EVARITE KARST IN CALATAYUD GRABEN (IBERIAN RANGE). EFFECTS ON FLUVIAL SYSTEMS AND ENVIRONMENTAL ASPECTS

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FIELD TRIP GUIDE - B6
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1. Introduction to the geology and geomorphology of the Iberian Range

The Iberian Range, with a dominant NW-SE structural and topographic grain, is one of the main mountain belts of the Iberian Peninsula. It stretches for about 400 km from its northwestern end in the Sierra de la Demanda up to the Mediterranean Sea, and reaches 200 km in width (Fig. 1). The topography is dominated by planation surfaces commonly in excess of 1000 m above sea level, and the highest mountains reach more than 2000 m in elevation. From the hydrographical point of view, the Iberian Range forms part of the divide of some of the most important Spanish watersheds: Ebro, Duero, Tajo, Guadiana, Jucar, and Turia River basins (Gutiérrez and Peña, 1994). The climate, with local variations largely controlled by the topography, is relatively dry and characterised by hot summers and cold winters. In most of the area, the number of days with minimum temperatures below freezing-point per year is more than 80 (Gutiérrez and Peña, 1994). From the geotectonic point of view, the Iberian Range constitutes an intraplate alpine orogen produced by the tectonic inversion of Mesozoic sedimentary basins as a consequence of the convergence and collision between the Iberian, Euroasiatic, and African plates (Alvaro et al., 1979; Alvaro, 1995; Capote et al., 2002; Sopeña et al., 2004). The rocks that crop out in this mountain belt record two large tectosedimentary cycles: the Variscan (Hercynian) and the Alpine cycles (Fig. 1).

The Variscan cycle is represented by rocks ranging from Precambrian to Permian in age, largely made up of siliciclastic sediments. The relatively scarce outcrops of these materials generally occur associated to alpine compressional structures (folds and thrusts) (Alvaro, 1995; Sopeña et al., 2004) and uplifted neotectonic blocks (Fig. 1). These inliers commonly have a relief that protrudes above the dominant plateau-like topography of the Iberian Range.

The Alpine cycle, developed from the Upper Permian till the Lower-Middle Miocene, is divided into two major stages: the sedimentary stage and the orogenic stage. During the sedimentary stage, from the Upper Permian to the end of the Cretaceous, an extensional tectonic regime gave place to sedimentary basins with shallow marine and continental deposition. Throughout the orogenic stage, from the late Cretaceous to the Lower-Middle Miocene, a new compressional regime caused tectonic inversion of the sedimentary basins and deformation of the Mesozoic and synorogenic Tertiary sequences (Alvaro, 1995; Capote et al., 2002; Sopeña et al., 2004).

Two major sedimentary cycles occurred during the sedimentary stage, each of them composed of two phases; an initial rifting phase with high-rate tectonic subsidence, and a subsequent post-rifting phase with slow thermal subsidence (Salas and Casas, 1993; Alvaro, 1995; Sopeña et al., 2004). During the rifting phases, deposition occurred in diverse sedimentary environments (shallow-marine, transitional, and continental). The post-rifting phases are characterised by thick and extensive carbonate sequences formed in shallow-marine platforms. These carbonate formations that constitute the most important outcrops, have played a decisive role in the
geomorphological configuration of the mountain belt. The folded Mesozoic carbonate rocks are commonly truncated by extensive planation surfaces that give a plateau-like appearance to large areas of the Iberian Range.

Figure 1. Location of the Iberian Range and simplified geological map showing the situation of Calatayud Neogene Graben (based on IGME, 2004).

The orogenic stage started by the beginning of the Tertiary, when the tectonic regime within the Iberian basins switched from extensional to compressional. The consequent shortening caused the tectonic inversion of the Mesozoic basins, largely through the positive reactivation of the normal faults that were active during the sedimentary stage. The result is a double-verging intraplate belt, with a relatively low grade of deformation and that is almost devoid of metamorphism (Capote et al., 2002). During this stage, relatively small continental basins with synorogenic sedimentation (molasse) were formed within the Iberian Range. These Tertiary sediments affected by compressional structures are mainly composed of terrigenous facies.
The contractional architecture of the orogen is largely controlled by the superposition of two structural levels with a markedly different rheology (Capote, 1983; Alvaro, 1995; Capote et al., 2002). The basement, with a dominantly brittle behaviour, includes the Palaeozoic rocks and the Lower and Middle Triassic sediments (Buntsandstein and Muschelkalk facies); the more ductile cover is made up of Jurassic, Cretaceous and Tertiary sediments. Both units are separated by a regional detachment formed by the Upper Triassic shales and evaporites (Keuper facies). These sediments commonly constitute the sole of the thrust structures and favour the generation of detachment folds. The compressional structures in the central sector of the Iberian Range show a dominantly thick-skinned tectonic style, with folds and thrusts involving the basement (Alvaro, 1995; Capote et al., 2002).

During the Lower-Middle Miocene, the tectonic regime changed gradually from compressional to extensional, resulting in the generation of grabens superimposed to the previous shortening structures (postorogenic rifting). These extensional basins reflect the westward propagation of the rifting that formed the Valencia Trough in the Mediterranean Sea (Simón, 1989; Anadón y Moissenet, 1996; Anadón y Roca, 1996; Capote et al., 2002). Although in the central sector of the Iberian Range extensional tectonics has been active from the Middle Miocene up to the present day, two main episodes of deformation can be differentiated.

The first extensional episode started in the Lower-Middle Miocene and generated the two largest intramontane basins of the Iberian Range; the Calatayud Graben and the Teruel Graben, both about 100 km long (Fig. 2). Calatayud Graben has a NW-SE orientation, whereas Teruel Graben has an oblique NNE-SSW trend, parallel to the western Maestrazgo grabens developed in the coastal fringe. Both internally drained grabens were filled by alluvial fans that grade distally into lacustrine environments of carbonate and evaporite deposition. Sedimentation under endorheic conditions ended in Lower Pliocene times in Calatayud Graben and in the Upper Pliocene in Teruel Graben (Gutiérrez et al., 1996). By the end of the first extensional episode, a great part of the Iberian Range was dominated by flat planation surfaces developed on folded pre-Neogene sediments. Several stepped planation levels have been recognised in some areas (Gracia et al., 1988). There is a particularly extensive planation surface, called the Main Planation Surface of the Iberian Range, that records a period of relative tectonic quiescence (Peña et al., 1984; Simón, 1984; Gracia et al., 1988; Gutiérrez y Gracia, 1997). Although this erosional surface is not considered to represent an isochron (Gutiérrez et al., 1996), its age has been locally constrained on the basis of its topographic connection with the top of Pliocene limestone units in Calatayud and Teruel Grabens (Gracia et al., 1988; Gracia, 1990; Gutiérrez, 1998). This surface and the uppermost Pliocene calcareous sediments of Calatayud and Teruel Grabens have been widely used as a marker to characterise the geometry of the neotectonic deformations developed subsequent to their formation (Peña et al., 1984; Simón, 1984; Gutiérrez and Gracia, 1997).
Evaporite karst in Calatayud Graben

