GROUND EFFECTS OF THE BAELO CLAUDIA EARTHQUAKE (4th CENTURY A.C.): GEOMORPHOLOGIC AND ARCHAEOLOGICAL DATA.

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Summary

After a review of the state of the art of the paleoseismological studies in Spain, the study case of the former Roman City of *Baelo Claudia* is considered. This study represents the first paleoseismic study in Spain in which archaeological remains are considered. *Baelo Claudia* located at the axial zone of the Gibraltar Strait (Cadiz, South Spain), contains abundant disrupted architectural relics probably related to historic earthquake damage. Main co-seismic structures are related to pop up-like deformations affecting to flagstone couplets of the ancient roman pavement. They show consistent orientations of N110-116ºE at the ancient *Forum* and more randomly distributed NE to SW arrays at the *Decumanus maximus* (Main Street). Main features indicate an anomalous westwards ground displacement oblique to the main gentle southward slope of the topography suggesting that compressive stress acted in a broad NE-SW/ENE-WSW orientation. Main disruptions and city abandonment have been related to relatively far away strong earthquakes (Menanteau *et al.* (1983). But the occurrence of a close moderate earthquake (mb 5-6), linked to the major NE-SW strike slip fault system, can also explain the observed deformations if we consider the unstable character of the ground at this zone.

Introduction: Paleoseismic studies in Spain.

Studies of neotectonic character have been widely developed in Spain during the last two decades. They have been mainly sponsored by the projects of the Neotectonic Map of Spain 1:1.000.000 (in press –ITGE-ENRESA-), and the Map of Recent Stress (Proyecto SIGMA, 1999 –CSN-). In the Mediterranean zone specific projects have been developed, as is the case of the Neotectonic, Seismotectonic and Fault Activity Maps of the Murcia Region (ITGE, 1994), and also the Neotectonic Study of the Gibraltar Strait (SECEGSA, 1995). More recently, only since the early 90's, paleoseismic studies have been really introduced. These deal with specific fault zones located in seismically active settings as the Lorca-Alhama, Palomares and Carboneras strike-slip Fault Zones (Eastern Betics, SE Spain) and the set of normal faults of the Catalan Coastal Ranges, where the first fault trenches have been developed related to Nuclear Plant assessment studies. Isolated segments of ancient major fault zones in the Palaeozoic Iberian Massif have been analysed too, as is the case of the Alentejo-Plasencia Fault Zone displaying unforeseen signals of pleistocene activity. On the other hand, studies about the identification of seismites of Quaternary and Late Neogene age have been carried out in the soft sedimentary filling of some Spanish basins. This is the case of the Madrid Basin, Eastern Betics Basins, and Palma de Mallorca Basins.

The set of data compiled in all these studies is still a short step in the evaluation of the real seismic potential and recurrence intervals of the investigated faults and/or zones in Spain. Anyway the main seismogenetic faults, capable to promote destructive earthquakes in Spain (as is evidenced by the historical record) are mostly identified in the Mediterranean realm, where recurrence intervals for destructive earthquakes can be provisionally bracketed between c.a. 100 and 400 years. On the other hand, these destructive earthquakes seem to hold an upper limit of magnitude ranging between 6.5 to 7 (mb), but recorded maximum intensities during destructive historical events range from VIII to X MSK in the Betic Cordillera, Pyrenees and associated foreland terrains. Peak intensities have been always recorded in unstable terrains such as Quaternary soft sedimentary fillings, Triassic and Tertiary plastic materials, and steep slopes. Therefore, ground shacking, more than surface faulting, seem to be the main critical effect/factor in the determination of the seismic hazard of these zones. In this way, from the publication of the New Spanish Seismic Code (NCS-94) we have a valuable tool to evaluate, and compare with geological evidences, the maximum expected ground horizontal acceleration at different sites ranging from 0.04g to 0.25g. It is important to note that the NCS-94 also takes into account the contribution of offshore, and relatively far away, seismic sources such as the Azores-Gloria Fault System responsible of the destructive 1755 Lisbon Earthquake, felt in the whole Iberian Peninsula.

