The Upper Permian Boniches Conglomerates Formation: evolution from alluvial fan to fluvial system environments and accompanying tectonic and climatic controls in the southeast Iberian Ranges, central Spain

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Abstract

The Boniches Conglomerates Fm. (Upper Permian) represents the first episode of sedimentation in the southeast border margin of the Iberian Basin, central Spain. The Iberian Basin commenced development as a rift basin running mainly NW–SE during the Early Permian and underwent its first general extensional period during the Late Permian. The Boniches Fm. was deposited as a small segment (less than 100 km long and 9–10 km wide) of the Iberian Basin that extended in a northeast direction during this period.

Detailed mapping and palaeocurrent analysis have shown that the Boniches Fm. is of a curvilinear, wedge-shaped morphology. Sediments close to the southwest main faulted border are of a maximum thickness of 230 m. Clear lateral variation in thickness controlled by the activity of secondary transfer faults perpendicular to the main NW–SE axis may be observed. This network of faults permitted the formation of blocks, limited laterally by the transfer faults. These blocks experienced subsidence and rotation against the elevated southwest footwall block which resulted in the isolation of reduced sub-basins with different sedimentary characteristics.

Based on facies and facies association, the Boniches Fm. is thought to have evolved vertically from two main alluvial fan systems in the lowest part of the formation, into fluvial braided systems flowing southeast. As expected, no flow orientations towards the footwall block are observed during the first episodes of the refill. This may be explained by erosion, or simply a lack of sedimentation due to the gentle slope. The change from alluvial fan to fluvial environments is interpreted as a relatively sudden tectonic reorganization of the whole segment favouring new longitudinal fluvial drainage from a transfer zone located to the northwest. Three different reorganization episodes, clearly marked in the Boniches Fm. as 'main boundary surfaces' (MBS) separate four members subdivided into 4–5 levels (3–4 m thick). Each level consists of fining-upward successions less than 1 m thick.

Tectonics and climatic factors clearly controlled sedimentation. Tectonic activity was probably of greatest importance and was conditioned by the movement of the main NW–SE and NE–SW transfer faults. The role of climate in ancient conglomerate sediments has not been well established. Palaeogeographical, mineralogical, sedimentological and clast analyses suggest that the Boniches Fm. was deposited under humid conditions by running water.

The differentiation between 'proper' alluvial fans and fluvial environments during the transition period of the Boniches Fm. is not clear since, in many recent alluvial fans, braided fluvial systems are associated with fans.

Keywords: fluvial; fans; tectonic control; climatic control; rifts; Permian

1. Introduction

The Boniches Conglomerates Fm. was initially described by López-Gómez and Arche (1985) and was interpreted as mainly consisting of alluvial fan deposits. Its present geographical extension is very reduced, cropping out basically at five outcrops related to anticline cores located in the south of the present Iberian Range, eastern Spain (Fig. 1). The sediments are of the early Thüringian (Late Permian) period, as dated by pollen and spore association (Doubinger et al., 1990). The sediments always lay unconformably on the Ordovician quartzites and slates or, locally, on the Tabarreña Breccias Fm., or on Stephanian (Upper Carboniferous) sandstones and coals (López-Gómez and Arche, 1993) (Fig. 2).

The scope of the present study includes interpretation of the sedimentary environments of the Boniches Fm. and the effects of tectonics and climate during sedimentation. The study is based on detailed mapping, sedimentary facies and mineralogical analyses of data related to the general and local tectonic evolution of the basin in which the Boniches Fm. was deposited. This basin represents only a segment of the larger intracontinental rift basin, the Iberian Basin, that evolved in the southern border of Pangea until invasion by the Tethys sea during the Middle Triassic period (Sopeña et al., 1988; Arche and López-Gómez, 1996).

The difficulties encountered during the study include the detailed estimation of the age of the sediments required to establish sedimentation and subsidence rates. Another difficulty related to climate, consists of the general lack of palaeoclimatological indicators present in conglomerates. It is important to emphasize that alluvial fan deposits in ancient settings have formed the subject of very few investigations in comparison to those of more recent origin. Studies on fans developed under humid conditions are of an even rarer nature.