Figure 2. Geological sketch showing the distribution of the Neogene and Plio-Quaternary grabens in the central sector of the Iberian Range (from Gutiérrez et al., 1996).
The second extensional episode began in the Upper Pliocene and has produced some of the most outstanding morphotectonic features of the central sector of the Iberian Range (Peña et al., 1984; Simón, 1989; Gutiérrez and Peña, 1994; Gutiérrez and Gracia, 1997). Extensional block tectonics in this episode deformed the Main Planation Surface, reactivated Calatayud and Teruel grabens locally tilting and faulting Pliocene formations, and generated new half-grabens located to the west of the previously existing Neogene grabens (Gracia and Gutiérrez, 1996). These Plio-Quaternary morphostructures are controlled by NW-SE faults in their eastern margins and in two cases the topographic depression is largely due to corrosional lowering in neotectonically controlled poljes, rather than to tectonic subsidence. These include, from north to south: Munébrega Half-graben (Gutiérrez, 1998), Daroca Half-graben (Gracia, 1990, 1992), Gallocanta Polje-Graben (Gracia et al., 2002) and Jiloca Polje-Graben (Gracia et al., 2003) (Fig. 2). The Jiloca depression, around 60 km long, has a N-S orientation and is controlled by three NW-SE trending faults with en echelon arrangement. Extensional neotectonics is still active as reveals the normal faults that affect Pleistocene and Holocene deposits and landforms (Capote et al., 1981; Gutiérrez et al., 1983; Moissenet, 1983; Simón, 1984; Burillo et al., 1985; Gracia, 1990; Gracia y Gutiérrez, 1996; Gutiérrez, 1998).

The change from endorheic to exorheic conditions in the Neogene and Plio-Quaternary structural depressions has taken place in a progressive fashion through the capture of the basins by the external drainage network and the headward erosion caused by the new drainage within each depression. This switch in the hydrologic regime constitutes an important landmark in the geomorphological and hydrogeological evolution of the grabens (Gutiérrez et al., 1996). Once each basin was captured, the new drainage network started to incise the endorheic infill of the grabens, developing stepped sequences of alluvial levels (pediments and terraces). The Teruel Graben was captured by a primitive Turia River through its southern margin in the Lower Pliocene (Fig. 2). The change to exorheic conditions progressed towards the central and northern sectors of the graben, where Upper Pliocene exorheic morpho-sedimentary alluvial units overlie Upper Pliocene calcareous lacustrine sediments (Gutiérrez, 1998). The initial capture of Calatayud Graben was achieved by a primitive Jalón River in the Upper Miocene or Lower Pliocene (Fig. 2). Laterly, the Jiloca River, a tributary of the Jalón River, captured by headward erosion the Daroca Half-graben, where there are several alluvial levels inset in the infill of the basin. Subsequently, the same river captured the Jiloca Polje-Graben. The south-central sector of this depression has remained as an internally drained area until its artificial drainage in historical times (Gracia et al., 2003; Rubio y Coloma, 2004). The Munébrega Half-graben was recently captured by a tributary creek of the Jalón River. The Gallocanta Polje-Graben still constitutes an endorheic lacustrine basin (Fig. 2) (Gutiérrez et al., 1996).

One of the most outstanding geomorphological characteristics of the Iberian Range is the presence of extensive planation surfaces elaborated on folded pre-Neogene rocks (Gutiérrez and Peña, 1994). These erosional landforms are commonly above 1000 m in elevation and are mainly developed on Jurassic and Cretaceous carbonate sediments. This plateau-like topography is locally interrupted by residual reliefs, commonly made up of resistant Palaeozoic rocks, neotectonic grabens, and fluvial valleys. The flat topography developed on Mesozoic carbonate bedrock has favoured the generation of numerous poljes, frequently controlled by an extensional neotectonic activity and lithological factors. Solution dolines and karren are common landforms in these planation surfaces and on subhorizontal Neogene limestones. Evidence of past and present-day periglacial activity has been found profusely in the highest areas, which locally exceed 2000 m in elevation. Some of the recognised periglacial features include nivation cirques,
Evaporite karst in Calatayud Graben

protalus ramparts, rock glaciers, patterned ground, talus slopes, talus streams, and grèzes litées (Gutiérrez and Peña, 1994). Pleistocene glaciation was restricted to several tens of cirques carved in the highest Palaeozoic massifs located in the north-western sector of the Iberian Range (Demanda, Urbión, Cebollera y Moncayo) (Gutiérrez and Peña, 1994). The trajectory of some of the main rivers is adapted to the post-orogenic grabens (Jiloca, Alfambra and Turia Rivers), whereas the Jalón River crosses transversally the Calatayud Graben (Fig. 2). The most extensive Quaternary alluvial deposits (alluvial fans, pediments, and terraces) occur in the neotectonic grabens and the areas with labile sediments where the drainage network has excavated broad valleys or erosional depressions. Fluvial incision in thick Mesozoic limestone sequences has given place to numerous canyons where tufa deposits are relatively frequent. Alternating episodes of incision and accumulation in the slopes of buttes and mesas have produced talus flatirons (Gutiérrez and Peña, 1994).

2. Geology and geomorphology of Calatayud Neogene Graben

The Calatayud Graben is a NW-SE trending extensional basin located in the central sector of the Iberian Range. It constitutes one of the largest intramontane depressions of the mountain belt; around 110 km long and up to 25 km wide (Figs. 1 and 2). The age of the post-orogenic sedimentary infill ranges from Lower Miocene to Lower Pliocene and exceeds 1 km thick. This section describes the main geological and geomorphological characteristics of the graben in Calatayud city area, where the field trip will be developed.

