



Palaeokarst and rauhwasche development, mountain uplift and subaerial sliding of tectonic sheets (northern Sierra de los Filabres, Betic Cordilleras, Spain)

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Received 28 July 1998; accepted in revised form 3 March 1999

Key words: Betic Cordilleras, continental deposits, gravitational sliding, mountain uplift, palaeokarst structures, rauhwasches

Abstract

The rauhwasches near Serón in the northern Sierra de los Filabres (S Spain), previously considered as true tectonic breccias, are reinterpreted on the basis of sedimentological, geomorphological and geometrical evidence as subaerial or nearly subaerial sedimentary deposits. Channel fills, parallel lamination, cross-lamination, graded bedding, sedimentary clastic dykes and other sedimentary structures and features occur in the rauhwasche body. These sedimentary rocks correspond to continental deposits of alluvial and karstic origin deposited over a karstified erosional surface of Nevado–Filabride marbles. Although no fossils have been found in the rauhwasches, a Tortonian age for these rocks is suggested on the basis of structural arguments and lithostratigraphic data from the nearby Almanzora basin. The rauhwasches were buried by slabs of Alpujarride rocks that gravitationally slid over them during the uplifting of the Sierra de los Filabres.

Introduction

Rauhwasches (cornieules or cargneules) are breccias with a calcareous matrix and mainly dolomitic components that weather to form cavernous rocks. Very often associated with evaporitic rocks, they are usually situated along brittle tectonic contacts. Their origin is still controversial; they have been interpreted as sedimentary breccias (e.g. Zeylmans van Emmichoven 1925, Krauter 1971), as a result of fracturing (true cataclases developing in relation with shearing along important detachments, Leine 1968) or hydraulic fracturation (Masson 1972), or, finally, as due to weathering of dolomite-bearing evaporitic rocks, involving karstification, dedolomitization and fracturing due to

an increase in volume during the change from anhydrite to gypsum (e.g. Warrack 1974, Vearcombe 1982).

The rauhwasches in the Internal Zone of the Betics have been considered as: a) sedimentary breccias of Triassic (Sierra 1915, Zeylmans van Emmichoven 1925) or Palaeogene (Bourgeois 1979, Puga et al. 1996) age, b) residual breccias formed by the dissolution of gypsum and other salts (Duplaix & Fallot 1960a, b, Fallot et al. 1960), or c) as true tectonic breccias (Leine 1962, 1968, Leine & Egeler 1962). According to Leine (1968, 1971), who has extensively studied the rauhwasches in the Serón area (northern Sierra de los Filabres), where a huge outcrop of rauhwasches up to 250 m thick appears over an area of 35 km²

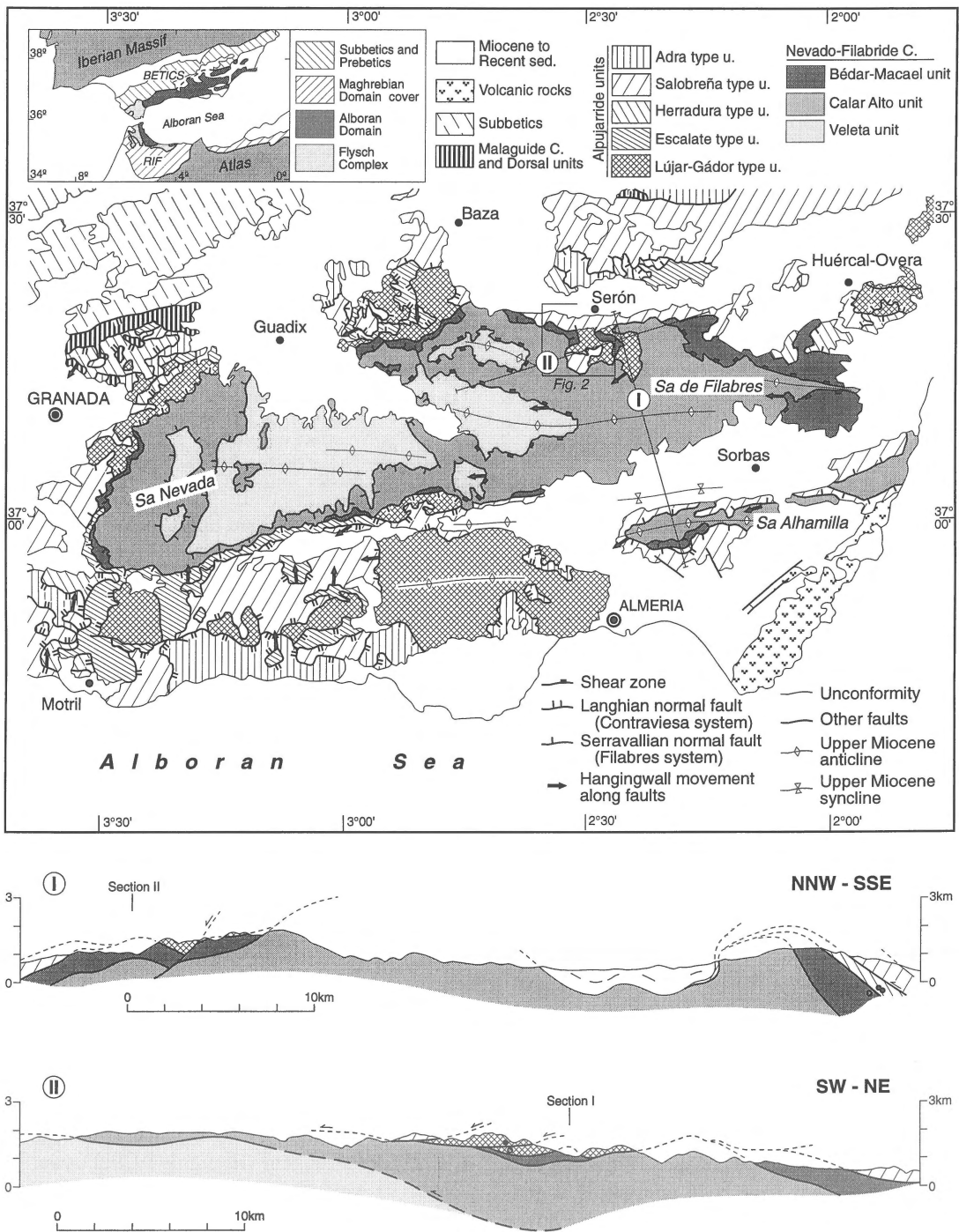


Figure 1. Upper part: Tectonic map of the central and eastern internal Betics. Boundaries between Nevado-Filabride units according to Martínez-Martínez et al. (1997). Alpujarride units according to Azañón et al. (1994). Kinematics criteria according to García-Dueñas et al. (1992), Azañón et al. (1994), Crespo-Blanc et al. (1994), Crespo-Blanc (1995), Martínez-Martínez & Azañón (1997), Azañón & Crespo-Blanc (in press), and own data. Lower part: Cross-sections showing geometrical features of the main extensional systems. Note the effect of the Late Miocene folding in the southern part of section I. Small circles indicate out-of-plane motion: ○ toward, ● away.

