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Paleoseismology, Quaternary slip-rate and heat flow of the Benis Fault (SE of Spain)

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Abstract: *We have carried out a paleoseismic analysis of the Benis Fault, located at the southeast part of Spain. We have estimated the last earthquake size-magnitude and time, from evidence of celling collapse and displaced broken carbonate blocks (M6 and 65 ± 18 ka BP). Our analysis suggests that the tectonic slip-rate of the Benis Fault is lesser than 0.01 mm/yr. Additionally we have measured the deep thermal profile of the Benis Cave (-350 m of vertical development, Cieza, SE of Spain), from single rock point temperature measurements in different field campaigns and for a period of 2 years. The temperature increases with depth, being in consequence a reverse thermal profile in comparison with normal gradients in deep caves. Furthermore, we have estimated the Vertical Geothermal Gradient with a value of 1.85ºC/100 m for the deepest zone (-150-290 m). Finally, we have calculated the heat flux of 0,46 mWm^2.*

Key words: *Paleoseismology, Benis fault, slip rate, heat flux, Spain.*

INTRODUCTION

Endogenous processes are commonly the cause for thermal anomalies into the lithosphere, mainly active tectonics and volcanism. There are a lot of thermal springs and roman baths (*thermaes*) within the Murcia province, i.e. Fortuna Basin, Alhama de Murcia (Muslim word for Arabian bath, al-hamma). Moreover, this area is one of the more active in seismicity of Spain, recording the earthquake of Lorca in 2011 (Mw= 5.1, Martínez-Díaz et al., 2011).

The study of the vertical geothermal gradient is useful for the geomechanical analysis of the upper part of the lithosphere, properties which can be used for the estimation of the deformation tectonic rates (i.e. Luetscher & Jeannin, 2004, García-Mayordomo & Giner-Robles, 2006, Doan & Cornet, 2007). Bearing in mind the presence of thermal zones and active faulting within the Murcia province (Spain), in this work we have calculated the vertical geothermal gradient for the first 350 m of the lithosphere, by using a punctual measurement of the rock temperature into the cave of Benis (Fig.1). The Benis cave is a cave developed throughout the Benis fault (Pérez-López et al., 2009, 2010), reaching 350 metres of depth in the deepest explored zone.

Figure 1 shows the relationship between caves and active faults in the zone. This is because the geological units are mainly carbonates, dolostones and detritic calcareous sandstones. The most of these caves have geothermal gradients related to high temperatures in the air cave: *Sima del Vapor* (-85 m, 43ºC), *Sima de la Higuera* (-105 m, 18ºC), *Sima del Pulpo* (-114 m, 21ºC), and *Sima de Benis* (-350 m, 25ºC), among others. We have chosen the Benis cave (Sima de Benis).

In this work, we have carried out a paleoseismic analysis of the Benis fault and we have described the thermal zonation, calculated the vertical geothermal gradient (VGG) and estimated the heat flow for the Benis cave.

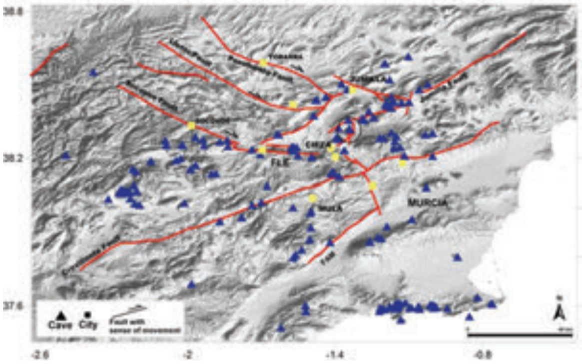

Figure 1: Active faults (red lines) and caves (blue triangles) in the Betic Cordillera. FAM: Alhama de Murcia Fault. The encircled central zone is the Benis fault with N-trending, close to the village of Cieza. Yellow squares are cities.

GEOLOGY OF THE BENIS FAULT

The Benis fault is located in the Betic geological units, in the southeast part of Spain (Jerez-Mir et al, 1972). Regarding the geometry of the fault, it is oriented N-S and dipping 75ºE (Pérez-López et al., 2009). The surface fault trace reaches 6 km, affecting upper Cretaceous limestone, Eocene carbonate units and Quaternary alluvial deposits (Fig. 2). The fault plane shows slickensides inside the cave, compatible with a normal faulting with left-handed strike slip component (Pérez-López et al., 2009).