In Calatayud sector, the graben is flanked by mountain ranges made up of resistant Palaeozoic rocks. The Neogene basin fill was deposited in alluvial fans distally related to lacustrine systems with evaporite and carbonate deposition. These sediments have a general subhorizontal structure and show abrupt lateral and vertical changes in facies (Bomer, 1960). The proximal conglomeratic facies at the margins of the graben grades sharply into fine-grained clastics and evaporite-carbonate facies towards the sedimentary axis of the graben (Fig. 3). In the environs of Calatayud city, located close to the depocenter of the basin, the stratigraphic succession is made up of:

- An evaporitic sequence around 500 m thick. The upper 200 m that crop out in Calatayud area are composed of laminar and nodular gypsum, with thin, interbedded marl partings (Fig. 3). The gypsum (CaSO₄·2H₂O) is a secondary diagenetic facies resulting from the hydration of anhydrite (CaSO₄) and the incongruent dissolution of glauberite (Ortí and Rosell, 1998, 2000). According to Collantes and Griffio (1982), in the surroundings of Calatayud, gypsum constitutes around 85% of the exposed evaporitic sequence. In addition to gypsum, borehole data indicate that a significant proportion of highly soluble deposits of halite (NaCl) and glauberite (Na₂Ca[SO₄]₂) are present at depth. This is a relevant aspect for the karstification potential of the evaporite bedrock, since halite and glauberite have solubilities of 360 and 118 gr/l respectively, whereas gypsum solubility is only 2.4 gr/l (Ford and Williams, 1989). The borehole described by Marín (1932) in Paracuellos de Jiloca (about 5 km south of Calatayud) shows halite at depths between 170 and 537 m. Recent boreholes carried out by MYTA S.A. a few kilometres west of Calatayud have crossed thick glauberite beds below a depth of 15 m. Probably the outcropping gypsum formation originally contained glauberite and halite beds which may have been removed by groundwater flow related to entrenchment of the drainage network.
- To the south of Calatayud city, the evaporite formation is overlain by a carbonate-detrital sequence less than 100 m thick (Hernández et al., 1983; Sanz-Rubio et al., 2003). These sediments form a sandwich of two fluvio-lacustrine limestone units with a reddish detrital unit in between (Fig. 3B). The upper tufaceous limestone unit constitutes the caprock of a large NW-SE trending structural platform slightly tilted towards the NW.
The sediments of the basin have been selectively excavated by the alluvial systems developed subsequent to the capture of the graben. Consequently, the topography is markedly controlled by the distribution of the different lithofacies (Bomer, 1960). The conglomeratic and carbonate facies form prominent reliefs, whereas the shale and evaporite sediments have been differentially eroded to form low relief areas (Fig. 3B). The distal carbonate sediments form the Armantes (968 m) and La Tronchona (870 m) mesas to the NW and SE of Calatayud city (533 m), respectively. The graben is transversally crossed by the Jalón River, whereas its main tributaries, the Jiloca and Perejiles Rivers, have carved longitudinal valleys at both sides of La Tronchona structural platform (Fig. 4). The evolution of these fluvial systems is recorded by stepped sequences of terraces and pediments.

Figure 4. Geomorphological sketch of the surroundings of Calatayud city (from Gutiérrez, 1996).

During the Upper Pliocene and Quaternary, the Calatayud Graben has been affected by extensional block tectonics. The neotectonic activity is mainly concentrated along the western margin of the graben, where NW-SE normal faults have generated the Munébrega Half-graben,
superimposed to Calatayud Graben (Figs. 2 and 3). The master fault of this tectonic depression produces a vertical offset of more than 2 m in a Pleistocene terrace of the Jalón River situated 45 m above the channel (Gutiérrez, 1998).

Stop 1: Evaporite dissolution and subsidence affecting Neogene sediments
To the NW of La Tronchona structural platform, and framed by the Jiloca and Perejiles floodplains, there are two zones where the detrital-carbonate units stratigraphically above the evaporite sequence have subsided due to the interstratal karstification of the underlying soluble sediments. These two zones have been called the Maluenda and the Perejiles areas, covering 4.4 and 12 km², respectively (Gutiérrez, 1996, 1998) (Figs. 3 and 4). We are at the east margin of the Jiloca River valley in the Maluenda collapse area (Fig. 5). Here, similarly to the Perejiles area, the supra-evaporitic subsided units are strongly deformed and locally hosted in the evaporites. They show numerous gravitational deformations including ductile structures (synforms, antiforms, and flexures) with a preferential NW-SE trend, and brittle structures (faults and breccias) (Fig. 6). The strike and dip of the deformed strata are very chaotic, showing sharp changes between nearby locations. In contrast, the adjacent older gypsum strata are solely affected by a joint network and maintain a subhorizontal structure. The cartographic boundary between the deformed units and the undeformed gypsum has a very irregular and interdigitated pattern (Figs. 4 and 5).

Figure 5. Morpho-structural map of Maluenda area. 1: Aggradation surface and thickened alluvium of the Lower Pleistocene terrace T9 (100-105 m above the channel); 2: Jiloca River floodplain; 3: Infilled creeks; 4: Alluvial fans; 5: Creeks; 6: Structural surface and scarps on non subsided limestone; 7: Structural surface and scarps on subsided limestone; 8: Ridges and bed traces of resistant beds; 9: Horizontal gypsum surrounded by deformed and subsided supra-evaporitic
Evaporite karst in Calatayud Graben


In both areas the supra-evaporitic sediments locally show synforms and basin structures in which certain units thicken towards the core. These thickness changes have been related to the synsedimentary development of dissolution-induced basins (Sanz-Rubio et al., 1997; Gutiérrez, 1998). However, most of the subsidence and deformation is postsedimentary. Probably it took place once the basin became exorheic and the new drainage network started to incise the sedimentary infill. In Maluenda area, the Neogene subsided sediments are locally fossilized by the deposit of a Jiloca River terrace (T9) located at 100-105 m above the channel (Figs. 5 and 7). This terrace deposit, dated magnetostratigraphically as Lower Pleistocene, is thickened by synsedimentary karstic subsidence, locally reaching more than 100 m in thickness. This implies that subsidence of the Neogene sediments was active before and during the sedimentation of the thickened terrace deposit (Lower Pleistocene). The fact that the floodplain deposits of the Jiloca and Perejiles rivers overlap the subsided sediments in Maluenda and Perejiles areas, respectively, and that the deposits of a Lower Pleistocene terrace fossilize the collapsed unit in Maluenda area, indicates that the subsidence has advanced vertically downwards below the base level (Fig. 7). Considering that the floodplains are at an altitude of 560-570 m, and the base of the supra-evaporitic sequence is above 770 m in elevation, the maximum subsidence in both areas has reached at least 200 m (Gutiérrez, 1996, 1998).