To date there is much controversy as to whether sediments seen in ancient records were in fact deposited as a fan, or deposited as a fluvial system related to that fan. The first studies on alluvial fans and their processes date back to the past century and the beginning of the present (e.g. Drew, 1873; McGee, 1897; Knopf, 1918). Recently, this controversy has been well discussed (Lecce, 1990; Blair and McPherson, 1994a,b) and some interpretations of classical examples, such as those of Hooke (1967); Bull (1972), Boothroyd and Nummedal (1978), Miall (1981) and Nemec and Steel (1984, 1988) have been questioned.

2. Tectonic and palaeogeographical setting

The Boniches Fm. shows an unconformable base on the Ordovician–Silurian basement, Stephanian sandstones or Autunian breccias. It represents the beginning of a sedimentary cycle that started during the first stages of the evolution of the Iberian Basin (Arche and López-Gómez, 1996). At the end of the Carboniferous period, the Iberian microplate was part of the Hercynian or Variscan Belt, a wide linear structure affected by intense deformation and magmatism from the southern Appalachians to the Bohemian Massif. This structure emerged due to the collision between the following different plates: Laurentia, Fennoscandia, Africa and several southern European microplates (Dewey and Burke, 1973; Ziegler, 1988).

The present-day Iberian Ranges started development as a rift basin during the Early Permian and experienced the first extensional periods during the Late Permian (Fig. 3). The present orientation of the Iberian Basin probably originated due to the field of stress created during the opposing movements of two transcurrent fault systems (Pyrenees–Biscay Gulf to the north and Gibraltar–Chedabucto to the south) during the Permian (Arthaud and Matte, 1977; Arche and López-Gómez, 1996) (Fig. 4A). This stress created movements along a series of NW–SE normal faults

