interaction of several processes.

Key words: neotectonics, non-tectonic faults, composite fault, active deformation

Resumen

En ciertos contextos, tales como los ambientes de alta montaña o los terrenos kársticos, las fallas activas pueden ser el resultado de procesos no-tectónicos. Estos procesos, junto con la neotectónica, pueden agruparse bajo el término "deformación activa". Para caracterizar el potencial sismogénico de una falla y por tanto, su peligro sísmico, es necesario determinar las causas de su actividad. Sin embargo, la naturaleza de la deformación a lo largo de fallas no es siempre obvia. Para tratar de resolver este problema, se han propuesto una serie de criterios que pretenden constituir un protocolo para determinar el origen de una falla. Se presentan dos ejemplos del Macizo de la Maladeta (Pirineos Centrales) para ilustrar cómo diferentes procesos pueden generar formas del paisaje muy similares y cómo una falla puede ser el resultado de la interacción de varios procesos.

Palabras clave: neotectónica; fallas no-tectónicas; fallas compuestas; deformación activa.

1. Introduction

Active faults can be defined as planes of fracture along which displacement takes place or has taken place in recent times. Besides the plate tectonics, other sources of stress in the upper crust must be taken into account as causes of deformation. The term "active deformation" might serve as an umbrella to cover all of the processes causing deformation along faults (Ortuño, 2008).

In certain settings, the magnitude of the non tectonic stresses might equal or overpass the tectonic ones. Straightforward examples are deglaciated regions where the isostatic forces are controlling the activity of pre-existing faults (i.e. Stewart *et al.,* 2000) or areas where the intrusion of magmatic or salt domes are responsible for fault generation or fault reactivation.

In contrast with these phenomena, that can take place up to tens of kilometres under the earth surface, surface processes might also be the cause of new generation or reactivation of faults. Such is the case of the instability phenomena (slope mass movements and subsidence) (i.e. Chighira, 1992) and the crust unloading effects produced by lake-drainage or ice-mass melting of ice (Hampel and Hetzel, 2006; Ustaszewsky *et al.,* 2008), both of them phenomena that can affect crustal depths ranging from to 5-10 km in Alpine glaciers (Ustaszewsky *et al.,* 2008) up to 100 km in continental glaciers (Stewart *et al.,* 2000). Accordingly, these forces must be interacting simultaneously in a particular area of the crust, and thus, the movement along a fault could be due to more than one process. To deal with this situation, Ustaszewsky *et al.* (2008) have proposed the term "composite faults" to refer to active faults in the Swiss Alps in which deformation is controlled by tectonic, gravitational, and elastic rebound forces.

Paleosismological studies are always preceded by the identification of active faults in the landscape through geomorphological and geophysical methods. However, in these studies, the causes of deformation are frequently obviated or not enough discussed.

Even when the seismogenic nature of the faulting can be showed, the possibility of deformation being owed to non-tectonic forces must be discussed since the misinterpretation of a fault origin could invalidate the results derived from paleosismological analysis (i.e. recurrence time, maximum magnitude earthquake, etc.). To better constrain the nature of faulting, we need to perform or consider more regional studies. In order to contribute to this task, a number of criteria are revised below.

Ortuño (2008) recognize the composite nature of several faults in the Spanish Pyrenees. Two of these active structures are analyzed in this work, to illustrate how the use of the discussed criteria can help to better characterize the nature of faulting, and thus, its sesimogenetic potential.

2. Useful criteria

The difficulties to differentiate tectonic from non-tectonic faults have constantly worried geologists. McCalpin (1999) collected and discussed criteria to distinguish tectonic from gravitational faults. This work has been reviewed and extended by Ortuño (2008), who proposed a guideline for the use of different criteria to determine the origin of faulting.

Criteria can be grouped into morphologic, kinetic-structural and others such as chronology of deformation or processes spatial distribution (Fig.1). Most of them have to do with the feasibility of the different processes causing deformation. For this reason, the origin of the fault is often deduced from the rejection of all other possible origins. Best results are achieved by combining the greater number of criteria.