Therefore, specific trenching studies on fault zones, focused to evaluating its real seismic potential, are still necessary. But paleoseismic studies devoted to the evaluation of seismic hazards in Spain should be focused on the identification of secondary coseismic effects, such as liquefaction structures and landslides, in the geologic and geomorphic records. Architectural relics must be also considered in the paleoseismic investigations devoted to the historical period. In this sense this paper present one of the first paleoseismological approaches based on disturbed architectural remains in the Iberian Peninsula, initially reported by Menanteau *et al.* (1983).

Geological and Neotectonic Setting of Baelo Claudia.

Baelo Claudia is situated in the axial zone of the Gibraltar Strait, the westernmost termination of the Mediterranean Alpine Chain. This region is currently experiencing a roughly NNW-SSE compression promoted by the convergence of the African and Euroasian plates. This stress orientation gives place to the generation of two conjugated major strike-slip systems defined by NE-SW sinestral faults and NW-SE dextral ones (Fig. 1) which constitutes large inland morpho-tectonic lineaments (up to 22 km length). This kinematics gives place to the occurrence of no conservative plane horizontal strain (Zazo et al., 1999) promoting the permutation of the stress tensor (σ_2-σ_3) on both lateral sides of the Strait axial zone, generating E-W tectonic expulsion of crustal blocks (Goy et al., 1995). Anyway, the presence of plastic materials along the Atlantic sector, promotes no homogeneous strain giving place to relative dextral offsets on some of the main NE-SW faults, consistent with coastline displacement (Zazo *et* *al.*, 1999) and observed faulting structures in Pliocene and Quaternary materials (Goy et al., 1995). In addition, aside from the moderate degree of seismic activity in this zone, this complex NE-SW fault system has been identified by Goy et al. (1995) as a probable seismic source of moderate events (Mb<5) at intermediate depths (40 km-60 km). Most of them are located in the offshore area along the prolongation of the main inland faults. *Baelo Claudia*, located in the coastal zone, is close to one of the major NE-SW dextral fault zone of the Atlantic sector of the Strait, the Cabo Gracia Fault Zone (Fig. 1). Most of these faults run along ancient thrust planes and geological contacts between enhances the natural instability of the ground in the settlement area, as is the occurrence of a relatively high water table at 3-3.25 m depth. From these data, geotechnical proposals relate the described deformations to volumetric changes of the expansive marly substratum. But, as we will se below, the occurrence of main deformations are linked to those zones founded on the loose upper materials *(Forum, Basilica and Decumanus maximus)* and never on those buildings partially founded in the plastic marly substratum (Theatre and Temple). These data suggest that the natural ground instability promoted by volumetric changes of the marly substratum is not the main triggering factor of the observed

