Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 90 (1997)

Heft: 3

Artikel: Soft-sediment deformation structures induced by earthquakes (seismites) in pliocene lacustrine deposits (Guadix-Baza Basin, central Betic Cordillera

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DOI: https://doi.org/10.5169/seals-168193

0012-9402/97/030531-10 $1.50 + 0.20/0
Birkhäuser Verlag, Basel, 1997

Eclogae geol. Helv. 90 (1997) 531–540

Soft-sediment deformation structures induced by earthquakes (seismites) in pliocene lacustrine deposits (Guadix-Baza Basin, Central Betic Cordillera)

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Key word: Soft-sediment deformation, earthquake, Pliocene, Betic Cordillera, Spain

ABSTRACT

The Guadix-Baza intramontane basin, located in the central sector of the Betic Cordillera (Southern Spain) contains Pliocene lacustrine and alluvial sediments in its central and marginal areas, respectively.

The Pliocene sediments contain many soft-sediment deformation structures, mainly located at the marginal sites of Guadix-Baza paleo-lake. This area is characterised by sandy, silty and clayey sediments with rare gravel horizons. The soft-sediment deformation structures include: load casts, pillows and water-escape structures, all indicative of sediment liquefaction or fluidization. An evaluation of these structures suggest that storm waves, overloading and artesian spring action can be rejected as possible genetic mechanism. Regional considerations favour tectonic activity during the Pliocene in this sector of the Betic Cordillera as the cause of the soft-sediment deformation structures in the Guadix-Baza basin, i.e. moderate-high magnitude seismic shocks.

RIASSUNTO

Il bacino di Guadix-Baza, localizzato nella parte centrale della Cordigliera Betica (Spagna meridionale), durante il Pliocene è stato caratterizzato da una sedimentazione di tipo fluviale e lacustre rispettivamente nei settori marginale e centrale del bacino. Lo studio dei depositi pliocenici ha evidenziato la presenza di differenti tipologie di strutture sedimentarie deformative che si localizzano principalmente nei depositi attribuiti al settore marginale del bacino di Guadix-Baza. Tale settore è caratterizzato da depositi sabbioso-arenacei, siltosi e argillosi con rare intercalazioni conglomeratiche. I differenti tipi di strutture sedimentarie deformative (load-cast, pillow- e water escape) sono legati a processi di liquefazione e/o fluidificazione. Le differenze morfologiche riscontrate sono state correlate con il sistema predeformativo e le forze agenti sul sedimento al momento della deformazione. L'analisi di facies condotta sulle successioni plioceniche e lo studio morfologico effecttuato sulle strutture sedimentarie deformative ha reso possibile formulare alcune ipotesi sui meccanismi genetice e sull'origine della deformazione.

E'stato possibile escludere l'influenza di processi di liquefazione e/o fluidificazione connessi con l'effetto ciclico delle onde di tempesta e con aumenti istantanei di pressione interstiziale legati ad episodi di sedimentazione di massa o a forti variazioni del livello di falda. Le strutture sedimentarie deformative del bacino di Guadix-Baza, anche in considerazione della presenza di una tettonica attiva durante la deposizione dei sedimenti lacustri, sono state interpretate como indotte da eventi sismici di magnitudo moderato-alta.

Introduction

Seilacher (1969) defined the term seismite as a bed with deformational structure of the sediments produced by seismic shocks, bounded at the top and base by undeformed horizons. Using this definition, numerous studies have since related several deformational sedimentary structures to seismic events. Although some of them may be connected with brittle deformation (e.g. Spalleta & Vai 1984, Anand & Jain 1987), most are considered as a result of liquefaction and fluidization processes in soft sediments (e.g. Saucier 1989, Seth et al. 1990, Plaziat & Poisson 1992, Guiraud & Plaziat 1993).

Pliocene outcrops of lacustrine sediments in the Guadix-Baza basin (central sector of the Betic Cordillera) show many different types of soft-sediment deformation structures. These structures are located close to the villages of Cúllar and Baza (NE of Granada province, Southern Spain). The largest and most laterally continuous outcrops occur in new artificial trenches along the roads which link Cúllar, Baza and Galera. A study of Upper Pliocene lacustrine sediments was initiated in this basin and six sites where exceptional examples of soft-sediment deformation have been examined: Cúllar (I), Venta Sabuenca (II), West Cúllar (III), Venta del Peral (IV), Mazarra (V) and Baza (VI) (Fig. 1B and C).