2.1. Morphological criteria

Morphologic features helping to infer the nature of active faulting are recognized through detailed geomorphological mapping, which often requires the survey of areas as large as 100 km2. This issue leads to consider the geomorphological cartography as compulsive in active tectonic studies. The features that should be considered can be grouped in quantitative and qualitative. The most useful quantitative criteria are slope and relief, rupture length, cumulative displacement, changes in offset along the fault trace, maximum offset to trace length ratio (D/L). Some relevant qualitative criteria are position and orientation of the fault with respect to the relief and the slope, curvature and continuity of the fault trace. Landform assemblage and landscape evolution might be definitive criteria.

2.2 Kinematic and structural criteria

Deformation observed both at trench and outcrop might provide important information regarding the nature of faulting. Quantitative criteria refer to cumulative displacement and slip rate as well as orientation of the fault, dip and slip with respect to the pre-existing tectonics and the present and recent stress orientation obtained from other sources (i.e. focal mechanisms, recent local and regional tectonics, break-out tests, etc.). Qualitative criteria refer to textural and structural features of deformation, as well as style of faulting (strike slip, normal or reverse).

2.3 Other criteria

The depth of deformation, often constrained by geophysical subsurface methods, might help to determine the deformational process on a fault. The temporal constrain of deformation might be a helpful criteria to explore a particular origin of faulting. For example, the occurrence of coseismic deformation would reinforce a seismogenic origin inferred by the use of other criteria. Faulting constrained to a deglaciation episode would suggest isostasy or elastic rebound as causes of deformation.

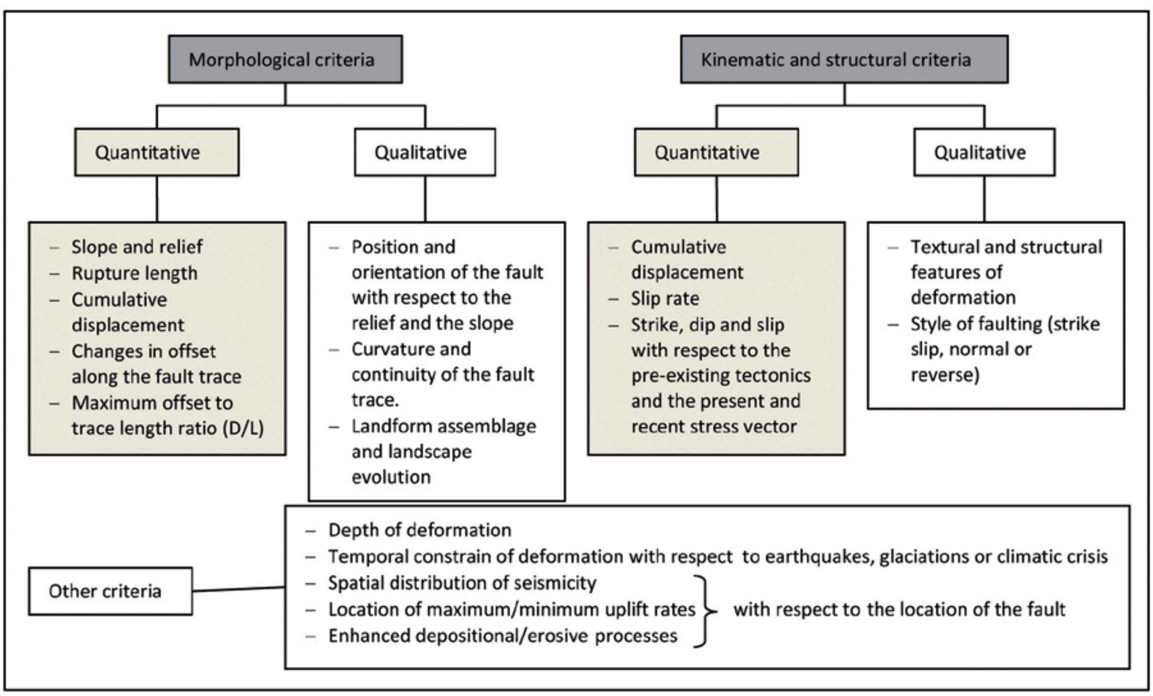

Figura 1. Cuadro sinóptico con los diferentes criterios para distinguir entre las posibles causas the fallamiento active mencionados en el texto.