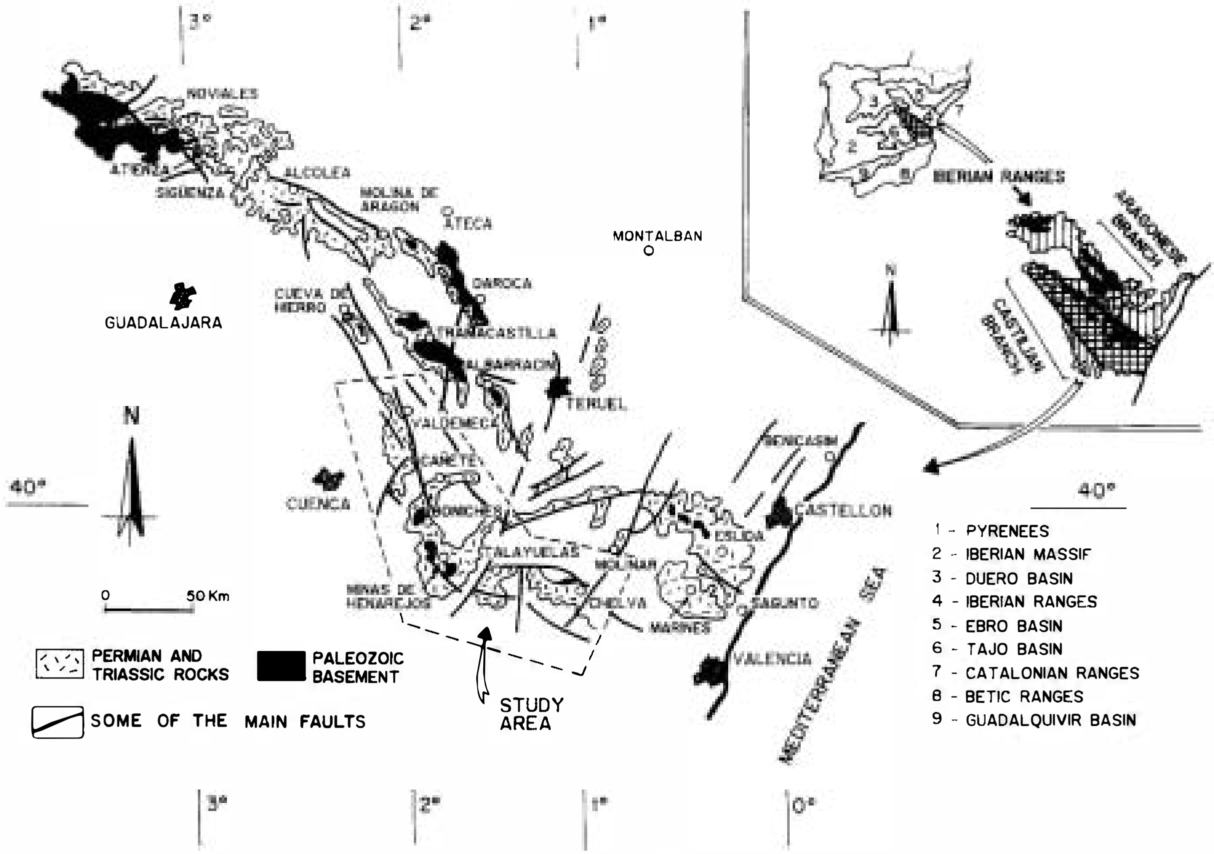


Fig. 1. General location of the study area.

at the end of the Permian (Fig. 4A), allowing the development of the rift systems, probably associated with localized contemporary volcanism and granitization episodes in the Iberian Basin (Arche and López-Gómez, 1996). Permian basins, associated with old Hercynian chains, developed in central Europe in a similar manner (Menard and Molnar, 1988).

The Iberian intracratonic rift basin initially evolved into different, subdivided segments or asymmetric sub-basins (Fig. 4) (Arche and López-Gómez, 1996) similar to that described for the recent evolution of the Great Eastern African Rift (Versfeld and Rosendahl, 1989). The present study focuses on the first stages of the evolution and infill of one of these segments (Fig. 4A). Based on detailed mapping and palaeocurrent analysis, a curvilinear wedge-shaped morphology of the segment was observed. This segment was separated from similar neighbouring basins by transfer areas. The Serranía de Cuenca fault represented the main southwestern border for this southeast part of the Iberian Basin (Fig. 4B), defining the drainage pattern inside the interior sub-basins. The small basin (less than 100 km long), in which the Boniches Fm. was deposited, was conditioned by the movement of different subsidiary interior blocks and also limited by curvilinear minor faults (less than 15 km long) (Fig. 4B) similar to those described by Ebinger et al. (1984, 1987) and Frostick and Reid (1987).

3. The sediments: lithology, sedimentary characteristics and their interpretation

The Boniches Fm. currently covers an area 72 km long (NW–SE) by 9 km wide (NE–SW). It is composed of two main outcrops (Boniches and Henarejos) and two smaller ones (Talayuelas and Chelva) sedimentologically associated with the latter