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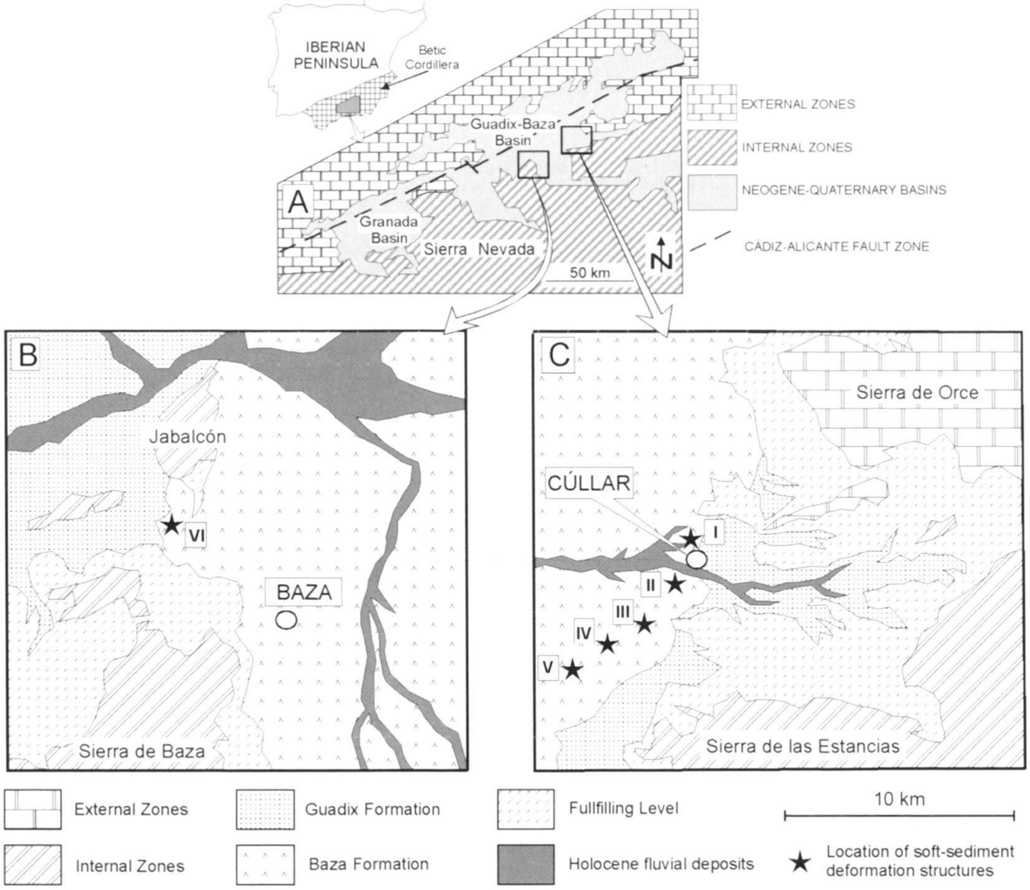

Fig. 1. A: Regional location of the Guadix-Baza basin. B and C: geological maps of the Baza and Cúllar sectors, where the location of the soft-sediment deformation structures is indicated.

Geological setting

The deposits investigated in this study belong to the Guadix-Baza basin. This is an intramontane basin in the central sector of the Betic Cordillera (Fig. 1A), whose substratum is formed by the Internal Zones (to the South) and the External Zones (to the North) (Vera 1970).

The sediments which fill the basin are continental deposits of late Miocene to Quaternary age. The initial division of the lithostratigraphic units was carried out by Vera (1970) who recognised two formations with lateral facies change: the Guadix and Baza formations. The former is characterised by alluvial facies *s. l.* and was deposited in the marginal areas of the basin, whilst the latter, consisting of lacustrine facies, accumulated in the central part of the basin and is today exposed over an area of > 800 km^2. Both formations are unconformably covered by the "Fullfilling Level", deposited in the basin in an endorheic regime. All of these units are exposed in the Cúllar sector.

Deformation structures occur in the Baza Formation, particularly close to the lateral transition into the Guadix Formation. The age of the deformed deposits has been established through correlation with adjacent sectors, and is Late Pliocene (Soria Rodriguez et al. 1987), Garcés et al. 1996).

Soria Rodriguez (1986) carried out a detailed structural study of the tectonic features of the basin infill close to Cúllar proving the existence of N55–80E oriented fractures and N80E oriented fold axes which developed during the Pliocene and are associated with a marked unconformity between the Pliocene and Pleistocene deposits. Diapiric movements, tilted blocks and synsedimentary faults also attest to this deformation. Soria Rodriguez (1986) ascribes all the forementioned tectonic deformations to movements on an important regional fault, the Cádiz-Alicante Fault Zone (Sanz de Galdeano 1983), whose outline coincides with the current position of Guadix-Baza basin (Fig. 1).