The Tronchona structural platform constitutes an exhumed surface resulting from the erosional removal of younger sediments (Rojo 2 and Páramo 2) preserved to the SE of Calatayud area. It is likely that the postsedimentary subsidence affecting the Neogene sediments has taken place subsequent to the exhumation of La Tronchona surface, since none of the younger units have been recognized in the collapse areas (Fig. 7). The intense karstification undergone by the evaporitic formations located to the NW of the Tronchona structural platform is related to the convergence of several factors:

- The Maluenda and Perejiles areas are located in the sector where the most soluble evaporitic facies where deposited (deposocenter), including a large proportion of glauberite and halite in the subsurface. Very likely, the interstratal karstification has operated at several stratigraphical levels (top of the evaporites and within the evaporite sequence) affecting preferentially the most soluble beds.

![Figure 6. Images of the subsided and deformed carbonate-detrital Neogene sediments and the subhorizontal gypsum strata in Maluenda area.](image)
Figure 7. Evolution of the subsidence affecting the supra-evaporitic Neogene sediments in Maluenda area (Gutiérrez, 1996). When this model was proposed the author didn’t know about the existence of halite and glauberite in the subsurface and the subsidence was attributed to gypsum dissolution mainly acting at the top of the evaporite sequence. Very likely the karstification processes which have caused the collapse of the Neogene sediments have operated both at the top of the evaporite unit and within this halite- and glauberite-bearing formation (Gutiérrez, 1998).
- The NW-SE-oriented Tronchona structural platform, about 20 km long and 3 km wide, is tilted to the NW towards the collapse areas and the main base level (Jalón River). This extensive and karstified platform constitutes a recharge zone, which has its main discharge area in its northwestern edge, where the Maluenda and Perejiles areas are situated. This idea is supported by the presence of tufa deposits located to the NE of Paracuellos de Jiloca, which have been related to a paleospring (Fig. 4).
- The entrenchment of the fluvial systems in the Neogene sediments from the capture of the graben has favoured the circulation of underground waters through progressively deeper stratigraphic levels.
- The subsidence in the Neogene sediments shows a prevalent NW-SE structural control. The NW-SE trending Munébrega Plio-Quaternary Half-graben and the offset of a Pleistocene terrace by its master fault in the southwestern margin of Calatayud Graben reveals that an extensional neotectonic activity has recently operated in the area with a dominant NE-SW \( \sigma_3 \). Probably this extension has generated or dilated previously existing NW-SE fractures in the Neogene sediments favouring karstification along these structures. The generation and dilation of fractures may also have been favouried by the debutressing effect produced by the entrenchment of the Jiloca and Perejiles valleys (Jennings, 1985).
- In Paracuellos de Jiloca, next to the Maluenda area, there is a spa that uses a spring of sodium chloride water that wells up at 16°C. This spring indicates the presence of halite in the area as it has been corroborated by borehole data. Additionally, the solubility of the gypsum may rise up to four times in NaCl-rich waters (Ponsjack, 1940).

**Stop 2: Quaternary terrace deposits affected by evaporite dissolution subsidence and paleosinkholes**

**The Jalón-Jiloca-Perejiles alluvial system**

The Jalón-Jiloca-Perejiles alluvial system has been affected by synsedimentary and postsedimentary subsidence phenomena caused by the karstification of the evaporitic bedrock throughout its Quaternary evolution (Gutiérrez, 1996, 1998). Ten stepped alluvial levels have been differentiated within the Calatayud Graben. The height of the terrace levels above the river channels are: T10: 115 m; T9: 105-100 m; T8: 90-85 m; T7: 75-70 m; T6: 65-60 m; T5: 55-50 m; T4: 45 m; T3: 35-30 m; T2: 25-20 m; T1: 5-3 m. Terrace levels T9 and T7 have been dated as Lower Pleistocene through magnetostratigraphic studies. All of these levels are represented by aggradation terraces. Degradation terraces developed in the deposits of older terraces (fill-cut terraces) have been recognized for some levels. The identified pediment levels are P10, P9, P8, P7 and P4 (Px correlative to Tx). These may be aggradation surfaces (mantled pediments) or degradation surfaces developed either in older alluvium or in Miocene gypsiferous bedrock. The degradation surfaces of each level occur upstream and in the margins of the sectors where the correlative Quaternary alluvium is thickened by synsedimentary subsidence. This distribution suggests that degradation processes have been related to gradient changes in the alluvial system caused by karstic subsidence.

Quaternary alluvial deposits overlying the evaporitic bedrock show conspicuous thickenings generated by synsedimentary subsidence. Abrupt thickness variations from less than 10 to more than 100 m have been observed in a single terrace. The thickened alluvium locally fills dissolution-induced basins with centripetal dips and cumulative wedge-out systems at the margins (Fig. 8A). These thickened terrace deposits show a high proportion of floodplain facies, whereas
in areas where the alluvium has not been affected by synsedimentary subsidence, channel gravel facies dominate. As a consequence of the local thickening of the alluvium, the deposit of a given terrace may be inset in the bedrock or be superposed onto the thickened deposits of an older terrace. However, the morphogenetic surfaces of both terraces are stepped along the whole valley reach (Fig. 8B).

Figure 8. Morpho-stratigraphical arrangement of terraces affected by synsedimentary dissolution subsidence. A: The thickened terrace deposits fill a dissolution-induced basin showing centripetal dips and cumulative wedge outs at the margins. B: The deposits of the subsequent terrace are inset in the bedrock upstream of the area affected by subsidence and superimposed by angular unconformity or paraconformity onto the thickened sediments of the previous alluvial level. The morphogenetic surfaces of both terraces are stepped along the whole valley reach (Gutiérrez, 1998).

The alluvial cover overlying the evaporite bedrock shows numerous gravitational deformations of both ductile and brittle type (Hoyos et al., 1977; Gutiérrez, 1996; 1998). Some of these dissolution-induced deformations also affect to the evaporitic bedrock. Excellent examples are found in the cuts of the A-2 Zaragoza-Calatayud motorway. Many of these deformations correspond to paleodolines that in some cases are filled with marl and carbonate palustrine facies that record the development of swampy environments in closed depressions. Remains of aquatic gastropods, amphibian, and fishes have been found in these facies. These structures and the associated sediments provide information about the subsurface processes involved in the currently active subsidence. Four main mechanisms of sinkhole generation have been identified through study of the subsidence structures recorded in the paleokarst (Fig. 9): (a) Progressive lowering of the evaporitic rockhead by dissolution and passive bending of the alluvial cover (Fig. 10A). (b) Development of dissolutional conduits and fissures (grikes) at the top the bedrock and downward migration (ravelling) of detrital particles from the alluvial cover. This process may cause progressive ductile deformation in the alluvial mantle, or the generation of cavities that may eventually give way to catastrophic collapses (Fig. 10B). (c) Sheet-like dissolution within the evaporitic bedrock and progressive downwarping of the alluvial cover and the bedrock sediments located above the horizon affected by preferential karstification. (d) Generation of dissolutional cavities within the bedrock and propagation of the void towards the surface through stipping processes, culminating in the formation of a catastrophic sinkhole (collapse doline) (Fig. 10C and D).
Evaporite karst in Calatayud Graben

Figure 9. Mechanisms of sinkhole generation inferred from the study of the subsidence structures recorded in the paleokarst (Gutiérrez, 2004a and b).