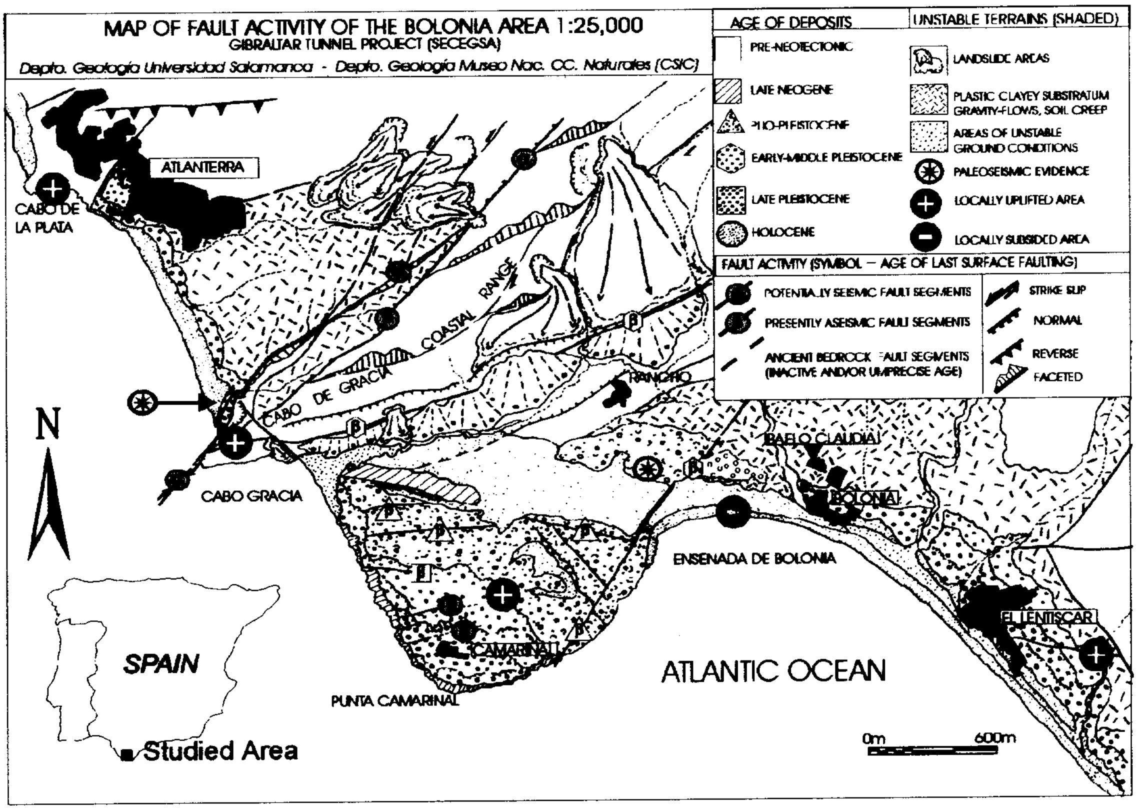

Figure 1. Neotectonic Map of the Bolonia Area (Cadiz, Souht East Spain)

the different formations of the Campo de Gibraltar Flysch units, such as the turbiditic Aljibe Sandstones and the more softer marls of the Bolonia unit (Esteras *et al.*, 1988). In detail, the city is founded on unstable variegated sandy marls, of Cretaceous-Eocene Age, of the so-called Bolonia Unit, whose thickness range from 2.30 to 6m in the urban area (Borja *et al.*, 1993). This are normally overlaid by an upper anthropic poorly consolidated silty-clayey level of 2.3-3 m thick, commonly topped by weakly developed vertic soils. This upper soil level was partially or totally removed during the earlier embankment works for city foundation (1st Century A.D.) so the bulk of the city is directly founded in the aforementioned loose anthropic materials. Only in the upper sector of the city the Theatre and the Temple are partially founded in the plastic marly substratum. Geotechnical parameters of these last materials indicate its high instability and expandability, reaching liquid limits of 44-61% and swelling potentials ranging between 0.6 to 1.70 kg/cm^2, but locally up to 2 kg/cm^2 (Borja et al., 1993). In addition, a complementary factor deformations. But, moreover, it could play an important role on the amplification of ground motion by the occurrence of eventual seismic shacking, as postulated by Menanteau *et al.* (1985).

Disturbed architectural relics at Baelo Claudia.

The main disturbed relics occur at the ancient *forum*, where flagstone couplets of the roman pavement are deformed showing pop up-like alignments. They are arranged in seven different lineaments crossing the entire pavement zone with consistent orientations N110E (Fig. 2). These lineaments show spacing ranging from 7.35 to 6.25 m, but in the southern sector there are some lees developed intermediate lineaments whit spacing of 2,5-3,7 m.. In most of the pop-up arrays, the flagstone couplets spur one each other, or even are partially uptrusthed, bearing maximum vertical displacements of 4-6 cm and overlapped sections of 3-2cm (Fig.2). Only in two isolated cases pop-up like deformation is produced by rupture of individual flagstones. In any case pop-up trends are strongly conditioned by the orthogonal disposition of the pavement, but they are developed in an anomalous way, oblique to the broad SW gentle slope of the ground. Outside the forum the most impressive deformations are located on the *Decumanus maximus* (Main Street) which is oriented N110E, running by the south side of the *forum*. In this case irregular shaped polygonal flagstones constitutes the pavement. They are highly disturbed showing pop-up like deformations mainly defined by the connection of ruptures in individual flagstones. They are arranged in two main orientations, N130-125E and N50-60E, but showing the first one the most important development. In this case vertical displacements close to 30cm and intra-flagstone uptrusthing, are common. At this site, pop-up like arrays are not apparently conditioned by any architectural pattern. The trend of the pop-up like lineaments display a clear arched geometry, curved towards the SW. Finally, as it occurs in the *forum*, in the zone close to the Basilica the ancient pavement is highly disorganized and deformed, showing a randomly oriented scour & ridge micro-topography. Flagstones are tilted a maximum of 25° in SW and SE orientations, vertical displacements are close to 50 cm and open fractures of 2-4 cm wide are observed. This deformational assemblage could be interpreted as consequence to the collapse of the Basilica columns.