Facies and depositional environments

Three groups of intercalated facies are recognised in the Pliocene sediments, which from the basin border to its centre are:

- *Fluvial facies* that are composed mainly of red silts and clays with pedogenic features -paleosols- and rhizoconcre-

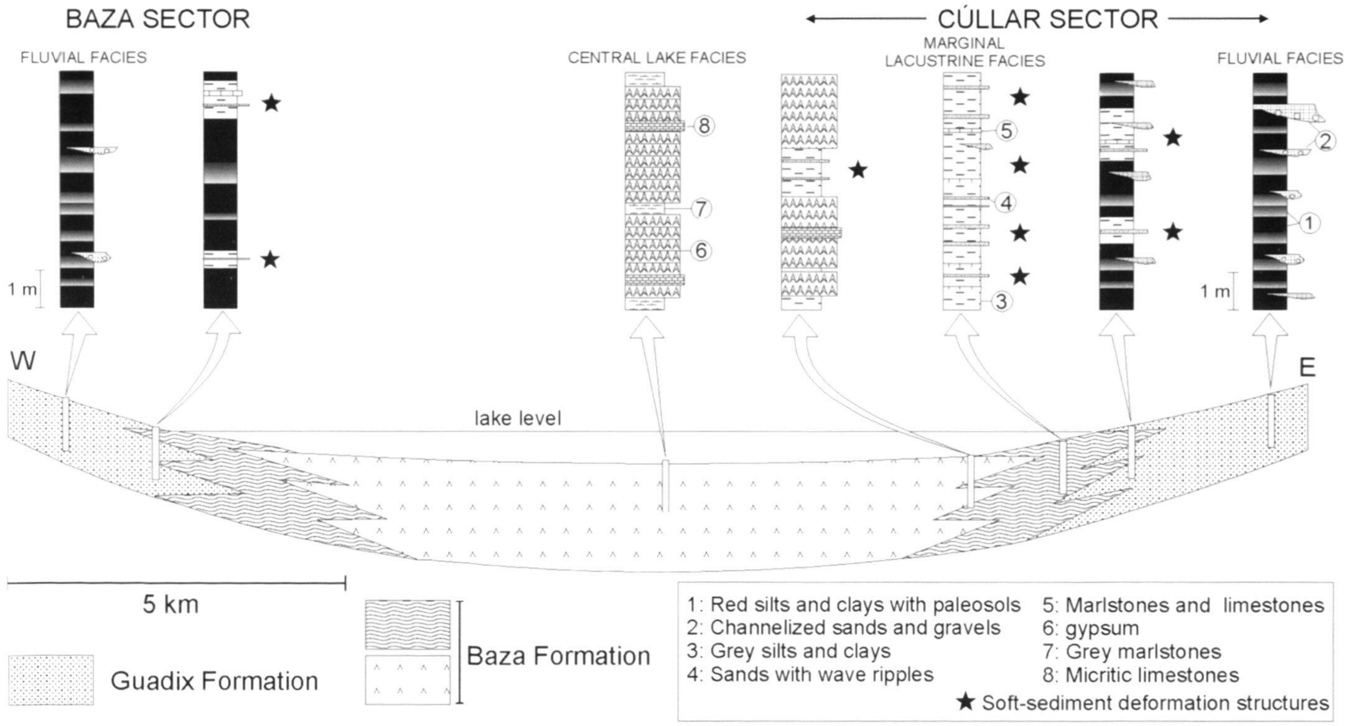

Fig. 2. Synthetic stratigraphic sections and sedimentary interpretation of the pliocene sediments studied (explained in text).

tions; they also include channelled gravelly and interbedded sandy horizons showing lateral accretion structures, and they are arranged in fining-upwards sequences. The facies association of these sediments are related to a subaerial floodplain, dominated by overbank interchannel processes.

- *Marginal lacustrine facies* composed of interbedded grey, yellow and white sand, silt and clay horizons; ferrous concretions are very common. Other characteristic features include the presence of sandy decimetric beds with wave ripples (wavy and lenticular bedding), small channels filled with gravel and sand, and centimetric marlstone and limestone beds with evaporitic casts. These sediments come from fluvial channels and were deposited in a marginal lake setting, where they were reworked by moderate wave action. Soft-sediment deformation structures are recognised only in these marginal lake facies (Fig. 2).
- *Central lake facies* are represented by a rhythmic evaporitic succession, composed of metric-scale tabular beds interbedded with centimetric beds of microgranular and selenitic gypsum, grey marlstones with large twinned gypsum crystals and rare micritic limestone beds. Its depositional environment is related to the central part of an endorheic lake where the chemical precipitation of evaporites dominated and without terrigenous input.