Figure 10. Dissolution and subsidence structures exposed in cuts the Madrid-Zaragoza motorway (A-2) in the vicinity of Calatayud city. A: Bending of the overlying terrace deposit caused by the dissolutilional lowering of the gypsum rockhead. B: Sections of dissolutional conduits filled with alluvium derived by ravelling from the overlying terrace deposits. C: Collapse structure made up of dome-shaped surfaces generated by karstification within the evaporitic bedrock. D: Collapse structure in the gypsum bedrock showing a bending synform affected by antithetic reversed “faults” and brecciation.

The lateral migration of the Jalón River throughout its evolution has generated an asymmetric valley with a stepped sequence of terraces in the SE margin and a prominent gypsum escarpment.
in the NW flank (Figs. 4 and 11). This long-term migration may have been influenced by dissolution subsidence. Subsidence is more active at the foot of the scarp where the alluvium is not thickened, confining the river channel to this side of the floodplain. In addition, it seems that the fluvial system is able to downcut more easily into the evaporitic bedrock than in its own thickened deposits; thus giving rise to a relief inversion (Fig. 11).

Subsidence is currently active in the Jalón River floodplain where some shallow and diffuse-edged closed dolines several hundred meters in length have been mapped. The path and sinuosity
of the Jalón River seems to be locally controlled by these depressions (Fig. 4). Upstream of the lateral change in facies from evaporites to marls, the Jalón floodplain has a concave geometry due to differential subsidence. In this sector, the river has been drained by means of an artificial channelization (Fig. 4). The generation of collapse sinkholes is relatively common in alluvial karst settings, particularly along unlined irrigation ditches and adjacent areas. The original trace planned for the Madrid-Zaragoza motorway was changed due to the existence of sinkholes. On the other hand, the high-speed Madrid-Barcelona railway that runs along the Jalón floodplain may be eventually affected by a sinkhole.

**Stop 2a: Superposition of the deposits of two terrace levels**

We are at the southeastern corner formed by the confluence of the Jalón and Jiloca Rivers; southern margin of the Jalón valley and eastern margin of the Jiloca valley. In this side of the Jiloca valley, and downstream of Paracuellos de Jiloca village, the deposits of several terraces fill a dissolution-induced trough more than 4 km long and 0.7 km wide where the alluvium thickness exceeds 100 m. The southern cut of the A-2 Madrid-Zaragoza motorway shows the superposition of two sedimentary units bounded by angular unconformity (Fig. 12). The thickened and deformed deposits of the lower unit have been ascribed to terrace level T8 (90-85 m above the channel), Lower Pleistocene in age. The deposits of T8 terrace are fossilized by the floodplain, reaching more than 90 m in vertical thickness (the stratigraphic thickness is higher). In this exposure the lower unit dips up to 25° and attenuates its dip towards the top of the sequence. The upper unit corresponds to terrace T4 (45 m above the channel). It has a high proportion of floodplain facies and is capped by a petrocalcic horizon (caliche). The T4 terrace deposits show a progressive thickness increase towards the NE and its aggradation surface is tilted in the same direction, indicating that the terrace has undergone a long-sustained or recurrent synsedimentary and postsedimentary dissolution-induced subsidence.

![Figure 12](image.png)

*Figure 12. Southern cut of the Madrid-Zaragoza motorway (A-2) to the south of Calatayud. The thickened and deformed deposits of terrace T8 are unconformably overlain by the deposits of terrace T4.*
Stop2b: Paleosinkholes

Exposure of the T4 terrace deposits in an aggregate pit showing several superimposed ductile and brittle subsidence structures (paleosinkholes) (Fig. 13). Their chronological sequence may be inferred based on crosscutting relationships:

- Synform made up of marls and fines deposited in a ponded or swampy doline developed by bending in the floodplain. The thickening of the strata towards the core and the upward attenuation of the dip (cumulative wedge out) indicate that subsidence was coeval to deposition. This paleodoline is affected by subsequent brittle subsidence structures (subvertical failure planes).

- Subvertical failure planes of a collapse paleosinkhole. The presence of ductile structures and loose sediment deformations associated with these failure planes suggests that collapse occurred during or soon after deposition, when the alluvium was still in a soft and water-saturated state.

- Irregular masses of gravel (gravel pockets) embedded in fine-grained facies associated with collapse structures. Similar structures have been interpreted by several authors as liquifaction-fluidization features (Postma, 1983; Johnson, 1986; Nocita, 1988). The observed gravel pockets may be explained as liquifaction structures caused by sediment shaking induced by the generation of nearby catastrophic sinkholes (Gutiérrez, 1998; Guerrero et al., 2003).

Figure 13. Subsidence structures observable in stop 2b. A: Synsedimentary synform affecting fine-grained terrace deposits with cumulative wedge outs. Professor Derek Ford at the outcrop. B: Subvertical failure surfaces defining the margin of a collapse paleosinkhole. Dr. Keneth Johnson at the outcrop.

Stop 3: Subsidence, flooding and rock-fall hazards in Calatayud historical city.

The city of Calatayud

Calatayud city was founded by the Muslims in 716 A.D. at an important junction of communication routes. In 1120 it was conquered by the King Alfonso I “the Battler”. This attractive city, from the historical and artistic point of view, was declared a Historical Monument in 1967, and currently has a population of around 17,000 inhabitants. The main economic activities are agriculture, primarily fruit production, and services. Although the urban area is located in an advantageous geographic situation, its geomorphological setting has posed numerous problems to the population since olden times. Calatayud is located in the NW margin of the Jalón River valley at the foot of a nearly vertical gypsum scarp, approximately 100 m high. It is positioned partly on an alluvial fan fed by La Rúa and Las Pozas streams, and partly on the Jalón River floodplain (Figs. 4 and 14). The city also extends onto the gypsum cliff, with cave dwellings excavated in the slopes (Fig. 15). Since its foundation, the urban development of Calatayud has been largely constrained by geohazards, including: (a) Floods caused by the River Jalón and the tributaries La Rúa and Las Pozas streams, that have affected the floodplain and the alluvial fan, respectively; (b)
Evaporite karst in Calatayud Graben

Rock-falls and topples that have constrained development on the gypsum scarp areas; (c) Subsidence that has affected both the floodplain and the fan areas.