(Figures 1, 2), these rocks essentially developed as the result of movements that occurred after the synkinematic Alpine metamorphism. According to him, the breccias themselves subsequently underwent both progressive and retrogressive Alpine metamorphism.

This paper presents a revision of the geology of the same area, in particular of the relationships between the rauhewackes and the surrounding rocks, and of the petrography and sedimentology of the rauhewackes. The data compiled reveal that most of the rocks which Leine (1968) considered as polymict rauhewackes, with fragments of various rocks, are alluvial and karstic sediments, probably Tortonian in age, which were deposited over a karstified erosional surface. These rocks were later buried during superficial sliding and perhaps also gravity-induced thrusting of Alpujarride rock sheets during the Late Miocene folding and uplifting of the Sierra de los Filabres.

Geological setting

The Alboran Domain

The Alboran crustal domain (Balanyá & García-Dueñas 1987), inside the Gibraltar Arc, essentially comprises three complexes with differing Alpine tectonometamorphic evolutions. These are, from bottom to top, the Nevado–Filabride Complex, the Alpujarride Complex and the Malaguide Complex (Figure 1). A complex pre-Miocene evolution which includes a high-pressure metamorphic event during continental collision characterizes the upper Nevado–Filabride units (Nijhuis 1964, Puga 1976, Bakker et al. 1989, De Jong 1991) and the Alpujarride Complex (Goffé et al. 1989, Tubía & Gil-Ibarguchi 1991). The Nevado–Filabride and Alpujarride Complexes have traditionally been considered as a post-metamorphic nappe-stack, as in many outcrops higher-grade rocks lie over lower-grade ones. Nevertheless, it has been shown recently that the contacts between the Alboran Domain units are mostly listric or low-angle normal faults (Platt et al. 1983, Aldaya et al. 1984, García-Dueñas et al. 1986, García-Dueñas & Martínez-Martínez 1988, Galindo-Zaldivar et al. 1989, Platt & Vissers 1989, Vissers et al. 1995).

During the Early and Middle Miocene, rifting and crustal extension affected the whole Alboran Domain (García-Dueñas et al. 1992) and the extensional denudation processes resulted in the opening of the Alboran Sea (e.g. Comas et al. 1992). Thus,

the present-day Alboran Domain units are extensional tectonic units, bounded by low-angle normal fault systems. In the central Betics, two of these systems have been described, showing subperpendicular extensional directions, as illustrated by the hanging-wall movement along the faults (Figure 1, cross-sections). The Contraviesa normal-fault system, mainly affecting Alpujarride units in the central part of the cordillera, is Late Burdigalian and Langhian in age, with an approximately N–S extension direction (Crespo-Blanc et al. 1994, Crespo-Blanc 1995). The Filabres normal-fault system, Serravallian in age, shows a west- to southwest-ward sense of transport (García-Dueñas et al. 1992). The sole detachment of the Filabres system corresponds with the boundary between the Alpujarride and Nevado–Filabride Complexes (García-Dueñas & Martínez-Martínez 1988). The large-scale geometry of these extensional systems can be seen in cross-sections I and II in Figure 1. Both sections show strong thinning of the units along the transport sense, that is, towards the north-north-west and the south-west respectively. These extensional processes were responsible for the tectonic exhumation and further erosion of the Alboran Domain. The clasts belonging to the syn-rift sediments reveal an unroofing sequence in which stratigraphically younger deposits contain debris from successively deeper levels of the Alboran Domain. As a matter of fact, the first clasts from Alpujarride units appear in Early Burdigalian sediments (Bourgeois 1979, Lonergan & Mange-Rajetzky 1994), while the oldest sediments containing Nevado–Filabride clasts are latest Serravallian to Early Tortonian (e.g. Völk & Rondeel 1964, Briend et al. 1990, Ott d'Estevou & Montenat 1990, Rodríguez Fernández & Sanz de Galdeano 1992).

New evidence from the Alpujarras region, south of the Sierra Nevada, has revealed the existence of large recumbent fold structures involving lithological ensembles previously considered as independent tectonic units (Orozco et al. 1997). These folds have been interpreted as extensional in origin, their development being connected with the event that produced the low-angle normal faults and extensional detachments in Early to Middle Miocene times (Orozco et al. 1998). This conclusion is based on the analysis of the relationships between recumbent folds and extension-related structures, including low-angle normal faults, stretching lineation and boudinage structures.

Finally, from the Late Tortonian to the Pliocene, the Alboran region underwent continuous N–S to