Soft-sediment deformation structures

In the study area we observe different types of soft-sediment deformation structures which can be classified into several morphological groups: load casts, pillows and water-escape structures. A detailed description of each of the observed structures is given below.

Load casts

Load casts (Reineck & Singh 1980, Allen 1982) are very common in the study area (Fig. 3 A and B). According to their morphology it is possible to define several types of cast structures: sagging load casts, dome-like load casts, drop structures, irregular load casts and pillows.

Sagging load casts

These structures occur in almost all of the studied outcrops. In this structure, both the lamination and the stratification are perfectly continuous and have a convex downward morphology. Between two convex lobes, the lamination and/or the stratification forms an acute upward angle (Fig. 4A). The size of these structures varies between 0.5–1 m in width and 1–1.5 m in height.

Fig. 3. A and B: General wievs of the marginal lake facies with load casts. The lateral extent of the deformed layers is noticeable, in both cases bounded at the top and base by undeformed horizons.

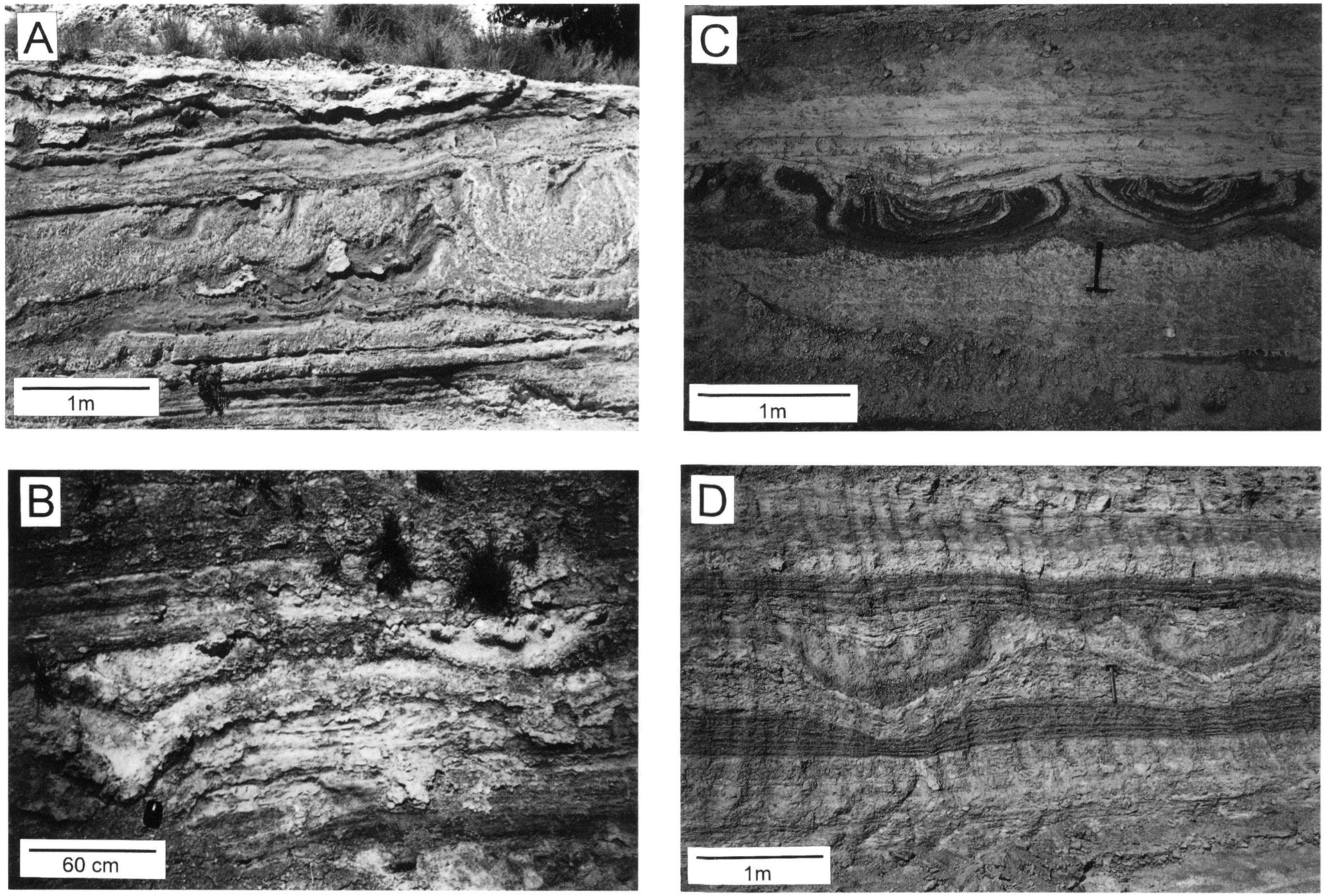

Fig. 4. A: Sagging load casts, showing convex downward lamination. B: Dome-like load casts, on the contrary with respect to the former, in this case with convex upward lamination. C and D: Twoo examples of sagging load casts with pillowy morphology. In the first case the load structure shows a flat base, as a result of the resistance of its substratum. In the second one, the structure shows a convex downward base.

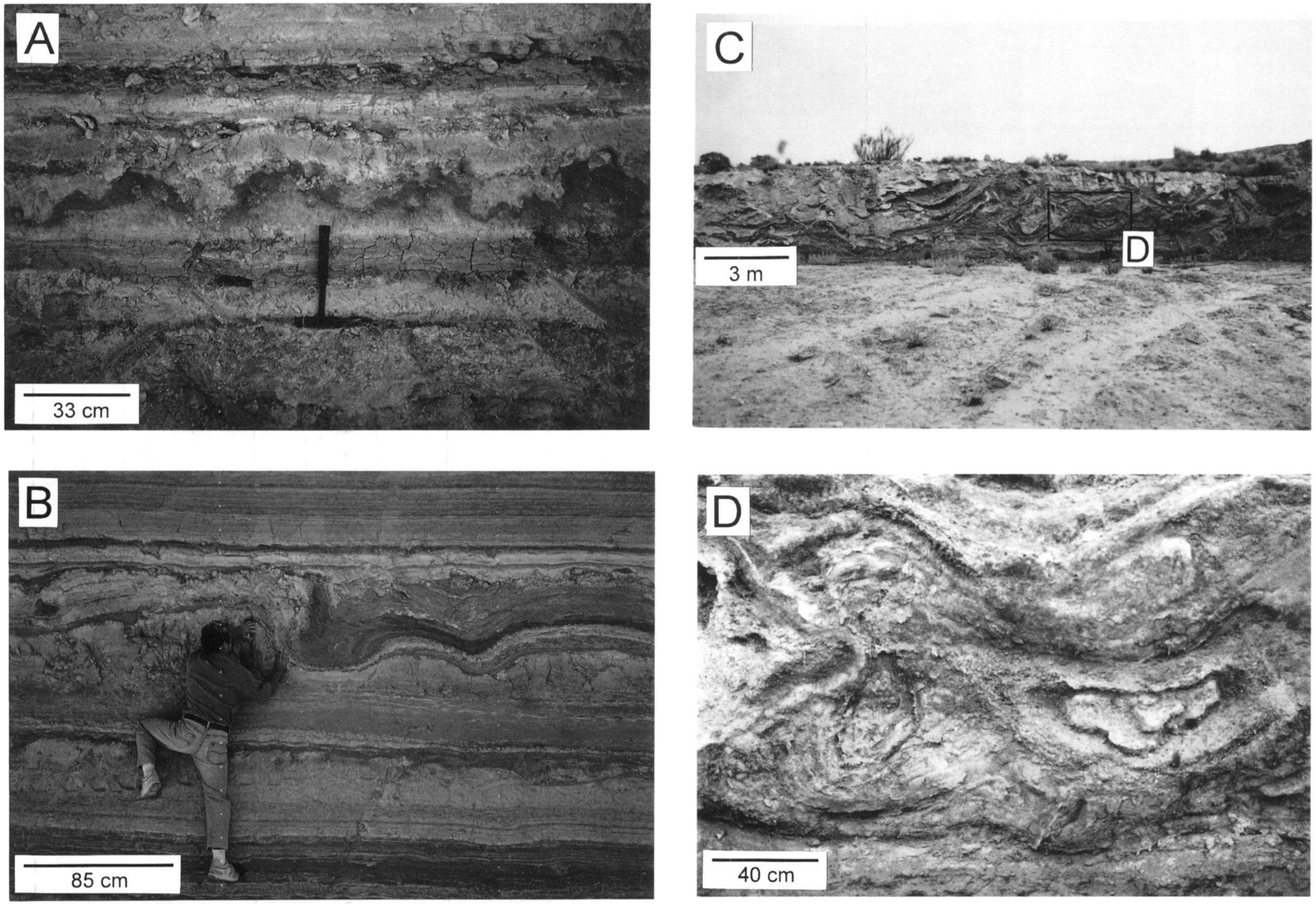

Fig. 5. A: Drop structures, a more accentuated deformation in relation to sagging load cast. B: Irregular load casts. C: General wiev of pillow structures. D: detail of the former. In this last type of structures the lateral continuity of the deformed lamination is missing, resulting in isolated bodies with concentric internal structure.