Pérez-López et al. (2010) have excavated and studied the complete skeleton of a *Lynx pardinus spelaeus*, which was found in the Benis cave (175m depth) in a normal position of death (Fig. 3). These authors suggested that the extinguished feline died by inanition from the bones and teeth analysis, probably related with a past earthquake which obstructed the exit of the cave by ceiling collapse. They dated the time of the death in 64.,4 ± 17.6 ka BP by racemization of amino acids of the teeth (Pérez-López et al., 2012).

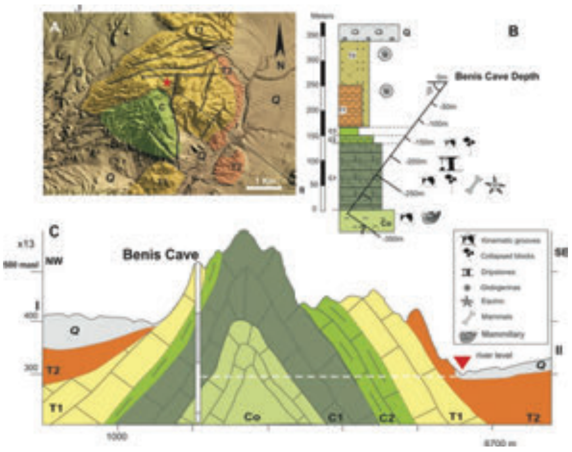

Figure 2: Geological cross section and vertical development of the Benis Cave. The cave affects Cretaceous limestone and dolostone and Tertiary carbonate. The Benis fault affects Quaternary alluvial fans. No dating available for the cave decoration.

Furthermore, this fault shows evidence of oblique movement affecting a glued block on both sides of the fault, with a net slip of ca 60 cm. Assuming this displacement as coseismic offset, the magnitude associated by using the Wells and Coppersmith (1994) empirical relationship is $6.4<M<6.5$. This value is lightly greater that using the length trace of the Benis fault and assuming a total surface rupture (6 km), with an earthquake of magnitude 6.3.

THERMAL PROFILE

We have measured punctual values of temperature in the rock of the Benis Cave and at different depth. We have used a THERMOCOUPLE device DELTA-OHM with a K-type sensor, 2 minutes of measurement time, 0.2°C of accuracy and 0.1°C of resolution. Besides, we have used a TELAIRE 7001 device for atmospheric CO_2 and temperature. Figure 4 shows the temperature profile obtained in different field work for a period of two years (2010-2011).

We have classified the thermal zones into the cave accordingly to the profile: (Z1) Hetero-thermic shallow zone: located between the pit cave and -50m, this is the zone of influence of the outside atmospheric conditions of temperature (seasonal variations) and CO_2 content. (Z2) Homo-thermic zone: located between 50 and 200 m of depth. The temperature is almost constant, ranging between 23°and 24°C. (Z3) Hetero-thermic deep zone: between 200 and 320 m of depth, there is an increase of temperature. These zones are similar in depth to those defined by Luetscher & Jeannin (2004) for different deep karst around the world, suggesting the thermal conduction as the main driving process for the rock temperature.

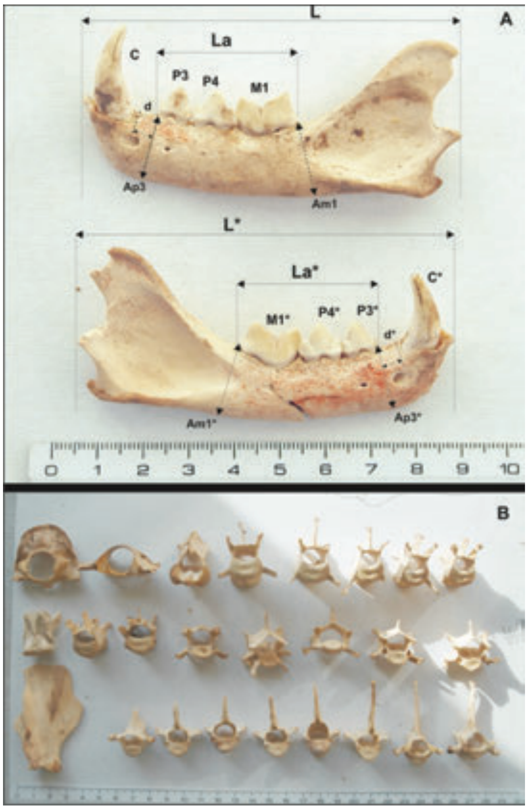

Figure 3: Paleontological record of the "Lynx pardinus spelaeus" excavated into the Benis cave. The racemization analysis was performed on the fangs of the feline.