Figure 1. Summary table with the different criteria to distinguish between the possible processes generating active faulting that are referred in the text.

The spatial distribution of seismicity, maximum uplift rates or enhanced depositional/erosive processes with respect to the location of the fault might as well be clue aspects to determine the fault origin.

3. Examples from the Maladeta Massif (Central Pyrenees)

The Maladeta massif (Fig. 2) is located at the core of the Pyrenean range, in the paleomargin between the Iberian and the Eurasian plates. Owe to the small convergence rate between these plates (< 0,5 mm/a; Nocquet and Calais, 2004), neotectonic faults in the Pyrenees are expected to behave as slow faults (with slip rates <0,2 mm/yr).

The study area has been scenario of two damaging historic earthquakes, one in 1373 AD (Mw~6.2) and the most recent one in 1923 AD (Mw= 5.8) (Ortuño *et al.,* 2008). The North Maladeta fault in the study area has been identified as the most probable seimogenic source of the latter earthquake and as a possible source of the former one. The fault was already active as a normal fault at the end of the Miocene, when it generated the Prüedo tectonic basin (Ortuño *et al.,* 2013). The Coronas fault is among other close seismogenic structures that could account for the 1373 AD event , and could be considered as the relief of the North Maladetat fault to the West (Ortuño, 2008).

Active faults in the area are mainly identified by the associated offset of glacial surfaces,