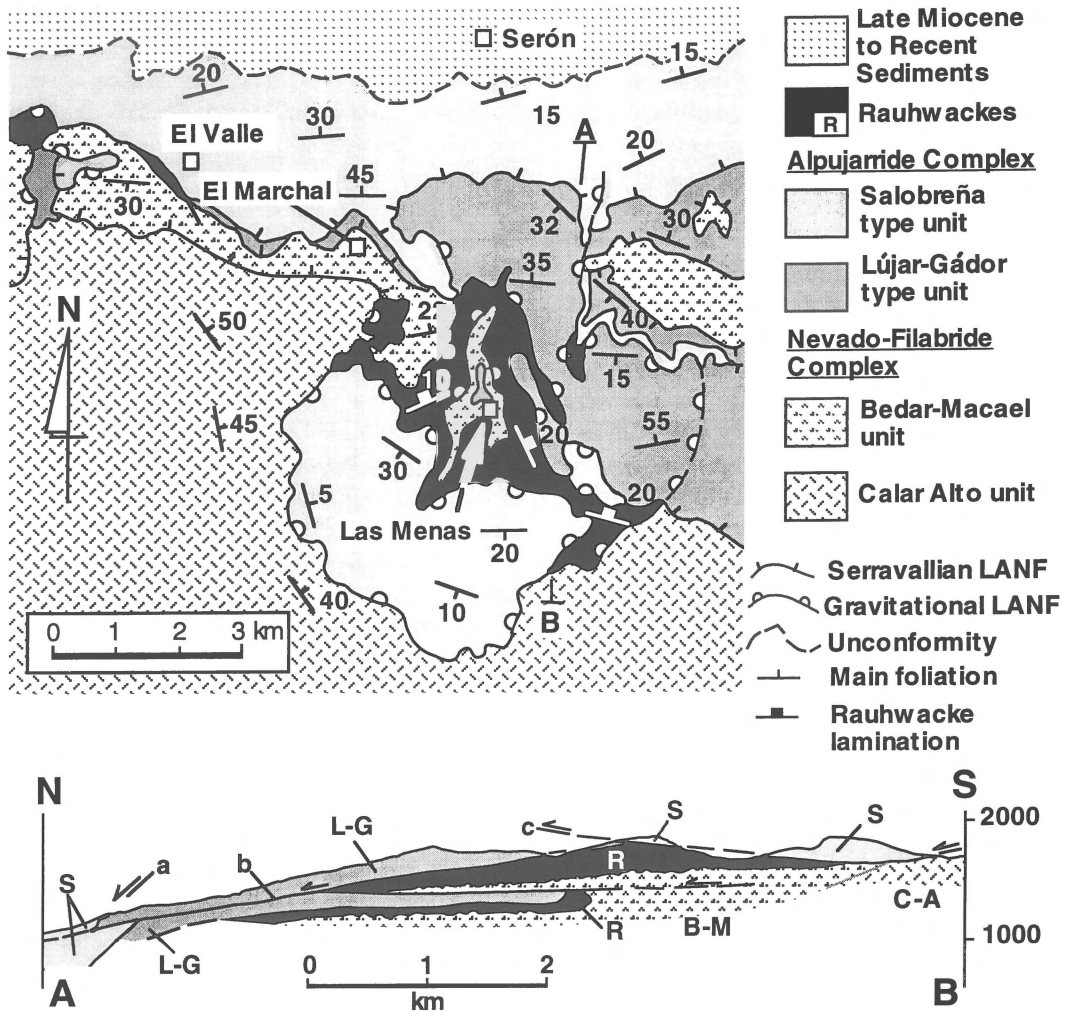


Figure 2. Detailed map of the Serón area, northern Sierra de los Filabres (see location in Figure 1). Note the geometry of the rauhwacke body, which reaches its maximum thickness in the area of Las Menas. The cross-section shows the geometrical relationships among the different sets of gravitational faults. Note the anomalous superposition of Nevado-Filabride rocks over Alpujarride ones. This is also evidenced by the tectonic window of Las Menas (see map). LANF = low-angle normal fault.

NW-SE compression, and the extensional fault systems were folded and faulted (Comas et al. 1992, García-Dueñas et al. 1992, Rodríguez-Fernández & Martín-Penela 1993, Crespo-Blanc et al. 1994). The axes of the main folds, mainly open multikilometric E-W directed folds, are shown in the map and cross-section I of Figure 1. The folds in the southern part of the section have been dated by Weijermars et al. (1985) and Briend et al. (1990) as Late Tortonian close to the Messinian boundary, because Messinian sediments are separated from the folded sediments by an angular unconformity.

The rauhwacke body of Serón

The rauhwackes that Leine studied, and that are the subject of this paper, are situated along the boundary between the Alpujarride and the Nevado-Filabride Complex, that is along the Filabres detachment. These rocks are exceptionally well developed in the northern Sierra de los Filabres (Figures 1, 2). Detailed geological mapping in the northern slope of this sierra, south of Serón village, reveals the existence of several units (Leine 1968, Molina 1981, Molina & Orozco 1983) separated by low-angle normal faults (Figure 2). From bottom to top the succession includes:

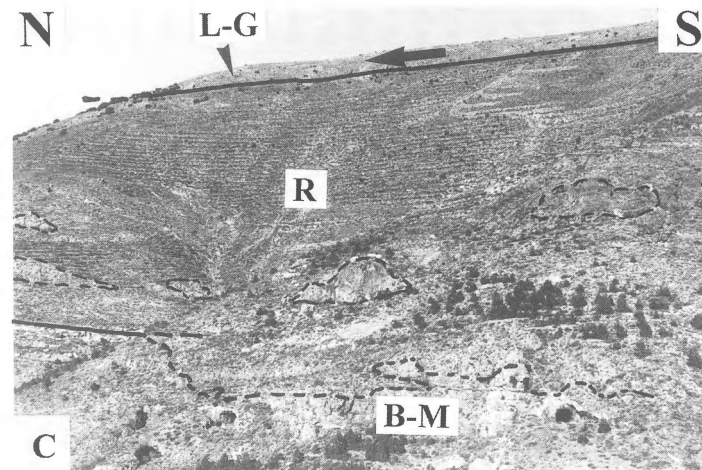
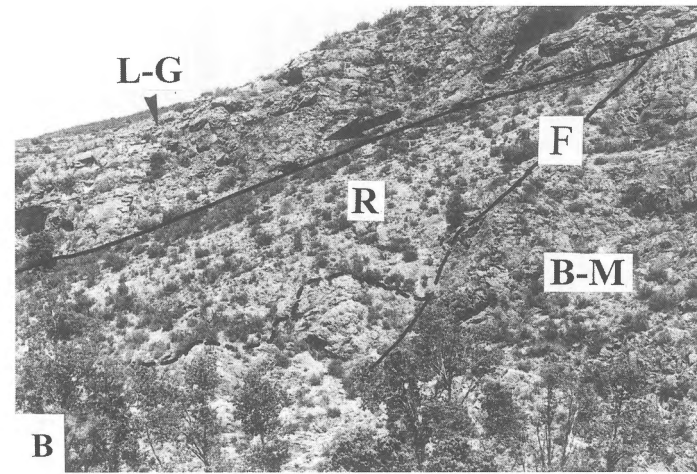
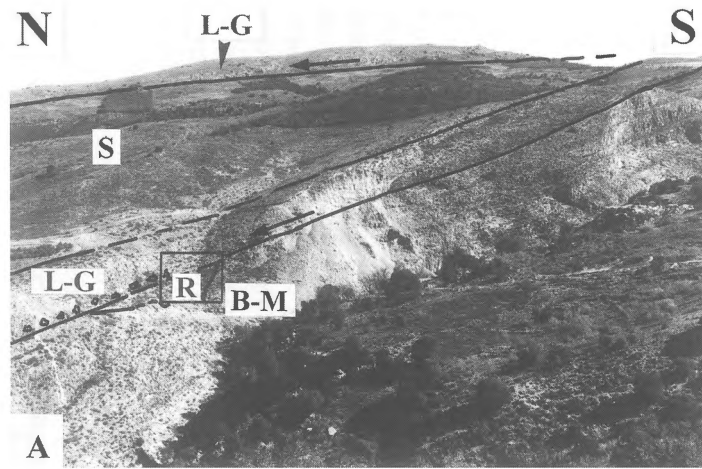


Figure 3. A) Panoramic view of the area east of El Marchal (see Figure 2). B–M = Bedar–Macael (Nevado–Filabride) marbles. R = rauhawackes. L–G = Lújar–Gádor (Alpujarride) unit (mainly carbonates). S = Salobreña (Alpujarride) unit (mainly phyllites). Note the wedge shape of the rauhawacke body. Arrows indicate the direction of movement of the low-angle normal faults. Angular (breccia) fragments above the lower low-angle faults are also indicated. B) Photograph showing detail of inset. The lower boundary (dashed line) of the rauhawackes corresponds with an irregular surface of karstic origin; the southern boundary of the rauhawacke body is a palaeofault (F). A tabular body of carbonate rocks (L–G) slid over the Nevado–Filabride marbles, sealing the afore-mentioned palaeofault and coming into direct contact with the rauhawackes. C) Rauhawackes (R) east of Las Menas (see Figure 2). The boundary between the rauhawackes and the underlying Nevado–Filabride marbles is marked either by a low-angle fault surface (left-lower corner) or by an irregular surface of karstic origin (dashed line; note iron mine entrances below the karstic surface). Within the rauhawacke body, large blocks of Alpujarride limestones (dashed lines) can be seen. The upper boundary of the rauhawackes is a low-angle normal fault that superimposes a sheet-like Lújar–Gádor carbonate body (L–G) over the rauhawackes. The thickness of the rauhawackes shown is ca 250 m. D) Sedimentary structures in the rauhawackes. Channell fill, 150 cm wide; 60 cm high; ca. 2 km SE of Las Menas.