GEOTHERMAL GRADIENT AND HEAT-FLUX

We have fitted a curve for the values of temperature in the hetero-thermal deep zone (200-320 m depth) (Fig.4), since this is the zone with inner heat input. Hence, we have obtained:

$$P= 1091-54*T \qquad [1]$$

Where P is the depth in metres and T is the temperature in °C. The coefficient of correlation is close to 0.61. According to the equation [1], the vertical Geothermal Gradient is 1.85°C/100m.

We have used the equation [2] for the estimation of the heat flux:

$$Q= ke*dT/dz \qquad [2]$$

Where "ke", is the thermal conductivity for limestone (k/100m), and in 100m depth of carbonates. We have assumed the k value for limestone of 2.5 $Wm^{-1}K^{-1}$ (Beardsmore & Cull, 2001). Therefore, we obtain a heat flux of Q= 0,46 mW/m^2. This value is very similar to the value obtained by García-Mayordomo and Giner (2006) (45 mW/m^2) into the Betic Range for the Prebetic units.

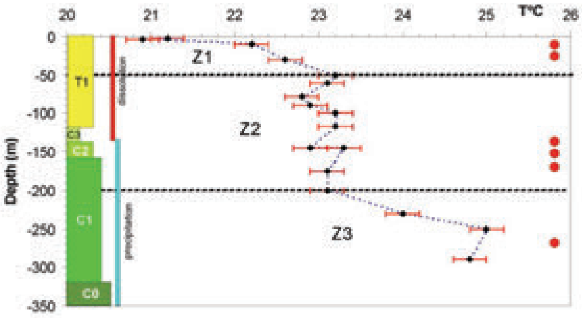

Figure 4: Thermal profile of Benis cave. The profile intersects the fault plane between 150m and 200 m. The upper part, 0-50m is the shallow hetero-metric zone, where there is influence of the outside, atmosphere and seasonal temperature are Cretaceous limestone (C0-C3) and T1 carbonate Tertiary deposits.

DISCUSSION

Firstly, assuming the size-magnitude of the last earthquake of the Benis Fault as M6.5, and dated at 64.4 ka BP, the tectonic slip-rate (SR) can be estimated by using the Slemmons (1982) empirical relationship. Therefore, the SR of the Benis fault ranges between 0.01 and 0.008 mm/yr.

Secondly, we have estimated the heat flux from the geothermal gradient associated to the fault plane. The expression defined by Lachenbruch & Sass, (1980) is:

$$Q = SR^{*}\tau \quad [3]$$

Where Q is the heat flux, SR the tectonic slip-rate of an active fault and τ is the tangential stress. Assuming the minimum value for the tangential stress as the gravity load, then:

$$\tau = \rho^{*}g^{*}z^{*}\sin(\theta) \qquad [4]$$

Where ρ is the averaged density of the limestone (2800 kg/m^3), g is the acceleration of the gravity (9.8 m/s^2), z is the fault width where the thermal gradient is estimated (320m) and θ is the dip of the fault (75º).

Finally, resolving the equation [3] and [4] shows that the heat flow of the Benis Fault is close to $1.345 \cdot 10^{-3}$ mWm^{-2}. This value is smaller than the value calculated from the thermal profile.

CONCLUSIONS

(1) The Benis Fault is a sinistral oblique active fault located northward of the Betic Range (Prebetic Unit). It is 6 km long, trending N-S and dipping 75ºE.

(2) The last earthquake was of $6.3<M<6.5$ size, from the empirical relationship of surface rupture long and the coseismic off-set (60 cm of net slip), and it took place 64.4 ± 17.6 ka BP, dated by racemization of amino-acids.

(3) The tectonic slip rate of the Benis Fault ranges between 0.008 and 0.01 mm/yr.

(4) The vertical Geothermal Gradient into the area is 1.85º/100m, defining a geothermal zone.

(5) The heat flux derived of the vertical geothermal gradient is 46 mWm^{-2}, being this value similar to others obtained by other authors. However, the heat flux for the Benis Fault is notably lesser, $1.34 \cdot 10\text{-}3$ mWm^{-2}. Therefore, the thermal anomaly within the area is related to karst convection instead of advection of heat by water flow across the fault plane or heat conduction from the fault activity.

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