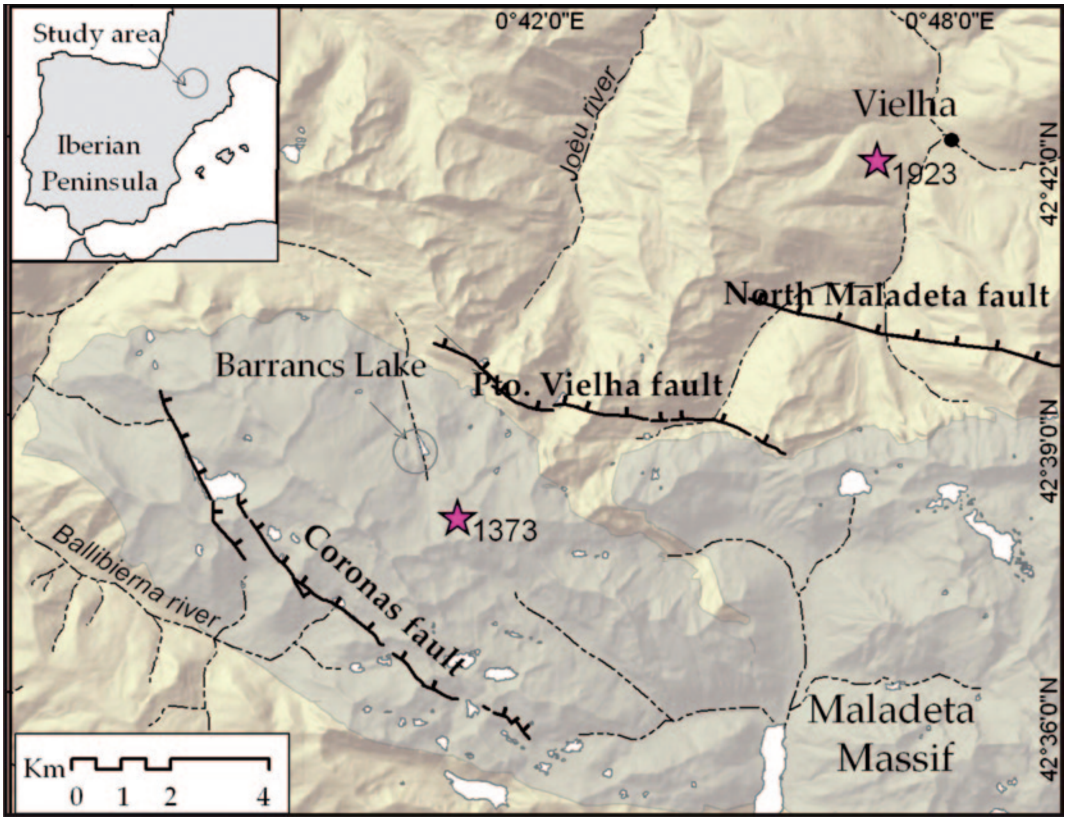

Figura 2. Representación del modelo de elevación del terreno de 30 m con la localización del Macizo de la Maladeta en la parte central de la Cordillera Pirenaica. Los epicentros de los dos sismos históricos se han marcado con estrellas y las principales fallas activas se han representado con trazo grueso. El área sombreada corresponde al batolito granítico.
Figure 2. 30 m Digital elevation model showing the location of the Maladeta Massif, in the core of the Pyrenean range, and the epicentres of the two damaging historical earthquakes (star-symbol). Main active faults in the area are indicated. The shaded area corresponds to the granitic batholith.

such as polished surfaces and valley walls. In all cases, faults are reactivated preexisting structures, inherited from the Variscan and Alpine orogenies. These faults mainly affect late variscan granitic rocks of the Maladeta massif, and occasionally, the metasedimentary paleozoic country rocks.

The landscape is characterized by deeply incised alpine valleys and a recent deglaciation history (Pallas *et al.,* 2006). Besides the neotectonic origin of the identified active faults, other possible causes of movement are: a) slope instability by slow gravitational deformation; and b) elastic rebound of the upper crust due to the postglacial rebound (see Ustaszwesky *et al.,* 2008 for details regarding this phenomenom).

3.1 The Coronas fault

The Coronas fault (Figs. 3 and. 4) is a 11.5 km length rectilineous scarp formed along a preexisting fault breccia outcropping along the northern Ballibierna valley. The systematic increase of the slope offset towards the centre of the fault trace (up to 155 m) does not seem to be the product of enhanced erosion and suggests that the structure is an active fault. This fault has been interpreted as a composite fault in which movement is controlled by neotectonics, but also by slow gravitational deformation.