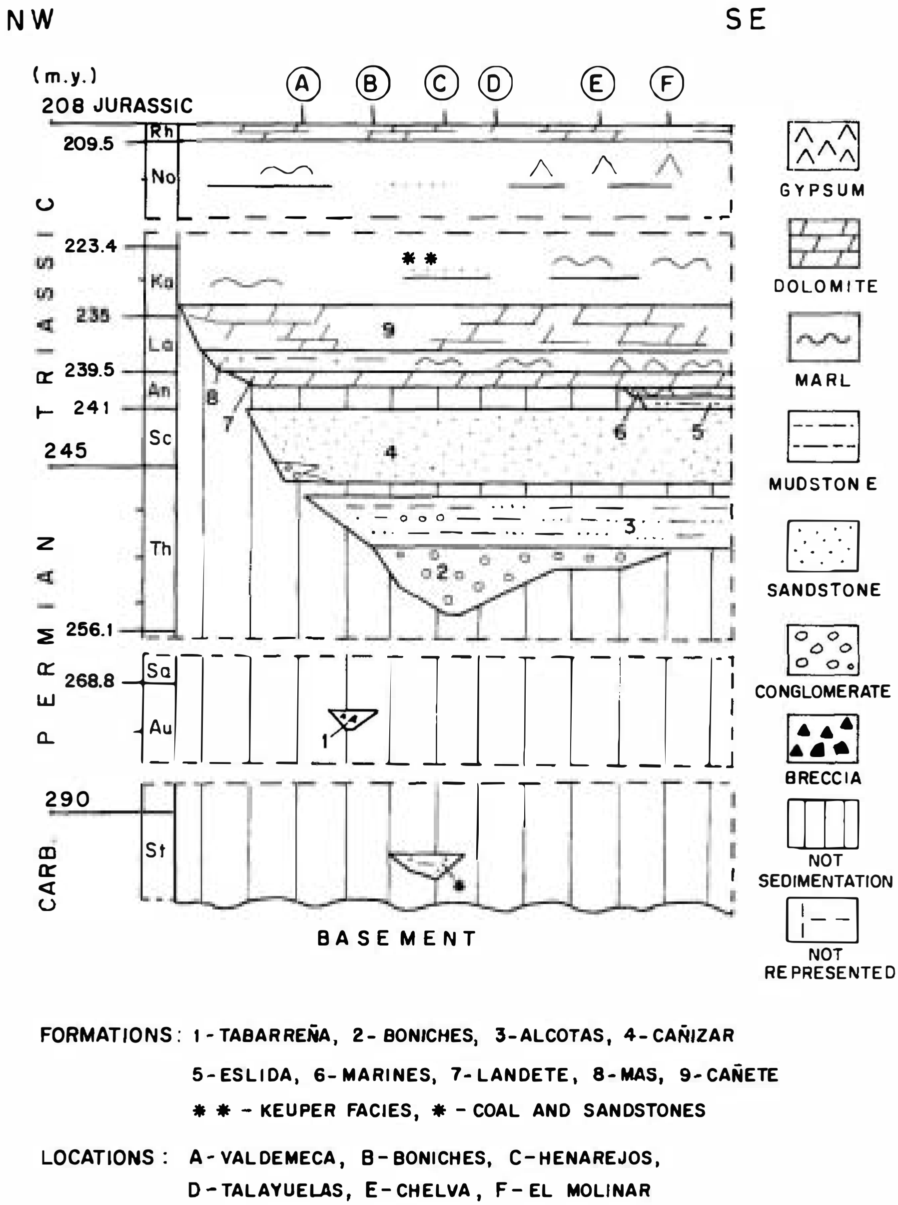


Fig. 2. Stratigraphical location of the Boniches Conglomerates Fm. in the general stratigraphical framework of the southern part of the Iberian Ranges. See Fig. 1 for geographical points. *St* = Stephanian, *Au* = Autunian, *Sa* = 'Saxonian', *Th* = Thüringian, *Sc* = Scytian, *An* = Anisian, *La* = Ladinian, *Ka* = Karnian, *No* = Norian, *Rh* = Rhaetian.

(Fig. 5). The sedimentological study was based on ten detailed logs (Fig. 6) plus detailed mapping of the whole outcrop area and the major and minor faults of the basin.

Sedimentation of the Boniches Fm. was conditioned by a marked Ordovician–Silurian palaeorelief composed of valleys incised on quartzites and slates, and locally infilled with Autunian sediments (debris flow sediments of the Tabarreña Fm.) (López-Gómez and Arche, 1994) (Fig. 7) or Stephanian sandstones with coal (Fig. 2). The palaeorelief and the style of the synsedimentary tectonics allowed an important lateral thickness change in the sediments ranging from 230 m in the central part of the basin (Henare-

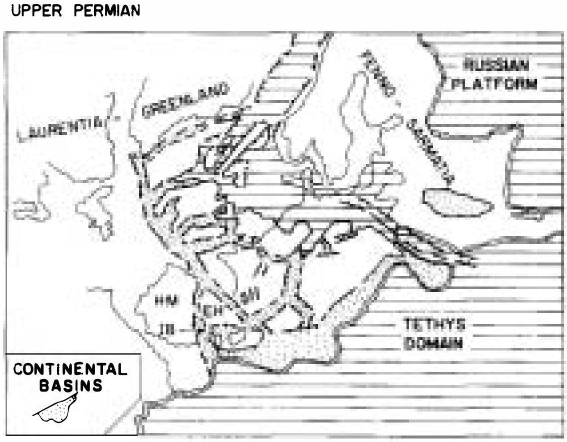


Fig. 3. Tentative reconstruction of the palaeogeographical location of the Iberian Basin during the Upper Permian. *IB* = Iberian Basin, *HM* = Hercynian Massif, *EH* = Ebro High. White zones represent elevated areas.

jos area) to less than 20 m in the northwest and southeast ends (Figs. 5 and 6).