The structures comprise a succession of alternating thin layers of lose medium-grained sand and sandy silt which may be cemented. In the lower part of deformation structures there are layers of silty sand, well-cemented fine-grained sand, and/or silty-clayey layers. In general, strata change thickness laterally; the very fine sand and silty layers are those which show the most accentuated variation. In the Baza outcrop, some beds of sagging load casts are brecciated.

In some examples, the load cast overlies a more resistant substratum. In this case, the convex downward lobe has adapted itself to the substratum to develop a flat based, lengthened morphology (Fig. 4C). When the load cast is supported over a clayey substratum, the latter has been compacted (Fig. 4D).

Dome-like load casts

This type of structure has been described by Anketell et al. (1970) and is exposed in the vicinity of Cúllar and Venta del Peral. They have a totally inverted morphology with respect to sagging load casts. The stratification and/or lamination have a convex upward morphology and the apex points downwards. Their dimensions vary between 1.5–3 m in width and 1–2 m in height (Fig. 4B)

These structures are composed of an alternance of fine sand, sandy silt, silty clay and some interbedded gravel layers of centimetric and decimetric thickness.

Drop structures

These structures have also been described by Anketell et al. (1970). Drop structures are exposed in the Venta del Peral and west Cúllar sites (Fig. 5A). They occur in thin strata approximately 20–60 cm thick. Most of these are down-sink drop structures. They comprise fine sand lobes which have collapsed into very fine sand or silt. They do not, however, lose their continuity with the upper source strata. These drop structures may penetrate up to 30 cm into the lower layer.

Irregular load casts

Load structures which do not have a regular morphology can be found in some outcrops (Fig. 5B). These structures have dimensions varying laterally in thickness between 5 and 50 cm. They develop in medium sand beds overlying very fine sand and clayey silt.

Pillows

As with the load casts, pillow structures have been extensively discussed in the literature (e. g. Pettijohn & Potter 1964, Reineck & Singh 1980, Hempton & Dewey 1983, Allen 1986, Moretti et al. 1995). In the study area, pillows are located in various deformed horizons in the Venta Sabuenca and Mazarra sites. In these structures the stratification and lamination are not continuous but form isolated bodies of pillow-like morphology. Occasionally they form perfectly concentric structures (Fig. 5C and D). Their dimensions vary between 0.5 and 2 m in width and 0.3–1 m in height. Pillows are made up of a succession of alternating medium sand and silt. In the Venta Sabuenca outcrop, where the larger pillows are found, the sediment comprises coarse sandy gravel layers. The body of the pillow is surrounded by silty sand or by clayey silt.

Water escape structures

Water escape structures occur in the West Cúllar outcrops. The dimensions of these structures are approximately 5 cm in width and 10 cm thick. These water escape structures are made up to fine sand which cut through a layer of clay about 10 cm thick. They can also be found in the Venta Sabuenca outcrop, although in this case the water escape structures are of larger dimensions (10–30 cm wide and 1–1.5 m high) and are associated with pillow structures.

Mechanisms of deformation

Most of the soft-sediment deformation structures described in this paper formed when the sediment had a low or zero shear resistance. This natural condition can be produced by liquefaction-fluidization phenomena (Lowe 1975, Allen 1982, Owen 1987) in cohesionless sediments, or by thixotropic processes in cohesive fine sediments.

An important feature of the studied deformational structures is the existence of one or more strata which show considerable lateral thickness variations. These horizons are generally represented by two main granulometric classes: fine sand and coarse silt with a high liquefaction potential (*sensu* Seed & Idriss 1982), and clayey silt which shows evidences of thixotropic behaviour.

The different resultant morphologies of the structures exposed in Cúllar depend on the initial sedimentary column and the driving force to produce the deformation (*sensu* Owen 1995), i.e. generally represented by a vertical gravitationally body force (load-casts and pillows) or by a vertical shear stress (water escape structures).