The main evidences to suspect a neotectonic origin are the length and continuity of the geomorphological trace, the step-like location with respect to the seismogenic North Maladeta fault, and the macroseismal location of the 1373 AD earthquake epicentre, about 3 km north of its trace. This epicentre location (Fig. 2) is in accordance with the surface projection of the Coronas fault plane, and with the 12 km depth estimated for the hypocentre location of the event. This estimation is based on the analysis of the macroseismic data of this earthquake and the maximum depth of the seismogenic crust of the area obtained from the instrumental seismicity (see Ortuño, 2008). According to the relations proposed by Wells and Coppersmith (1994) and assuming the total rupture of the fault length (11.5 km), this fault would be capable to produce a 6.2 Mw event. However, the earthquake location uncertainty (25 km radius) leads to consider other faults in the area, such as the North Maladeta fault or the Port de Vielha fault, as possible seismogenic sources (Fig. 2).

Figura 3. Escarpe de falla de Coronas. El pulido glacial del plano de falla se ha atribuido al avance glaciar durante el último máximo glacial (ocurrido en el área hace 23-25 ka), lo que indica que el escarpe ya estaba formado en ese entonces.

Figure 3. The Coronas fault scarp. The polishing of the fault plane is owed to the last glacial advance (during the last glacial maximum ~23-25 ka ago in the area), indicating the scarp formed prior to this climatic episode.