Figure 14. Map showing the geomorphological location of Calatayud city and the flood correction measures carried out to divert the drainage of the Rúa Stream away from the city (Gutiérrez, 1998; Gutiérrez and Cooper, 2002).

Figure 15. General view of Calatayud city.
Stop 3a: Flood hazards

In the 8th century, the original Muslim settlement was located in a walled enclave on the upland gypsum area. In contrast, the Jewish and the Mozarabs (Christians) occupied the alluvial fan areas, which were threatened by the frequent storm-derived floods of the La Rúa and Las Pozas streams (Galindo, 1984). To mitigate this hazard, the runoff of the flashy La Rúa stream was diverted in Muslim times from the middle of its basin into an adjacent catchment. This control measure required the construction of a small dam in the stream (called the “Sacred Dam”). The drainage was linked by an artificial channel from La Rúa stream to the El Salto stream, then via the Ribota River to the Jalón River (Fig. 14). This artificial capture of the drainage diverted the runoff from 77% of the drainage basin (6.3 km²), including the steep slopes of the headwaters. During the 12th century and the first half of the 13th century, the urban area grew significantly, occupying most of the alluvial fan. At that time, La Rúa channel across the alluvial fan was the main axial road of the city, and flooding was a constant concern. Additional control measures were accomplished with the construction of the Balsa de Valparaiso Dam in the Rúa channel, close to the basin mouth. This regulates and controls the surface runoff contributed by 1.7 km² of the basin downstream of the “Sacred Dam” (21% of the catchment area). In 1932, a tunnel about 1 km long was excavated in the gypsiferous rocks to divert the surface runoff from the Valparaiso Dam to the Longia stream (Fig. 14). Because of these control measures, the runoff from 98% of the basin area is diverted, and flooding from the Rúa stream is prevented (Gutiérrez, 1998; Gutiérrez and Cooper, 2002).

In contrast, the Las Pozas stream, although draining a smaller catchment (4.2 km²) with a lower relief, produces frequent floods in the urban area. The runoff in this stream is evacuated through an underground pipe buried in the alluvial fan along Las Pozas Street. Several flood events have demonstrated that this pipe has an undersized section susceptible to being clogged up by the solid load carried by the water. The latest storm-derived floods (1999, 2000 and 2003) have caused considerable financial losses (Fig. 16). Several signs advise not to park vehicles in the flood-prone Las Pozas Street during storm periods.
In the 19th and 20th centuries the city has expanded across the floodplain towards the opposite margin of the valley. The Jalón River floods have affected buildings on the distal fan area and on the floodplain. Several documents describe a damaging flood event that occurred in 1855. The largest recorded flood took place in May 1956, with a peak discharge over 300 m$^3$/s. During this event the flood stage reached 2 m in the lower part of the city. Since 1961, the Jalón River floods have been partially laminated by the Tranquera Reservoir, located in a major tributary of the Jalón River upstream of Calatayud (Piedra River).

Stop 3b: Rock-fall hazards in Calatayud city
Slope movements along the unstable gypsum scarp also restrict urban development (Gutiérrez, 1998; Gutiérrez and Cooper, 2002). Rock-falls and topples are the most common types of mass movement. Lateral spreading caused by the plastic deformation of interstratified marl layers may also take part in the development of some topples. These movements are controlled by a dense network of joints and unloading cracks that affect the rock mass. A stress release in excess of 60 kg/cm$^2$ (6 MPa) is estimated for the unconsolidated sediments at the top of the scarp. The generation of rock-falls and topples is largely favoured by karstification acting along discontinuity planes. The dissolitional widening of these planes transforms the gypsum strata into a loose mass of gypsum blocks with low mechanical strength. Dissolution and subsidence at the foot of the scarp also seems to favour the formation of slope movements, since the most unstable stretches of the escarpment are associated with large subsiding depressions located in the floodplain at the scarp foot (Figs. 4 and 14). Rock-falls from gypsum scarps are the types of rapid mass movement which has caused the largest number of casualties in Spain. Several rock-fall events in the gypsum cliff overlooking Azagra village (Ebro Valley, Navarra) have killed more than 100 people. Damage from rock-falls and topples in Calatayud gypsum scarp include one person killed in 1988, loss of buildings, and frequent cuts in the roads that run along the scarp foot.

The rock-fall at this stop occurred catastrophically on June 20, 1997, irreversibly affecting the structure of a recently built house that was occupied at the time of the event. Fortunately, the rooms where the tenants were sleeping were not affected (Fig. 17). In 1999 the collapse of large gypsum blocks from the scarp closed the Calatayud-Terrer road (former Madrid-Barcelona road), and in 2004 a rock-fall cut the Calatayud-Soria road. Some sectors of the scarp have been covered with cable nets, although this measure is only effective for the fall of small blocks.
Figure 17. Rock-fall occurred on June 20, 1997, severely damaging a recently built house.

**Stop 3c: Subsidence damage in Calatayud city**

Most of the old buildings in the city have been damaged by subsidence, and some important monuments have been demolished. Calatayud is considered the geotechnically most problematic city of Aragón Region, both for remediation of the historical buildings and for modern development. Subsidence damage in the buildings includes tilting and cracking, sloping floors, sheared door and window openings, and collapsed roofs (Figs. 18 and 19). Peripheral damage includes broken pipes, with the consequent extra water supply to the subsurface, and pavement sagging and collapse. The full cost of the damage is difficult to estimate, but the losses to the irreplaceable artistic and historical heritage are large. The spatial distribution of the subsidence and its causes have been analysed in previous studies, based on the geotechnical characterisation of the materials beneath Calatayud and a systematic building damage assessment (Gutiérrez, 1998; Gutiérrez et al., 2000; Gutiérrez and Cooper, 2002).

Figure 18. Examples of subsidence damage in Calatayud city. A: Collapse formed beside the Ocho Caños Fountain (16th C) in April 1995. See location in figure 21. B: Photograph of La Dolores Mesón taken in 1996. The field trip lunch will be celebrated in this intensively restored inn.
Evaporite karst in Calatayud Graben

Figure 19. Examples of subsidence damage in Calatayud city. A: Large open fractures with plaster tell-tales in Colegiata de Santa María la Mayor (13th-18th C). Photograph taken in June 1996. B: Tilted tower (11th-12th C) of San Pedro de los Francos Church (14th C). The upper 5 m of the tower was removed in 1840 to avoid its collapse in the palace located in the opposite side of the street where the Royal family used to be hosted.