In the rest of the city, still partially buried, only isolated deformations can be observed. They are related to the occurrence of individual pop-up like arrays at the Theater, with similar orientations than those observed at the forum. But also, other less diagnostic features such as uptrusthed staircase slabs, and westerly tilted walls (10-20°) occur.

Geomorphologic assessment of surface faulting and paleoseismicity in neighbors zones.

In the Bolonia area, the major fault zone is the Cabo Gracia Fault (Goy *et al*., 1995) located 2,5 km west to Baelo Claudia. This is a NE-SW dextral strike-slip fault zone of about 400 to 650 meters wide and 8,65km long. It holds a complex braided pattern comprising ancient reactivated betic thrust planes and folded mechanical contacts (Aljibe Sandstone Fm.) connected by new generated NNE-SSW to N-S fault segments (Fig. 1). It promotes a broad NE-SW horst-like topography (Cabo Gracia promontory range) defined by large faceted range front-faults and more discrete bedrock fault scarps mainly facing to the SE (Bolonia Bay), from which a precise fault timing is impossible to asses.

On the contrary, the NW flank of this structure is defined by a more discrete, but continuous, range front fault generated along the main fault trace, which mainly affects to bedrock materials (Fig.1). Only in its littoral terminal zone, along a discrete NNE-SSW restraining bend, marine and dune sandy deposits of late Pleistocene age are deformed, giving place to a spur-ridge of 9m high topped by a more recent alluvial gravel-level displaying antiform-like deformation (Goy *et al*., 1995). In detail this spur ridge display a positive flower internal structure, defined by NNE-SSW reverse faults with upwards fan-like arrangement, displaying localized phenomena o fluidification. Late Pleistocene deformed marine-aeolian deposits belong to the ISS 5e (128 Ky. BP, Zazo *et al*., 1999). This deformational assemblage has been interpreted as a paleoseismic feature in which accumulated events are difficult to differentiate. Anyway, last reactivation event along this fault segment seems to be younger than 128 Ky. BP.

In the southern flank of this promontory ranges, recent ground failure events, of probable paleoseismic origin, are recorded along more discrete N55-76°E reactivated fault segments. They are located less than 0,8 km NW of Baelo Claudia, and related to deformed karstic levels of early-middle Pleistocene unconsolidated gravel-sandy deposits outcropping in a raised marine platform (+67m) at Punta Camarinal (Fig. 1). Two undisturbed aeolian levels bearing Bronze Age and Roman remains top the deformed materials, bracketing the main deformational events from the Middle Pleistocene to the Bronze Age (Goy *et al.*, 1995).

Conclusions.

The set pop-up like lineaments described at this paper can be related to historical earthquake damage as formerly proposed by Menateau et al (1983). Geotechnical proposals explaining the pop-up like deformations in relation only to the swelling potential of the silty-clayey ground and subsidiary slope creeping processes (Borja et al., 1993) need to be properly tested. No evidence of soil creeping can be observed around the ancient city. In addition, most of the disturbed relics are located at the lower sector of the city, where natural slope is near horizontal. On the contrary the steepest slopes are just present in the upper part of the city (Theater sector), where only isolated pop-up like deformations have been observed. Likewise, main disturbed zones are those founded in the loose upper anthropic level, and not those funded on the plastic layer mentioned by these authors.