The slow gravitational component of the movement is attributed to the fault on the basis of its position in the Aneto massif. The great altitude difference between the ridge (up to 3404 m) and the Esera river (~1900 m), shown in Fig. 4, supports the hypothesis of the northwards gravitational collapse of the ridge. The observed offset can be linked to a deep seated slope gravitational deformation (DGSD) of huge dimensions. Physical models performed in analogous conditions (Bachmann *et al.,* 2006) support the feasibility of the gravitational failure, which would be linked to the development of a new formed sliding basal plane, branched in depth to the Coronas fault. The northwards movement would be generating a great rear scarp (the Coronas scarp, Fig. 3) as well as smaller antislope scarps in the opposite valley (cross section in Fig. 4). This component of the mo-

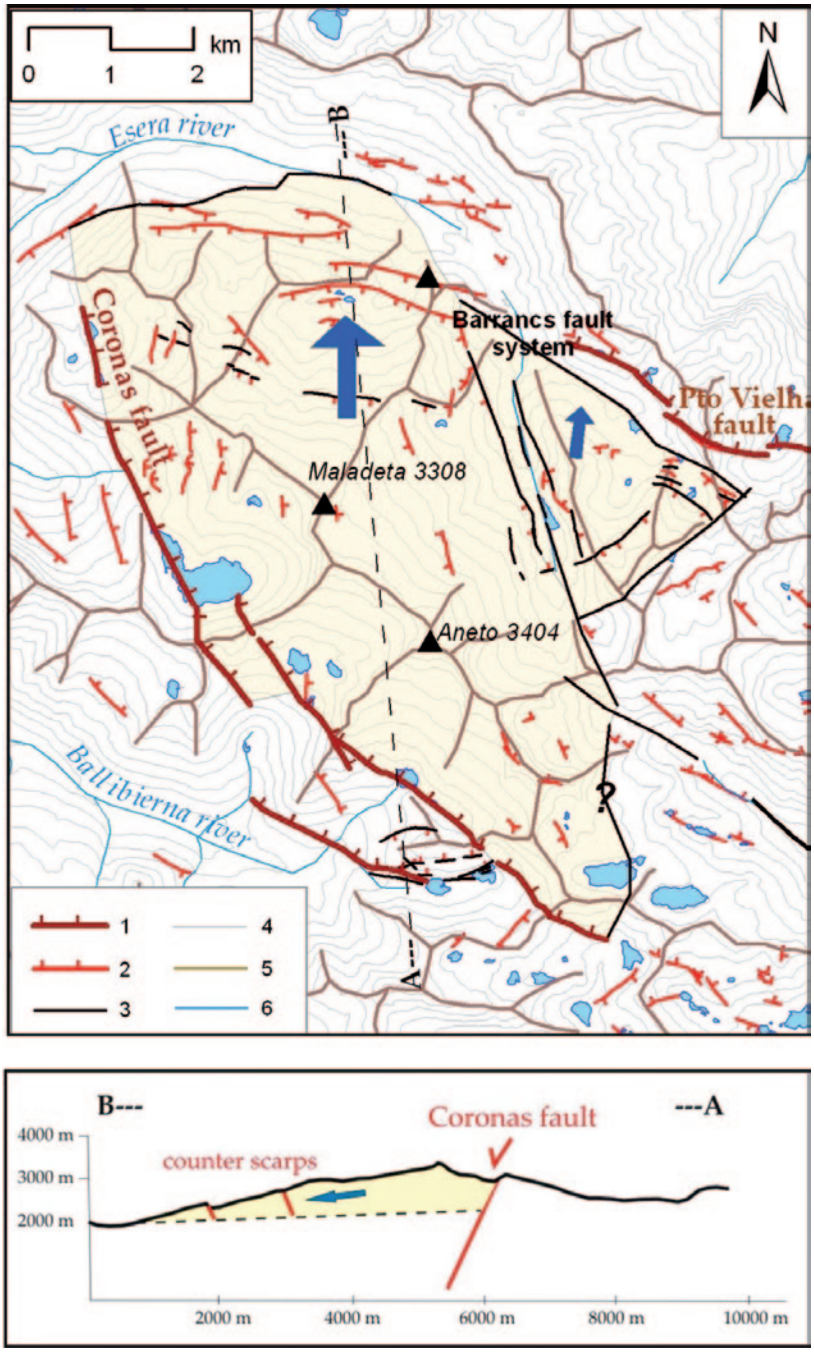

Figura 4. Arriba; Esquema geomorfológico que muestra la localización de la falla de Coronas, el sistema de fallas de Barrancs y otros escarpes, con respecto a la topografía. 1. Fallas principales; 2. Escarpes menores; 3.Límites inferidos de la deformación gravitacional; 4, Curvas de nivel cada 100 m; 5, Divisoria de aguas; 6 Ríos. Abajo: Perfil topográfico a través del deslizamiento e interpretación del colapso gravitacional del macizo de la Maladeta. El área sombreada corresponde al sector del macizo que se estaría deslizando hacia el norte.