- 1) The Nevado–Filabride Complex; this is here mainly represented by garnet-bearing schists, gneisses, quartzites and, in the upper part, by marbles with scarce intercalations of schists; all these rocks belong to the upper Nevado–Filabride Calar Alto and Bédar–Macaël tectonic units (García-Dueñas et al. 1988).
- 2) The rauhwaacke body; this consists of breccias with a calcareous matrix and mainly dolomitic clasts. These rocks, described in detail below, reach a maximum thickness of 250 m in the central part of the study area and thin out laterally (Figure 2). The great volume of rauhwaackes around Serón made Leine (1968) select this area to investigate these rocks and to establish his well-known monomict/polymict rauhwaacke classification. The boundary between the rauhwaacke body and the underlying Nevado–Filabride rocks corresponds either to a low-angle normal fault or to an irregular surface of palaeokarstic structures, as described below.
- 3) The Alpujarride Complex, which in this area comprises two units. The lower one, the Lújar–Gádor unit according to Azañón et al. (1994), consists of a thick sequence (> 300 m) of Triassic (Braga & Martín 1987 and references therein) limestones and dolomites, with some gypsum and diabase bodies. The carbonates overlie a thin, discontinuous formation of phyllites and quartzites, attributed to the Permo-Triassic. The upper unit, the Salobreña unit according to Azañón et al. (1994), is composed of a metapelitic sequence comprising Palaeozoic dark-coloured garnet- and biotite-bearing schists, Permo-Triassic light-coloured phyllites and quartzites, and Triassic carbonates.

It must be stressed that due to omissions or repetitions caused by late faults, this column can be incomplete, and/or that some terms can occur in a different geometrical position.

The geometrical relation between the rauhwaacke body and the Alpujarride and Nevado–Filabride tectonic complexes

Most of the rauhwaacke-type rocks overlie the marbles of the upper Nevado–Filabride Bédar–Macaël unit, with the lower boundary corresponding to a surface dipping slightly towards the north (Figure 2). This boundary corresponds either to a low-angle normal fault, with a top-to-the-north hanging-wall movement,

as observed in Figures 2 and 3(A), or to an irregular surface of palaeokarstic depression structures, more specifically dolines and grikes (Figures 3(B), C), fully described below. The upper boundary of the rauhwaackes corresponds to low-angle faults, as shown below.

A characteristic feature of the Serón rauhwaackes is that they are overlain by sheet-like bodies of Alpujarride rocks up to several hundred metres thick (Figures 2, 3(A)). This is significant since it rules out the interpretation of the rauhwaackes as present-day or very recent hill-slope deposits. In addition, the existence of northward-dipping laminar structures in the rauhwaackes (Figure 2 shows the strike and dip of this lamination), and the presence of fractures cross-cutting the lamination, argue against hypotheses such as that of Jeanbourquin (1986) considering rauhwaackes in the Alps to be Pleistocene to recent sedimentary deposits related with karstic phenomena.

A particular, very illustrative, case of the relationships between the rauhwaacke body and the surrounding rocks can be observed in the El Marchal area (Figures 2, 3(A, B)), where the rauhwaackes appear as a wedge of 20 m maximum thickness, between the Nevado–Filabride Bédar–Macaël unit and the Alpujarride Lújar–Gádor unit. This wedge thins towards the north, where the Alpujarride Complex finally lies directly over the Nevado–Filabride Complex (Figure 3(A)). Part of the boundary of the rauhwaackes with the Nevado-Filabride marbles shows an irregular surface corresponding to a karstified morphology (Figure 3(B)). The upper boundary of the rauhwaacke wedge is a low-angle normal fault, as evidenced by the presence along the fault zone of angular fragments of different sizes of rocks from the overlying tabular body of carbonate rocks, the Lújar–Gádor unit, which is brecciated close to its lower boundary. The whole is in turn overlain by phyllites of the upper Alpujarride Salobreña unit (Figure 3(A)). The Alpujarride rocks lie over the Nevado–Filabride marbles to the south, and over the rauhwaackes to the north. The low-angle fault cuts a high-angle N-dipping one that bounds the rauhwaacke wedge to the south (F of Figure 3(B)). The rauhwaackes were sealed by the Alpujarride rocks sliding over them along a superficial fault. A slab of carbonate rocks belonging to the lower Alpujarride Lújar–Gádor unit overlies the phyllites of the upper Alpujarride Salobreña unit, by another, more gently dipping low-angle normal fault (Figure 2, map, 1 km E of El Marchal, and Figure 3(A)).

In the central part of the studied area, where the rauhawacke body reaches its maximum thickness (Figure 3(C)), the upper contact of this body is characterized by faults dipping slightly towards the north, and the body is overlain by various Alpujarride tectonic units (Figure 2). In the northern and eastern part of the study area, the carbonate rocks of the Lújar–Gádor unit lie over the rauhawackes, as the light-coloured phyllites of this unit appear only as lenses along the boundary, while in the southern and western part various lithological formations of the upper Alpujarride Salobreña unit lie over the rauhawackes, with the lowermost Alpujarride unit missing.

The sequence of the different faults of the upper boundary of the rauhawackes can be established from the analysis of the cross-cutting relationships evidenced in the geological mapping. In particular, the cross-section in Figure 2 illustrates how, from north to south, the northernmost fault, which dips about 35° towards the north (labelled 'a'), is cut by a fault dipping slightly towards the north ('b'). Fault 'b' in turn is cut by a third one, subhorizontal or dipping slightly towards the south ('c'). The listric character of this third fault is coherent with the geometric relationship of its hanging wall with its footwall, as the Salobreña unit lies, from south to north, over the Nevado–Filabride Complex, over the rauhawacke unit and over the Lújar–Gádor unit. The main foliation of the rocks belonging to the Salobreña unit dips moderately towards the south.