The materials beneath Calatayud city

The lithostratigraphical and geotechnical characteristics of the rocks and soils beneath Calatayud city have been studied from 43 boreholes, 18 of which reached the evaporitic bedrock. From the surface downwards, these materials include (Fig. 20):

- A top layer of unsorted and unconsolidated made ground whose thickness decreases towards the Jalón River. The maximum thickness has been found in the vicinity of La Rúa and Las Pozas streets that cover the old La Rúa and Las Pozas channels, respectively. Compaction of the made-ground rubble may locally affect buildings resting directly on the fill.

- Beneath the made-ground, the alluvial fan deposits are formed mainly of gypsiferous silts with scattered gypsum and limestone clasts. These gypsiferous silts interfinger with the fluvial facies of the Jalón River at depth, and wedge out from more than 12 m thick in the proximal fan area, thinning towards the floodplain. These soils are characterised by a very loose packing fabric, with the silt particles bound by gypsum “bridges”. This texture may undergo a rapid reduction in volume with the addition of water, due to dissolution of the intergranular gypsum bonds and the consequent collapse of the structure (hydrocollapse or hydrocompaction). This type of subsidence may affect structures in the fan area.

- Fluvial deposits underlie the gypsiferous silts in the fan area and the made-ground in the floodplain. In the floodplain area, the thickness of these deposits ranges from 7 to 24 m. The thickness variations are largely related to synsedimentary subsidence phenomena. They are made up of channel gravels and floodplain fines, including palustrine facies deposited in swampy
subsidence depressions that locally reach more than 6 m in thickness. The consolidation-compaction of these deposits may cause subtle settlement of the ground surface.
- A karstic residue, up to 9 m thick, composed of soft, dark grey marls with scattered gypsum particles is found between the alluvium and the evaporitic bedrock.
- The karstic residue grades downwards into the evaporitic bedrock with a well-developed endokarstic system. In outcrop, the Miocene bedrock consists of about 85% gypsum. Beds of glauberite and halite may exist in the shallow subsurface beneath Calatayud city. Karstification of the evaporites may cause gradual and/or catastrophic subsidence in any part of the urban area.

Figure 20. Cross-section showing the geology of Calatayud city. 1: Miocene evaporites; 2: Slope breccia; 3: Fluvial gravels and fine-grained deposits; 4: Gypsiferous silts; 5: Anthropogenic deposits; (vertical exaggeration about x13) (Gutiérrez, 1998; Gutiérrez and Cooper, 2002).

Spatial distribution and causes of the subsidence damage
In order to analyse the spatial distribution of the subsidence, a building damage map of a broad sector of the city (35 ha) was prepared (Fig. 21). The selected area includes buildings varying in age from 12th century to modern, and includes a wide range of morpho-stratigraphical settings, from the proximal fan area to the riverbank. The damage was assessed in 1996-97 by examination of the building façades. A damage category was assigned to each building on a scale of 0-5, based on the Subsidence Engineers’ Handbook ranking system established by the British National Coal Board (NCB) for the evaluation of mining subsidence damage (N.C.B., 1975). Peripheral effects and internal damage of the buildings were not surveyed in the study; so only four levels of damage 0, 3, 4, and 5 were used (Table 1). Thus, level 0 on the map also includes damage attributable to levels 1 and 2 in the NCB ranking. Although this methodology has clear limitations, mainly because of the heterogeneity of the “subsidence markers”, the damage levels map provides of rough idea of the distribution of the subsidence effects and allows an interpretation of the causative processes.
Table 1. Ranking of damage categories established by the British National Coal Board used for the building damage survey in Calatayud. The assessment is based on the features and criteria shown in bold type.

<table>
<thead>
<tr>
<th>Class of damage</th>
<th>Description of typical damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No damage</td>
</tr>
<tr>
<td>1</td>
<td>Hairline cracks in plaster, perhaps isolated slight fracture in the building, not visible from the outside (this category was not used at Calatayud).</td>
</tr>
<tr>
<td>2</td>
<td>Several slight fractures showing inside the building. Doors and windows may stick slightly. Repairs to decoration probably necessary. Not visible from the outside (this category was not used at Calatayud).</td>
</tr>
<tr>
<td>3</td>
<td>Slight fractures (millimetric) showing on outside of building (or one main fracture). Doors and windows sticking. Service pipes may fracture.</td>
</tr>
<tr>
<td>4</td>
<td>Service pipes disrupted. Open fractures (up to 1cm) requiring rebonding and allowing weather into the structure. Window and door frames distorted. Floors sloping noticeably. Some loss of bearing in beams. If compressive damage, overlapping of roof joints and lifting of brickwork with open horizontal fractures.</td>
</tr>
<tr>
<td>5</td>
<td>As above, but worse (with centimetric cracks), and requiring partial or complete rebuilding. Roof and floor beams loose or non-bearing and in need of shoring up. Windows broken with distortion. Severe slopes on floors. If compressive damage, severe buckling and bulging of the roof and walls.</td>
</tr>
</tbody>
</table>

The map of the subsidence categories shows that the buildings affected by severe damage (level 5) are found in the all the sectors of the selected area (Fig. 21). However, the proximal fan area has a higher concentration of buildings with the highest damage level. In this area, the blocks flanking La Rúa Street are the most severely affected. The presence of buildings affected by severe damage throughout the whole study area, including sites without anthropogenic rubble or gypsiferous silts, indicates that karstification of the bedrock is one of the main causes of the subsidence. The relatively greater impact of subsidence in the proximal fan area indicates that hydrocollapse and possibly dissolution of the gypsiferous silts contribute significantly to subsidence in this area. The higher subsidence activity in La Rúa Street may be explained by the high thickness of the anthropogenic rubble and the existence of preferential underground flows along the buried La Rúa channel. Other processes, like compaction of made-ground, consolidation of fluvial deposits, or the collapse of old cellars, may also play a relevant role at specific sites, but do not seem to contribute in a significant way to the subsidence that affects a great part of the urban area. Other arguments support the important role that bedrock karstification plays in the subsidence: (a) The occurrence of sudden sinkholes reveals the formation of dissolution cavities; (b) The presence of large diffuse-edged depressions in the floodplain (Fig. 4); (c) The highly variable thickness of the alluvium and karstic residue are indicative of synsedimentary subsidence and suballuvial dissolution, respectively; (d) The great amount of subsidence structures caused by the karstification of the bedrock that affect the Neogene sediments and the Quaternary alluvium in the vicinity of Calatayud.
The Ocho Caños Fountain
Although this fountain dates back to 1598, in 1969 it was moved to its current position. In April 1995, a sinkhole about 3 m in diameter, suddenly formed beside it (Figs. 18A and 21). It is probable that subsurface flow, together with leakage from the fountain, may have generated the cavity responsible for the collapse.