Figure 4. Above: Geomorphologic sketch showing the location of the Coronas fault and the Barrancs fault system and other scarps with respect to topography. 1. Main faults; 2. Minor scarps; 3. Inferred limits of gravitational deformation; 4. 100 m countour lines; 5 Watershed; 6 Rivers. Below: Topographic cross section and interpretation of the Maladeta massif gravitational collapse. The shaded area corresponds to the part of the massif that would be sliding towards the north.

vement allows explaining the great fault offset with respect to its length, which yields a D/L value of 0.013, one order of magnitude greater than the expected for pure neotectonic faults. The fact of the fault being also neotectonic and seismogenic reinforces the feasibility of the ridge collapse, since the seismic shacking, amplified in the ridges, will facilitate the movement along discontinuities (see Ortuño, 2008 for further discussion).

3.2 The Barrancs fault system

Faults in the Barrancs fault system bound the Barrancs lake longitudinally and are oriented NNW-SSE, oblique to the major neotectonic features in the area (Fig. 2). The two main faults are identified by the offset of a polished glacial whaleback hill located at the bottom of the Barrancs valley. The scarps develop on old shear zones, have lengths between 0.2

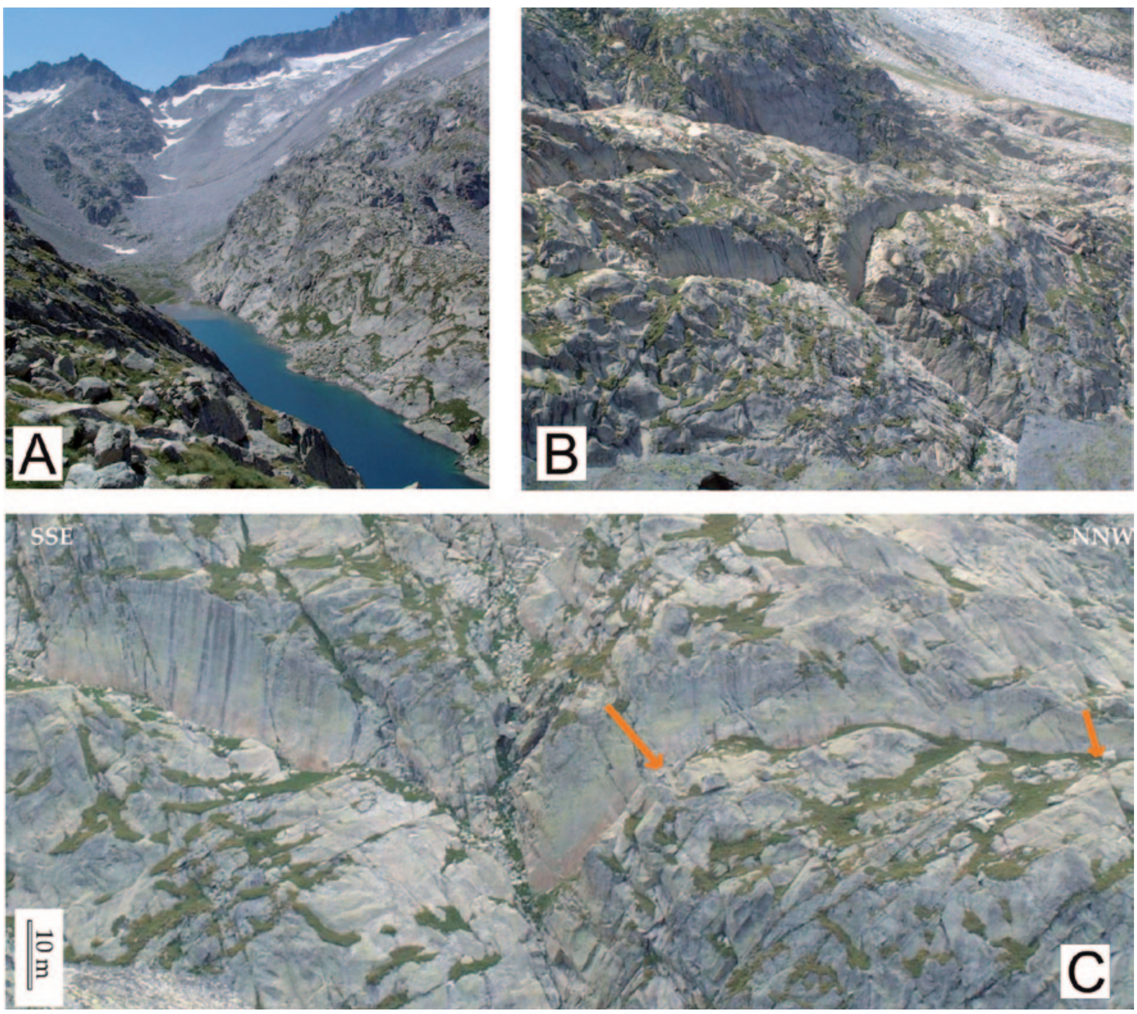

Figura 5. A) Escarpes de Barrancs desplazando superficies de pulido glaciar. B) Vista del lago de Barrancs, al fondo, Glaciar de Tempestades. C) Escarpe de falla en el sistema de fallas de Barrancs. El vector de desplazamiento se ha marcado con una flecha que indica un componente en buzamiento principal con un componente menor de desplazamiento lateral siniestro. Nótese las tres bandas de diferente grado de alteración paralelas al pie del escarpe (de abajo a arriba) que sugieren tres episodios consecutivos de exhumación.

Figure 5. Fault scarp in the Barrancs fault system. Slip vector is marked by an arrow that indicates main dip slip with minor left lateral displacement. Notice the three bands of different weathering degree parallel to the scarp base (from the base to the top) on the fault plane suggesting three consecutive episodes of exposure.