An anomalous superposition of the Nevado–Filabride Bédar–Macaël unit (schists and marbles) over the Alpujarride Lújar–Gádor unit is observed in the central part of the study area in the Las Menas window, and northwest of El Valle village (Figure 2). This superposition is due to faults with similar characteristics to those described above, that is, low-angle normal faults with a northward transport sense. In these examples, the faults produce the development of hectometre-scale north-vergent folds (see also Molina & Orozco 1983 and Voet 1967, a few kilometres to the east).

Rauhawacke description

A full petrographic description of the Serón rauhawacke body can be found in Leine (1968). This author grouped these rocks into two main types, monomict and polymict rauhawackes, both being tectonic breccias. In the monomict rauhawackes, the brecci-

ated structure originated through fragmentation of a single rock type, usually dolomite, while the polymict rauhawackes formed through the fragmentation and mixing of two or more rock types. According to Leine (1968), clasts of limestones, dolomites, phyllites, shales, quartzites, diabases and schists are present in the polymict rauhawackes of the Serón area. Their size may vary from less than 1 mm to large blocks that may attain a length of more than 400 m. The fragments show all stages of rounding, from angular to well-rounded. The fine porous matrix of the rauhawackes is mainly composed of xenoblastic calcite crystals, although rhombohedra of dolomite that have usually been partially or entirely calcitized are also present. Other, non-carbonate minerals, e.g. gypsum, can be seen as well, usually in small quantities. As a result of the mechanical destruction of rock fragments, grains of various minerals such as quartz, mica, chlorite, epidote and garnet have been incorporated into the matrix. However, Leine (1968) believed that most of the non-carbonate minerals in the matrix formed in situ under static conditions during the Alpine metamorphism. This seems to be unrealistic.

Our study in the area south of Serón, which includes a detailed analysis of the rauhawackes and their structures at the outcrop and at microscopic scale, reveals that most of the rocks are of sedimentary and not of tectonic origin, as has been proposed by Leine (1968).

Outcrops of rauhawackes with unquestionable sedimentary structures are scarce, but distributed all along the rauhawacke body. They vary from some decimetres to 20 m maximum thickness and are lenticular in shape. The individual beds have thicknesses of up to 60 cm. This bedding is clearly folded on a hectometre to kilometre scale in some places, occasionally dipping more than 35° (Figure 2).

These outcrops are generally yellow or brown and show the following types of sedimentary rocks: 1) calcisiltites with horizontal parallel and/or wavy lamination; 2) calcareous sandstones, cross-laminated and/or stratified; 3) conglomerates, breccias and calcareous sandstones, massive or locally with grain-size sorting, and 4) 'vadose silt' with parallel lamination.

In the outcrops these sedimentary rocks appear with the following main structures and features:

- a) Channel fill (Figure 3(D)), parallel lamination, low-angle cross lamination (< 20°; Figure 4(A)) and high-angle cross lamination (between 20 and 40°). Palaeocurrents have been measured, from

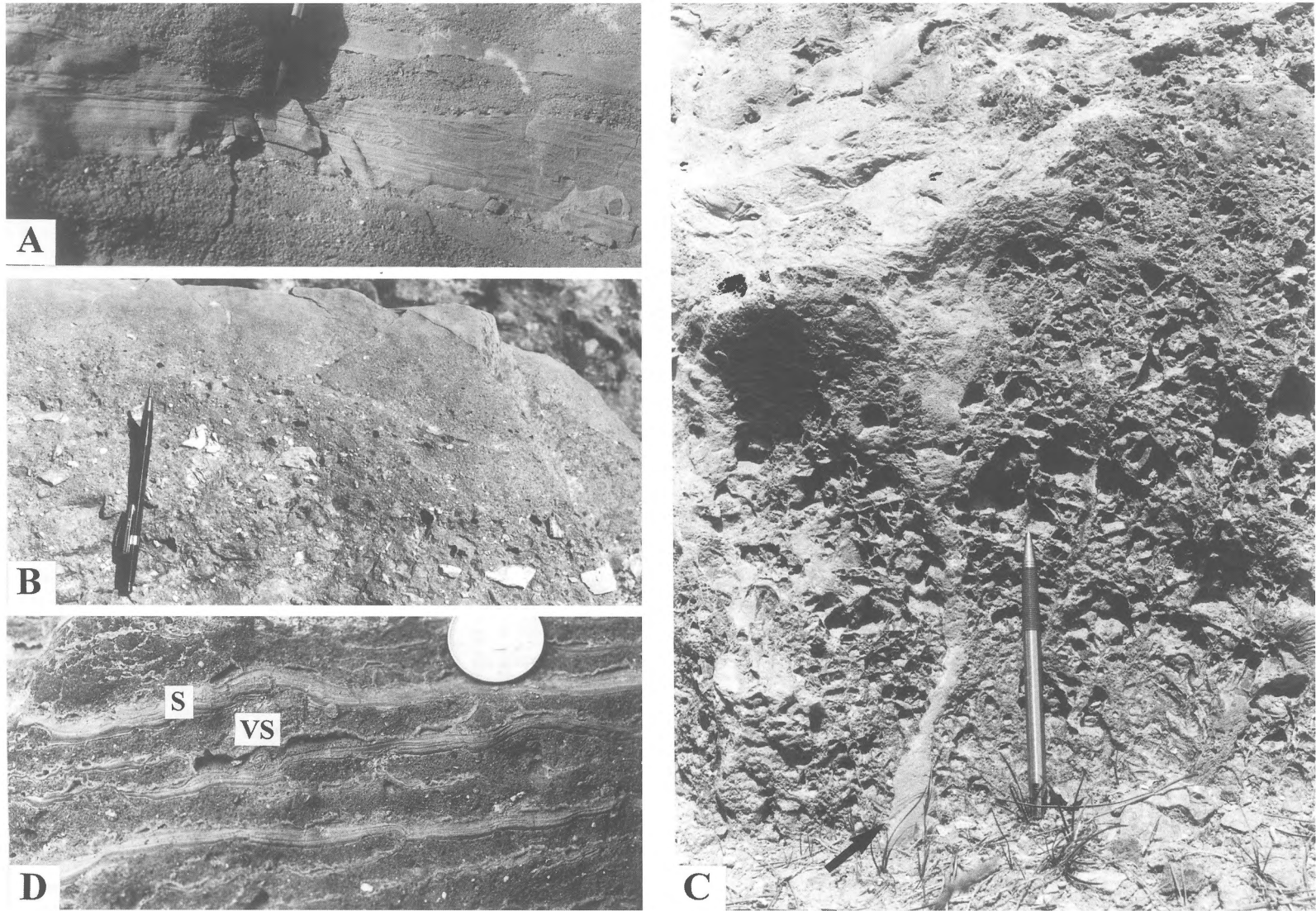


Figure 4. Sedimentary facies in the rauhewackes. A) Low-angle lamination in calcisiltites and calcareous sandstones; ca. 1.5 km N of Las Menas. B) Interbedding of breccias, sandstones and siltstones showing normal graded bedding; ca. 1.5 km N of Las Menas. C) Karstified dolomites with cellular (or boxwork) structure cut by sedimentary clastic dykes. Arrow shows sedimentary sandglass lamination in the calcisiltite filling the dyke; ca. 2 km SE of Las Menas. D) Vadose silt (VS) with parallel lamination and speleothems (S); ca. 1.7 km SE of Las Menas. Coin diameter is 2.2 cm.