Figure 2. Pop-up like deformations of Flagstones in the *Forum* of *Baelo Claudia.*

Earlier stages of city abandonment have been dated between the 2nd and 3rd Centuries A.D. Numismatic evidence indicates the occurrence of a first important decay period between the years 268 and 364 A.D. (Menanteau *et al*., 1983). The period of main destruction of the city walls has been bracketed between the years 350-370 AD (Didierjean *et al.*, 1978). But the definitive city abandonment took place in the late 4th Century AD or early 5th Century AD, when the partially collapsed Basilica was eventually abandoned. The main problem is that no earthquake is listed in the Spanish catalogue in the study zone during that period. Menanteau *et al.* (1983) linked city destruction to relatively far away strong earthquakes, such as those occurred in the Alboran Sea (North Morocco: 365 A.D.) or in the San Vicente Cape (South Portugal: 382 A.D.), with estimated magnitudes up to mb 6 (Sathl, 1971; Hatzfeld, 1976). The interpretation of Menanteau et al. (1983) is largely based on the fact that during the destructive 1755 Lisbon Earthquake, nucleated close to the San Vicente Cape, the zone of the Gibraltar Strait underwent intensities of VII MSK.

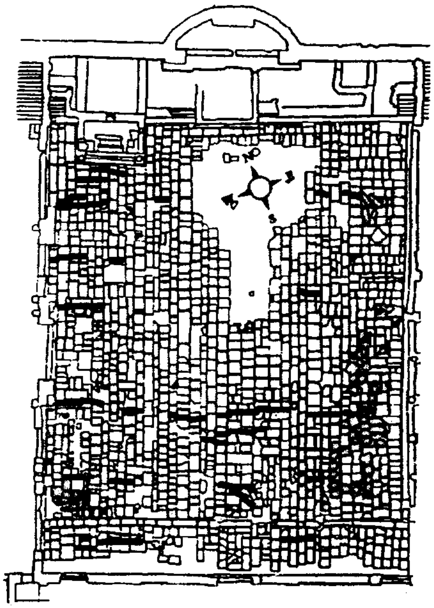

Fig. 3. Arrangement of the Pop-up like lineaments (Bold lines) and disorganised pavement sectors (grey) observed at the Forum of Baelo Claudia.

Anyway, from the newly collected data, a different interpretation can be outlined. Nearest NE-SW trending dextral faults display signals of recent paleoseismic activity and they are presently related to moderate seismicity (mb<5). It is possible that a moderate earthquake, not noticeable in other zones (mainly unpopulated for that time) could generate the observed deformations. In this case, it is necessary to assume that seismic shacking was amplified at the Baelo area by the natural unstable conditions of the ground. In this sense, recent works demonstrated that similar pop-up like structures can be developed by close moderate earthquakes, such as the Ms 6.1-5.6 Egion Earthquake (Mariolakos *et al.*, 1998). These authors report the occurrence of pop-up like structures in floor-stone couplets on a 0.3 m thick cemented mole founded on loose coastal deposits, at the village of Eratini, located about 8-10 km away from the epicentre.

In our case, the suspect faults are located less than 3km away (i.e Cabo de Gracia Fault), and the roman pavement has only a thin and poorly cemented mole and is founded on unstable ground, favouring its disruption from an eventual earthquake. This means that a moderate earthquake (5-6 mb), with epicentre close to *Baelo Claudia* (<3km) could promote the set of described pop-up like arrays, and partial damage on the city, maybe promoting its earlier abandonment. In this sense, the new Seismic Code of Spain (NCS-94) consider average horizontal accelerations of 0.06-0.07g for this area, but considering the specific ground conditions of the zone, local peak accelerations of 0.1-0.15g can be obtained for recurrence intervals of up to 500 years. These values would be sufficient to promote the observed pavement disruption. For example, unreinforced adobe buildings can even collapse under horizontal accelerations as small as 0,1g (Bolt, 1993).

On the other side, the orientation of the pop-up like arrays indicate that main ground movement took place in a main NE-SW orientation (N35-45E), refracted in the *forum* due to the orthogonal pattern of the ancient roman pavement. This orientation is parallel to the main NE-SW dextral faults of the zone, and therefore consistent to their kinematics behaviour. In this sense, the arched geometry of the pop-up like arrays affecting the *Decumanus maximus*, and the anomalous counter-slope upthrusthing of the broken flagstones, seem to indicate that ground movement was produced in the offshore area (SW of the city), maybe along the prolongation of the Cabo the Gracia Fault

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