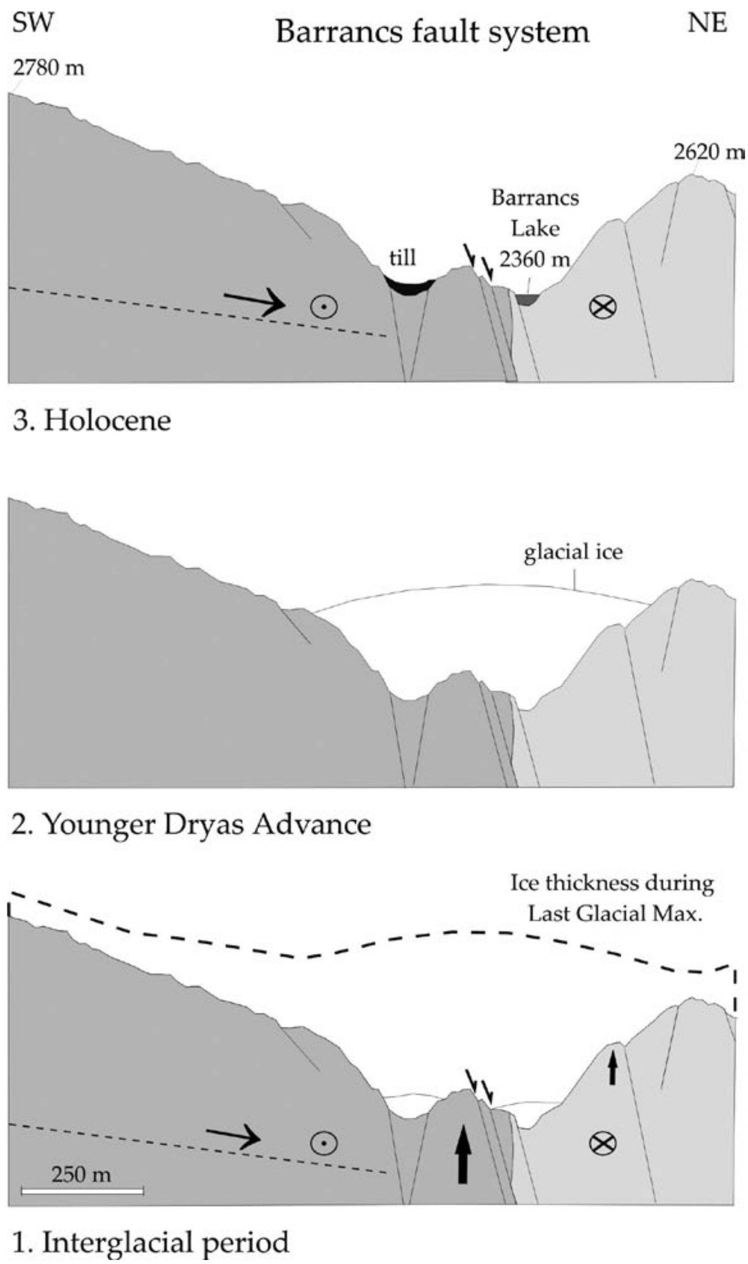

Figura 6. Propuesta de evolución de la formación y modificación de los escarpes en el sistema de Barrancs. 1; Tras el último máximo glacial, el colapso gravitacional del macizo del Aneto produjo el movimiento ascendente del fondo del valle y un movimiento lateral izquierdo a lo largo de las fallas; 2, Una vez exhumados los escarpes, el avance glaciar durante el Dryas reciente dio lugar a la generación de estrías glaciares sobreimpuestas en los planos de falla y a la obliteración de escarpes pre-existentes; 3, Es probable que se haya dado algún movimiento menor en las fallas durante el Holoceno debido a la deformación gravitacional profunda de laderas y el *triggering* sísmico.

Figure 6. Proposed evolution for the genesis and modification of the scarps in the Barrancs system; 1, After the last glacial maximum, the gravitational collapse of the Aneto massif would have produced uplift of the valley bottom and left lateral slip along the faults; 2, The advance of the ice masses during the Younger Dryas accounts for the generation of glacial striae in the fault face; 3, During the Holocene, some minor movement is likely to have occurred along the faults due to DSGD and seismic triggering.

and 1.2 km and a maximum height of 20 m. Displacement vector can be estimated restoring the shape of the offseted whaleback surface, that dates from the last glacial maximum (~ 23-25 ka, Pallas *et al.,* 2006). Episodic displacement on one of the faults is evidenced by 3 different weathering strips on the fault plane (Fig. 5). Fault planes do not show glacial polishment. However, preservation of glacial striae on the fault scarps at several locations indicate that the fault surface is affected by glacial erosion, probably during the Younger Dryas episode (~ 12-15 ka; Pallas *et al.,* 2006). Although these smaller faults could be secondary tectonic features produced by seismic shaking along the Coronas fault or the Port de Vielha fault, their short lengths do not allow to attribute them a seismogenic potential. The D/L ratio of the scarps and the high slip rates inferred from their postglacial age (>0,8 mm/a) do not support the pure neotectonic origin for these faults.

These faults have been interpreted as secondary faults in association with the northwards collapse of the Aneto Massif (Fig. 4). Evidences accounting for this origin are the measured displacement vector and the relative position with respect to the Coronas fault. According to the model for the collapse of the massif (Fig. 4), the slip along the Barrancs faults could be the result of differential movement of the Barrancs block and the Aneto block. Fig. 6 shows the proposed chronology for the formation and modification of the scarps.

4. Conlusion

The exposed examples of composite faults from the Maladeta Massif illustrate the difficulty to determine the origin of faulting in certain settings. The combination of the greatest possible number of criteria helps to reject or accept the different causes of movement along faults. Analysis of the geomorphological and structural recent evolution, together with the comprehension of the litho-structural heritage and the regional setting are essential to understand the nature of faulting, and therefore, the relevance of future paleosismological and trenching studies in a particular area.

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