N45°W to N10°E, based on these sedimentary structures.

- b) Interbedding of siltstone, sandstone and breccias with good examples of normal (Figure 4(B)) and normal-inverse graded bedding.
- c) Blocks of cellular dolomite (Figure 4(C); *cargneule*) more than 2 m in maximum diameter. There are significant changes in bedding thickness, with wedge-shaped and irregularly shaped beds adapting to such blocks of dolomite, and to bottom irregularities, covering pre-existing topographic irregularities, progressively levelling them. On a smaller scale the lamination in thin section is also adapted to small clasts.
- d) Angular clasts of laminated siltstone with the appearance of 'vadose silt' (Figure 4(D)). 'Vadose silt' as described in, e.g., Tucker & Wright (1990, p. 328) are internal sediments consisting of cement fragments, thought to be derived from internal erosion in reef and other cavities during exposure and meteoric diagenesis (Dunham, 1969).
- e) Sedimentary clastic dykes (Figure 4(C)) showing a parallel lamination of the infill which originated by gravitational deposition, not forceful injection.

The sedimentary rocks recognized in the *rauhwackes* correspond, according to the facies classification of Miall (1996), to the lithofacies Ss (scour-fill sand), Sm (massive sand) and Gmm-Gmg (matrix-supported gravel). Locally, the Sp lithofacies (planar-cross-bedded sand) appears. We will briefly comment on the sedimentological interpretation of each facies, mainly according to Miall (1996). The characteristics of lithofacies Ss indicate rapid deposition of a poorly sorted, coarse bed load and may comprise the basal fill of channels or scour hollows. The sediments of lithofacies Sm are deposits of sediment gravity flows and occur characteristically in small channels resulting from bank collapse. The gravel lithofacies Gmm and Gmg commonly have sharp lateral terminations, and show massive beds (Gmm) or grading of clasts and/or matrix (Gmg). These two last facies are formed by high-strength debris flows occupying preexisting alluvial topography, for example channels. The sediments attributed to lithofacies Sp are very fine sand or silt, formed by the migration of dunes.

Karst structures

The top of the Nevado–Filabride marbles

The top of the Nevado–Filabride marbles, immediately below the *rauhwackes*, appears as an irregular surface with palaeokarstic depression structures, more specifically dolines and grikes. The dolines and grikes have observable maximum depths of 10 m and 1 m, respectively. These features have been recognized near El Marchal and east of Las Menas (Figures 3(A–C)). In both areas, the dolines are controlled by karstified palaeofaults in the marbles, with dominant directions of approximately N75°E and N40°E (Figure 3(B)). The marbles change greatly in thickness, from 0 to 80 m, which could be due, apart from the effect of tectonic faults, to the karstification.

This karstification in the upper part of the marbles may be closely related to iron ores (Figure 3(C)). As a matter of fact, in the area near Las Menas, iron ores show a general tendency to line up along N45°E directions, indicating tectonic control by palaeofaults. In Alquife, ca. 50 km WSW of Serón, detrital accumulations composed of hematite and goethite, fill karstic cavities developed mainly in the upper parts of the Nevado–Filabride marbles (Torres-Ruiz 1983). In the upper parts of these economically important karstic deposits, pieces of calcitic and dolomitic marble, mica schist and quartzite occur together with ore fragments.

Karstification in the rauhwackes and associated rocks

The most important karstic features recognized in the *rauhwackes* are:

- a) Karstified dolomites in which a boxwork structure is well developed (Figure 4(C)). This structure occurs in microfractured dolomites where the fractures are filled with calcite. Under incongruent dissolution conditions, the dolomite was weathered but the calcite veins were preserved and now protrude between 'Dolomitsand', which is a fine powder of loose dolomite crystals that occasionally show a somewhat rhombohedral form.
- b) Speleothems, mainly parallel to the bedding (Figure 4(D)).
- c) Karstic passages or caves with collapse breccias.
- d) Karstified palaeofaults and fractures (Figure 3(B)).
- e) Vadose silt with 'sandglass' lamination filling karstic cavities (Figure 4(C)).

Polyphasic karstification can be recognized in the *rauhwackes* and associated rocks, as well as in the

large blocks of dolomites enveloped by the rauh-wackes. The existence of several karstification phases is evidenced by the presence of karstic structures not only in the Nevado-Filabride marbles, but also in the rauh-wackes filling the karstic cavities previously developed at the top of the marbles. Channels, dykes and other cavities cut across older rauh-wackes and are in turn filled by younger rauh-wacke deposits. The existence of several generations of this breccia-like rock is also clear from microscopic observations. Fragments from a previous rauh-wacke are enclosed within a younger breccia. The rauh-wackes are composed mainly of dolomitic silt and fine sand matrix, essentially of dolomitic (vadose) silt, with a sandglass lamination, deposited in a subaerial environment.

Within the rauh-wackes in the Manzano ravine, ca. 2.5 km SE of Las Menas, there are karstic cavities with a typical pear or approximately triangular shape. In vertical section they measure 1.5 m high by 1.9 m wide. They contain abundant breccias with dolomitic clasts, surrounded by a yellowish laminated silty matrix.

Discussion

Karstic features

As Ford & Williams (1989, p. 510) commented, the 'preservation of recognizable karst features in the buried rock record is a matter of chance'. The best possibilities are where karstic processes are overwhelmed by rapid deposition, especially of terrigenous sediments, followed by prolonged subsidence. In our study area the preservation is mainly linked to the tectonic superimposition of an Alpujarride rock sheet.

The karstic morphologies can be interpreted as consisting of two different types:

- 1) The karst at the top of the Nevado-Filabride marbles is a palaeokarst or buried karst, completely decoupled from the present hydrogeochemical system; it is fossilized. Only in places, where the cover bed has been removed by natural erosion or by mining works, is an exhumed karst revealed.
- 2) The karstic features affecting the rauh-wackes and associated rocks, mainly dolomites, can be considered as relict karsts, as they are removed from the situation in which they principally developed, although they remain exposed to, and are modified by processes operating in the present system.

Specifically, these relict karsts arose due to: a) a change in the hydrographic setting, b) an alteration in the climatic, morphogenetic situation, and c) the tectonic superposition of the Alpujarride rock sheets. The karstic processes in relation with the rauh-wackes continue their evolution to the present day.