Two principal "predeformation" sedimentary systems are identified:

a) reverse density gradient system (Anketell et al. 1970)

This initial system is formed by a higher bulk density (medium sand) horizon overlying a lower bulk density horizon (very fine sand and silt). When the shear strength of these sediments is reduced by liquidization and thixotropic processes, a gravitational readjustment occurs. The layer of relatively higher density collapses, and the underlying layer moves upward. This deformation results from a reverse density stratification in sediments and depends on their dynamic viscosity (k) contrast (Fig. 6):

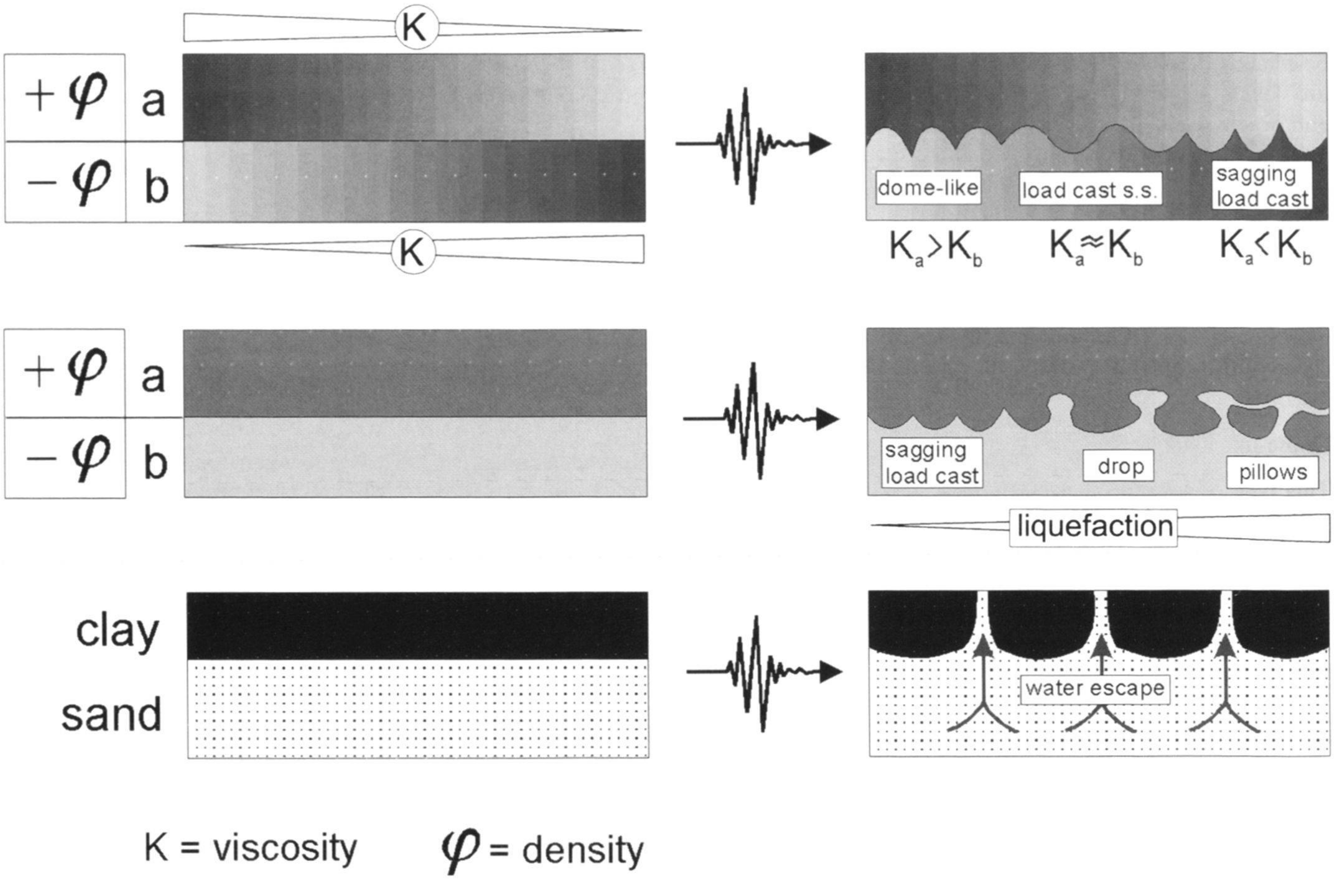

Fig. 6. Mechanisms of deformation for the soft-sediment deformation structures studied. In sediments with reverse density gradient (two upper sketches) different morphologies depend of the relative viscosity and the intensity of the liquefaction. In sediments with a impermeable barrier (lower sketch) water escape structures are favoured.