Colegiata de Santa María la Mayor
Constructed between the 13th and 18th centuries, this building, considered the foremost monument in the city, has outstanding features of Mudéjar (a 72-m-high tower) and Renaissance styles. Micropiling works, applied only to one part of the cloister, were followed by alarming differential settlements, which accelerated substantially the deterioration of the structure (Fig. 19A and 21). The building has been extensively restored in recent years.

San Pedro de los Francos Church
Situated on La Rúa Street, this 11th to 14th century church is seriously damaged by subsidence. The most striking effect is the tilting of the 25-m-high tower, which leans towards, and overhangs, the street by about 1.5 m (Figs. 19B and 21). The church, constructed around 1330-1340, is younger than the tower. Locally, the brickwork of the church indents the pre-existing tower fabric, which probably dates from the 11th century or the beginning of the 12th century. This indentation, and the non-alignment of the church and the tower walls, indicate that most of the tower tilting occurred prior to the construction of the church. The cracking of the indentation indicates a later, slight differential tilting of the tower subsequent to the church construction (SanMiguel, 1998). In 1840, the upper 5 m of the tower was removed and the lower part buttressed for the safety of the Royal family who used to stay in the palace located on the opposite side of the street (Barón de Wersage Palace). On June 3, 1931, San Pedro de los Francos was declared a “Monument of Historical and Artistic value”. Due to its ruinous condition, the church was closed to worship in 1979. Micropiling to improve the foundation was started in 1994, but this corrective measure was interrupted when only half of the building was underpinned. In the following year, very rapid differential settlement of the building took place, aggravating the problem. A new remediation project has been accomplished in the last years.
Evaporite karst in Calatayud Graben

Figure 21. Map showing the distribution of subsidence damage in the sector of Calatayud city selected for the survey (Gutiérrez, 1998; Gutiérrez and Cooper, 2002). The asterisk indicates the location of the Blue House affected by a sinkhole in November 10, 2003.
The November 9-10, 2003, catastrophic sinkhole of the Blue House
The Blue House was a 5-storey building with basement built in the 1970s on the Jalón River floodplain (see location in figure 21). On the night of November 9, 2003, some of the tenants of the 52 flats detected strange noises and the occurrence of cracks. At around 3:30 a.m., subsequent to the evacuation of the building, a sinkhole formed suddenly and noisily in the pavement next to the Blue House. The collapse doline was about 6 and 4 m in major and minor axial length respectively (Fig. 22). The water table, located at a depth of 3 m, made it impossible to observe the bottom of the depression. On the morning of November 10, the sinkhole started to be filled with gravel to prevent the widening of the hollow by mass wasting processes. After dumping 350 m$^3$ of aggregate, a volume much greater than the expected volume for the depression, the technical party of the City Council suspected that the cavity could extend underneath the basement of the building. This hypothesis was corroborated by means of boreholes drilled in the basement; they detected a funnel-shaped cavity with a 10-m-deep apex located beneath the Blue House (Fig. 23B). An additional 250 m$^3$ of concrete was needed to fill the void. In subsequent days, intense geotechnical investigations and stabilization works were carried out. A few months later, the Blue House was demolished. Considering estimated costs of 3 million euros for the flats, 1 million for the stabilization works and geotechnical investigation, and 0.8 million for the demolition, the direct economic losses caused by this single subsidence event exceed 4.8 million euros. Additional costs have been derived from housing rentals, businesses closing, removals, or land depreciation (Gutiérrez et al., 2004).

The boreholes drilled next to the sinkhole demonstrate that the sinkhole originated from cavities located within the evaporitic bedrock (Fig. 23C). These voids were generated by karstification processes under phreatic conditions. The boreholes showed that the dissolutional cavities were still partially empty (water filled) after placing the artificial fill, indicating that their original volume was greater than 600 m$^3$. The cavity propagated upwards by the progressive collapse of its ceiling and the downward migration of the overlying detrital material (ravelling) (Fig. 23A). Possibly, once the cavity reached the rigid base of the building and the pavement, it would enlarge.
laterally giving place to a funnel-shaped void (Fig. 23B). The undermining of the foundations of the building caused the brittle deformation of its structure. Subsequently, a portion of the pavement suspended on the cavity failed, producing the collapse sinkhole (Fig. 22) (Gutiérrez et al., 2004).

Figure 23. Cross-sections perpendicular to the façade of the Blue House showing the evolution of the cavity that produced the sinkhole (A and B) and interpretation of the post-fill situation based on borehole data and the drills carried out from the basement (C).
References


IGME (2004). Geological map of Spain; 1:2,000,000 in scale. Instituto Geológico y Minero de España, Madrid.


ROAD LOG:

Departure from the Conference Hall at 8:30

0-86 km  A-2 (E-90) Motorway to Calatayud city. **Coffee stop** at Calatayud Hotel

86-92 km  Road N-234 to Maluenda village. Stop at the junction with the track that goes up to the San Gervasio Hermitage. 15 minutes walk along a relatively steep track. The hike will not pose difficulties to those persons with regular physical conditions. Stop at a panoramic point to see the main geological and geomorphological features of Calatayud Graben (section 2) and evaporite dissolution subsidence phenomena affecting Neogene sediments (**stop 1**).

92-99 km  Road N-234 to Calatayud. We will stop before getting in Calatayud city centre. A 5-10 minutes walk along a track will take as to **stop 2** to see Quaternary terrace deposits affected by evaporite dissolution subsidence and paleosinkholes. Panoramic view of the Jalón River valley and Calatayud city.

9-100 km  The coach will take us to the city centre and we will walk (5 minutes) to Mesón de la Dolores Restaurant for **lunch** (Fig. 18B). The location of the restaurant is indicated in figure 21. The rest of the trip (**stop 3**) will be a walk with several stops in Calatayud historical city to examine aspects related to subsidence, flood and rock-fall hazards affecting the urban area.

100-186 km  Highway A-2 to Zaragoza (about 1 hour).

Expected arrival time to the Conference Hall: 19:00.