The uplifted Triassic Nevado-Filabride marbles were subaerially exposed before the last important normal faulting. Meteoric waters seeped through the fractures, which formed during the uplift, so the development of the drainage system and doline morphologies were basically determined by the tectonic pattern. Dolines such as those described at the top of the Nevado-Filabride marbles are one of the principal landforms in temperate-climate karsts but can also develop in warmer and colder extreme climates (e.g. White 1988, Ford & Williams 1989). Some of the dykes and small caves with rounded shapes in cross-section might correspond to hydrothermal passages.

We are dealing with a complex system with karst of interstratal and hypogene, possibly palaeohydrothermal origin. The karstified rocks are preserved chiefly in the carbonates since features in the weaker evaporites tend to anneal over the long burial times involved. Iron Age salt mines (ca. 2500 years BP), for instance, have closed up completely at Hallstatt, Austria, and are recognized only by tools now trapped inside the massive rock (Ford & Williams 1989).

Alluvial sedimentology

The analysed sedimentary environment corresponds to highlands undergoing rapid uplift in which local thin (< 20 m) alluvial sediments were preserved from erosion as hillslope sediments. We interpret these sediments as steep alluvial fans (2–25°) of limited extension (perhaps < 2 km). The indicated facies variability was controlled principally by climate and geomorphology. The fans were probably constructed mainly by catastrophic fluid gravity flows or sediment gravity flows generated through failure of bedrock cliffs or colluvial slopes. The primary deposits were remolded by secondary processes, such as wind erosion, overland flow of water, karstification and tectonics.

The transport distances between the sites of erosion and deposition were short, often only a few metres; consequently, these hillslope sediments usually retain the mixture of particle sizes derived from the erosion site, with little or no attrition, rounding, sorting or bedding evident in the final deposit. Such

sediments are seldom preserved in the geological record as they are easily subject to erosion by fluvial, periglacial and, less commonly, aeolian processes. Fortunately, in this case they were covered by the thick sheet of rocks that gravitationally slid over them and thus allowed their preservation.

Small debris-flow deposits in the *rauhwacke* body could also derive from translational landslides. The material is unsorted and ranges in size from coarse gravel to clay. Debris flows are an important form of mass movement in semi-arid zones and in more humid environments with a prolonged dry season, such as some 'Mediterranean' climate zones. Such debris flows often evolve into fluvial debris torrents on alluvial fans; the fluvial influence results in modifications of the debris-flow deposits, with the change from debris flows to fluvial transport often being gradational.

According to the fluvial sequence model of Shanley & McCave (1993), showing the relationship between shoreline and fluvial architecture as a function of base-level change, the deposition of these sediments corresponds to a falling stage systems tract, with the development of incised valleys and fluvial terraces, changing to a lowstand systems tract. Base-level lowstands also lead to the localized erosion of floodplains and to the development of incised valleys and flanking terraces.

Erosion and deposition of alluvial sediments may also accompany shallow overthrusts. As pointed out by Willemin (1984), the thickness of an advancing overriding rock sheet is a major determinant of the overburden stress and hence of the basal resistance to movement and the maximum stable length of the sheet. The sheet continues its advance as an essentially coherent slab until basal resistance exceeds its strength; thereafter, the slab breaks, imbrication and tectonic overlap occur, and the slab front ceases to advance. These relationships are well illustrated in the Keystone Thrust of Nevada, U.S.A., in which a mountain more than 4 km high advanced 25 to 50 km (Johnson 1981). That the displaced mass did indeed move across the land surface is demonstrated by stream channels now exposed beneath the thrust plane, under the displaced carbonate mass. These channels contain gravels derived from that mass, thereby heralding its approach.

Geometry and kinematics of the faults

As pointed out in the foregoing paragraphs, the Serón *rauhwackes* are usually overlain by a more or less thick slab of Alpujarride rocks. The boundary between the *rauhwackes* and the overlying rocks is a top-to-the-north low-angle normal fault that usually extends beyond the *rauhwacke* body to penetrate the neighbouring rocks, putting the Alpujarride rocks in direct contact with Nevado–Filabride material (Figure 2, map and section, Figures 3(A, B)).

From the geological mapping and the cross-cutting relationships it has also been concluded that the *rauhwacke* body and neighbouring rocks have been affected by several sets of faults showing slight differences in dip. Faults occupying the most northerly positions are usually the oldest and the most steeply dipping ones. This is illustrated by the rather steeply-dipping fault ('a', ca. 35°N) shown in the northern part of the cross-section in Figure 2 and by the fault in the El Marchal area (Figure 3(B: F)). Both faults have been cut by less dipping faults. This can be clearly seen in the cross-section (fault 'b') in Figure 2, and in Figure 3(B). Nevertheless, evidence of late movements along low-angle normal faults postdating the formation of more gently dipping faults that produce the anomalous superposition of Nevado–Filabride over Alpujarride rocks can also be found (Figure 2, map and central part of section).

The evidence described above suggests that the development of the different sets of north-dipping low-angle normal faults took place contemporaneously with the uplifting of the Sierra de los Filabres. Once the uplifting of this sierra started, faults developed preferentially along older detachments, e.g., the Alpujarride/Nevado–Filabride boundary, at sites where the equilibrium slope was exceeded, e.g., at a local topographical scarp, and the sliding of rock sheets occurred. The gravitational faults thus generated, as well as the other pre-existing surfaces such as bedding, foliation, and sedimentary laminations within the *rauhwacke* body, underwent an increase in dip towards the north during subsequent uplifting movements of the sierra. During these uplifting and widening movements, new low-angle normal faults developed that cut across the older and now steeper ones, producing the kind of geometry existing in the northern part of the Sierra de los Filabres.

The age of the rauhwackes in the northern Sierra de los Filabres

Several attempts to find fossils have been made. A search for micromammalian remains in the fine-grained portion of the rauhwackes proved to be unsuccessful. Therefore, the rauhwackes must be dated on indirect evidence.

The development of a karst surface at the top of the Nevado–Filabride marbles implies direct aerial exposure. The Miocene tectonic unroofing of the Alboran Domain accounts for the strong thinning of the units overlying the Nevado–Filabride rocks. It must be stressed that the Serón area corresponds to a high-extension area (Gibbs 1984), due to the intersection of the Contraviesa and Filabres extensional fault systems, which are of Langhian and Serravallian age respectively (Figure 1). Thus, the Nevado–Filabride marbles were not exposed to weathering before the end of the Serravallian. This is consistent with the fact that the first clasts of Nevado–Filabride provenance generally appear in Early Tortonian sediments (e.g., Briend et al. 1990). Moreover, the rauhwacke body is folded. The sedimentary stratification within the rauhwackes generally dips toward the north, due to the Sierra de los Filabres antiform (Figures 1, 2). The E–W directed folds have been dated as Late Tortonian close to the Messinian boundary in the Sierra Alhamilla area (see ‘Geological setting’). This structural evidence constrains the maximum age of the rauhwackes to the latest Serravallian and their minimum age to the latest Tortonian.