If the dynamic viscosity of the lower layer (kb) is greater than the dynamic viscosity of the upper layer (ka), sagging load casts are formed. In this case, the lower viscosity of the upper layer (a, see Fig. 6) makes this more mobile and tends to sink. If ka > kb, dome-like load casts are formed. The greater viscosity and subsequent lesser mobility of the upper layer gives the underlying layer (b, see Fig. 6) a tendency to rise. If the deformation is more accentuated, drop structures are formed, which in the majority of cases are down sink drop structures.

The deformed layers of the above mentioned structures maintain a perfect continuity with source strata. The collapse of the load cast in the underlying liquefied sediment can reach the substratum to deform it if it is soft (clayey) or adapting itself to te substratum if it is more resistant (Fig. 4C and D). If, previous to the liquefaction, irregularities exists in the sedimentary column due to the characteristics of the depositional environment, irregular load cast form. When a partially lithified condition exists, deformation is brittle to produce a brecciation.

Finally, when the deformation is more accentuated, the continuity of layers with the source strata becomes lost and pillow structures form. In some cases, they are associated with water escape structures.

b) normal density gradient system

This system comprises a sandy layer overlain by an impermeable clayed bed. During the liquefaction process, the interstitial pore pressure increases and the water tries to escape upwards. If it breaks the upper clayed bed, it forms a water escape structure. In this case the clayey layer behaves in a brittle manner. The escaping water can then vent with the fine sediment to produce fluidization structures.

Origin and conclusions

In the Guadix-Baza basin, located in the central part of the Betic Cordillera, many horizons show soft-sediment deformation structures. The deformation occurs in marginal lacustrine sediments of late Pliocene age. Soft-sediment deformation structures observed in Cúllar have been subdivided into load casts (l.c.) (sagging l.c., dome like l.c., drop structures and irregular l.c.), pillows and water escape structures. These soft-sediment deformation structures are related to liquefaction-fluidization and thixotropic processes.

These processes can be triggered by different genetic mechanisms such as storm waves, overloading, artesian springs or seismic shocks. In the particular case of the Cúllar structures, storm waves as the cause of liquefaction in the shallow lake environment (Martel & Gibling 1993) can be eliminated as the causal process because this process is not compatible with the particular depositional environment: in this small basin the bathimetric conditions were insufficient to produce waves large enough to induce liquefaction of a 1-m(or more)-thick horizon, as occurs in Cúllar outcrops. Also, there is no evidence of the sudden deposition of material capable of generating these deformation structures by overloading phenomena. Finally, artesian spring action is rejected because the related structures have a very different morphology and mechanism of deformation (see cylindrical structures described by Dionne 1973, Deynoux et al. 1990, Guhman & Pederson 1992, Holzer & Clark 1993, Li et al. 1996). All these processes are "internal" to the depositional environment. The soft-sediment deformational structures of Cúllar require an "external" causal process. They are best interpreted as the result of liquefaction and/or fluidization phenomena induced by moderate-high magnitude seismic shocks ($M > 5$; Audemard & De Santis 1991). In this sense, the soft-sediment deformation structures of the Guadix-Baza basin are seismites (*sensu* Seilacher 1969).

Generally, lacustrine sediments are considered very favourable for the genesis of liquefaction features (Sims 1982). Soft-sediment deformation structures related to earthquakes in lacustrine sedimentary environments have been described previously (Sims 1973, 1975; Ben-Menahem 1976, Hesse & Reading, 1978, Russ 1979, Hempton & Dewey 1983, Plint 1985, Brodzikowski et al. 1987, Ringrose 1989, Beck et al. 1992, Karlin & Abella 1992). In this case the specific occurrence of seismites in marginal lacustrine facies is related to the favourable conditions of this depositional environment (appropriate granulometry, presence of driving force systems in the initial sedimentary column, saturated sediments, etc.) and by the absence of significant erosional agents (high potential of preservation).

The Cúllar seismites also provide evidence of tectonic activity in the Guadix-Baza Basin during the latest Pliocene-earliest Pleistocene and they are clearly related to the neotectonic activity of Cádiz-Alicante Fault Zone. They constitute a new example of seismites in the Betic Cordillera, which can be added to other outcrops (Montenant 1980, Rodriguez Fernández 1982, Kleverlaan 1987, Roep & Everts 1992, Clauss 1993, Estévez et al. 1994, Alfaro et al. 1995, Rodriguez Pascua et al. 1996).

Acknowledgements

We thank H.G. Reading, K.T. Pickering and S. Obermeier for helpful suggestions. This study has been financed by the projects "Fondi M.U.R.S.T. 40% Pieri 1993; C.N.R. Pieri 1993" and "AMB95-1557 D.G.I.C.Y.T.".

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Manuscript received December 19, 1996
Revision accepted May 28, 1997