3.1. Lithology

The Boniches Fm. is composed of packets 3–4 m thick, separated by thin sandstone layers less than 0.6 m thick (Fig. 8). The conglomerates are composed mainly of quartzite clasts, but also contain a reduced proportion of slates (<1%) occurring in layers close to the basement. The matrix is mainly composed of arkoses of medium grain size. The conglomerates are clast-supported, with the exception of the uppermost parts of the formation. In this region they are supported by the matrix.

Quartzite clasts are mainly subrounded although subangular and round-shaped specimens also appear in the lower and upper parts of the formation, respectively. The largest clasts measure up to 37 cm towards the upper part of the formation. Mean values range between 5 and 13 cm in most of the layers (Fig. 9). Only a few angular quartzite blocks from the basement exceed 60 cm. Fig. 9 shows the lack of abrupt change in clast size between layers in the evolution of the formation.

Fig. 10 shows the mineralogical composition of the sandstone which consists mainly of phyllosilicates, quartz, haematite and feldspars. The clay is composed of illite, pyrophylite and kaolinite. The general mineralogical composition shows that there is a marked change at the top of the lower third of the standard log (log A, Fig. 6). This shows a reduction in the quartz and pyrophyllite content and an increase in phyllosilicate and illite levels as far as the upper third of the log. Here, kaolinite shows

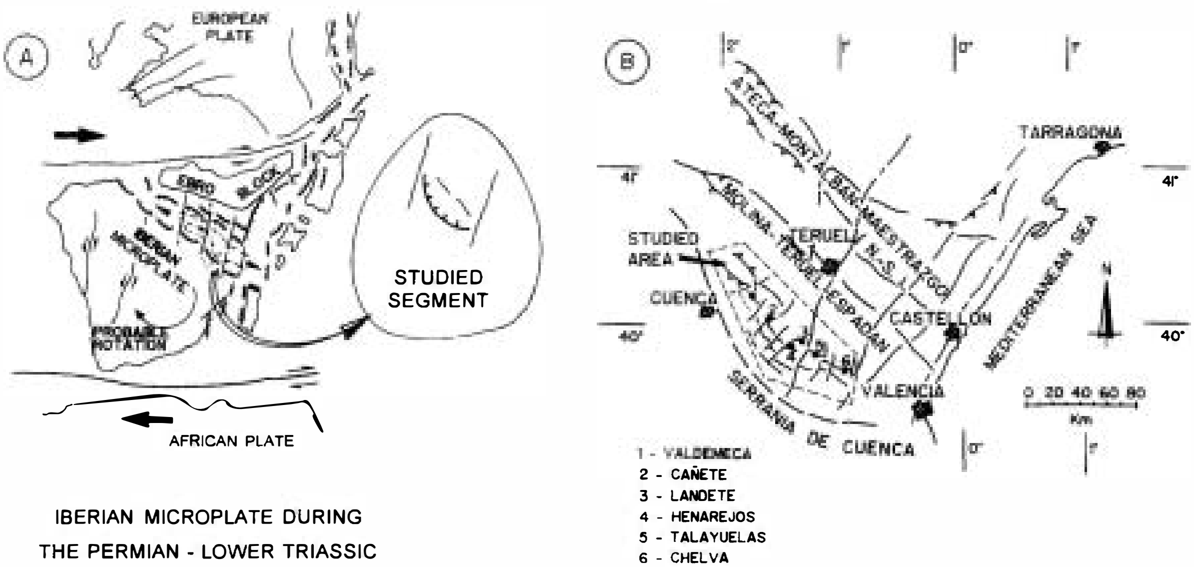


Fig. 4. (A) The Iberian Rift Basin of the Iberian microplate during the Permian–Early Triassic. Location of the study segment. (B) Sketch of the present day main NW–SE faults and the transversal NE–SW secondary faults of the Iberian Basin. The segment indicated in (A) corresponds approximately to the studied area in (B).