In addition, in the Almanzora basin, situated immediately to the north of the Sierra de los Filabres, an undated continental formation, composed of large angular blocks of Nevado–Filabride provenance, is overlain by a reef formation dated as earliest Tortonian by Guerra-Merchán (1993). According to this author, the continental sediments are related to the existence of steep northward facing slopes. Both formations are dipping towards the north in the southern border of the Almanzora basin, and are unconformably covered by horizontal layers of a sands and gravels formation dated as Late Tortonian (lower part of *Neogloboquadrina humerosa* Zone, Guerra-Merchán 1993). Thus, the large antiformal structure of the Sierra de los Filabres developed probably between the earliest Tortonian and the latest Tortonian, which is also the time interval during which the Serón rauhwackes were deposited, folded, and finally covered by Alpujarride rock sheets due to gravity sliding. This is consistent

with the presence of abundant carbonate rock fragments of Alpujarride provenance within the sands and gravels formation (Guerra-Merchán 1993), as the Alpujarride rocks which overlapped the rauhwackes at the end of the Tortonian supplied sediments to the Almanzora basin.

Although a Tortonian age for most of the rauhwacke body of Serón seems to be probable, it cannot be excluded that some rauhwackes developed after a second or third episode of karstification of the previous rauhwackes.

Conclusions

The foregoing paragraphs present sedimentological, geomorphological and geometrical evidence indicating that most of the rauhwackes of the Serón area are subaerial or nearly subaerial sediments. These sediments are of continental, alluvial and karstic origin and developed over dolomites and marbles. The sedimentary facies analysis suggests that the erosion of a rapidly evolving relief probably predates the formation of the rauhwackes. An astonishing feature of the Serón rauhwacke body is the superposition of an Alpujarride rock sheet, several hundred metres thick, over the rauhwacke body, involving important subaerial mass sliding. In fact, the geometry of the upper boundary of the rauhwacke body, and the relationships between the different sets of north-dipping normal faults analysed above, can be used to attempt a reconstruction which requires the uplifting of a mountain range south of the study region. The following succession of events may be envisaged (Figure 5):

- 1) The starting situation at the end of the Serravallian was represented by a partially outcropping Nevado–Filabride Complex underlying a dismembered and tectonically thinned Alpujarride Complex as a result of Miocene extension. Material resulting from denudation of the upper Alpujarride sheet accumulated at the base of the expanding Almanzora basin (phase 1). Weathering and karstification of the locally uncovered Nevado–Filabride marbles could start.
- 2) Alluvial sediments, the future rauhwackes, formed along the fast-growing reliefs, due to the doming of the Sierra de los Filabres in the south and the development of new north-dipping normal faults. These sediments are mainly hillslope sediments. As the Sierra de los Filabres rose, collapse structures and normal faults that occasion-

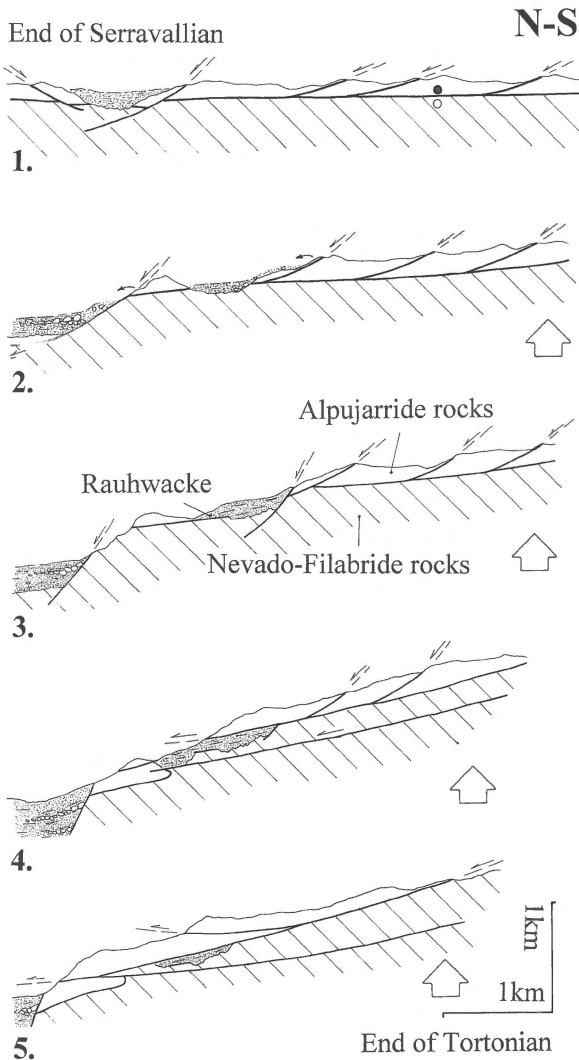


Figure 5. Schematic reconstruction showing the development of rauhawackes and their relationship with the doming (large arrows) of the Sierra de los Filabres, from end Serravallian up to end Tortonian. Phases 1 to 5 are explained in the 'Conclusions'.

ally coalesced with the older Alpujarride/Nevado-Filabride detachment formed. Breccias and other detrital material accumulated at the feet of the scarps and within the irregular cavities generated by the karstification of the marbles. Repeated karstification probably affected the underlying marbles and previously formed rauhawackes (phases 2 and 3).

- 3) In some northern sites of the growing Sierra de los Filabres, where the equilibrium slope was exceeded, gravitationally-induced slides developed. Sheets of Alpujarride rocks advanced down-slope

over the underlying Nevado-Filabride rocks and, locally, were superposed over the rauhawackes deposited at the foot of an old scarp. Low-angle normal faults and perhaps also gravity-induced thrusts, north-vergent folds and other gravitationally driven structures also formed (phase 4). Anomalous superpositions of Nevado-Filabride rocks over Alpujarride ones were also formed in this way (phase 5). Repeated mountain-slope steepening may have given rise to an increase in dip and a reactivation of older faults and to the formation of new ones that cut across older and usually steeper faults.

The origin of the analysed rauhawackes appears to be a complex interaction of a) sedimentation in small alluvial fans, b) the polyphasic karstification of evaporites, dolomites and protoliths of the rauhawackes, under different conditions from subaerial to possibly hydrothermal, and c) tectonics linked to the late, gravitationally-induced emplacement of the Alpujarride rock sheets which seal the rauhawacke body.

Acknowledgements

Financial support from the Dirección General de Enseñanza Superior e Investigación Científica, grants PB95-1219 (M.O & F.M.A-C), PB96-0429 (J.M.M) and PB96-0924 (A.C-B) is acknowledged. Comments and suggestions from two anonymous reviewers and D.A.J. Batjes are also acknowledged. The assistance of A. Ruiz Bustos, palaeontologist of the Instituto Andaluz de Ciencias de la Tierra (Consejo Superior de Investigaciones Científicas – Universidad de Granada) is also gratefully acknowledged. Thanks are also given to C. Laurin for her assistance with the English version of the manuscript.

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