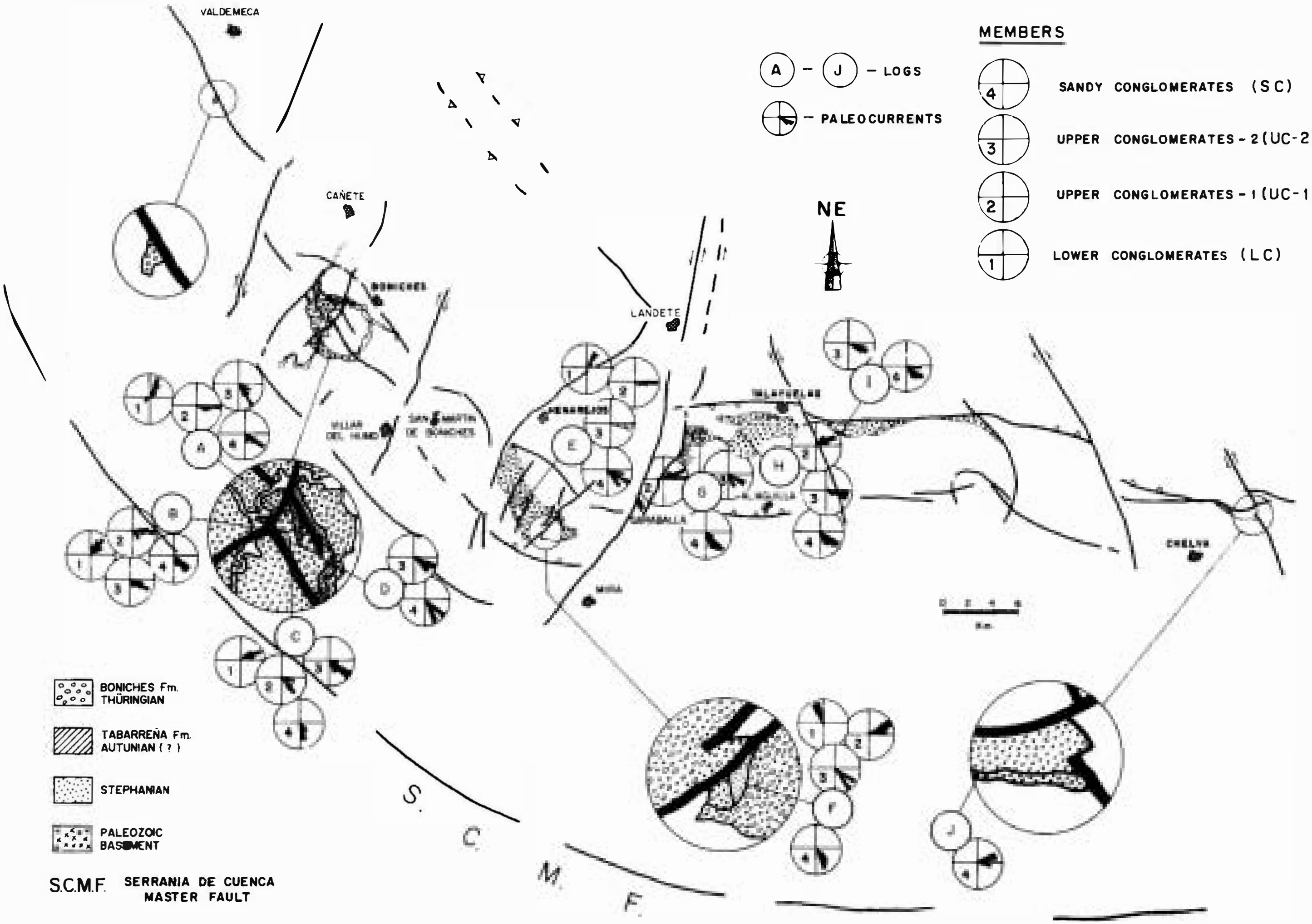


Fig. 5. Mapping of the Boniches Conglomerates Fm. showing main and secondary faults. Palaeocurrents (mean) are indicated in the outcrops for the different members (*1–4*) into which the Boniches Fm. is subdivided. See Fig. 2 for lithology and location of the Tabarreña Fm. and Stephanian sediments. See Fig. 6 for the location of logs *A* to *J*. More detail about palaeocurrents are included in Fig. 6.

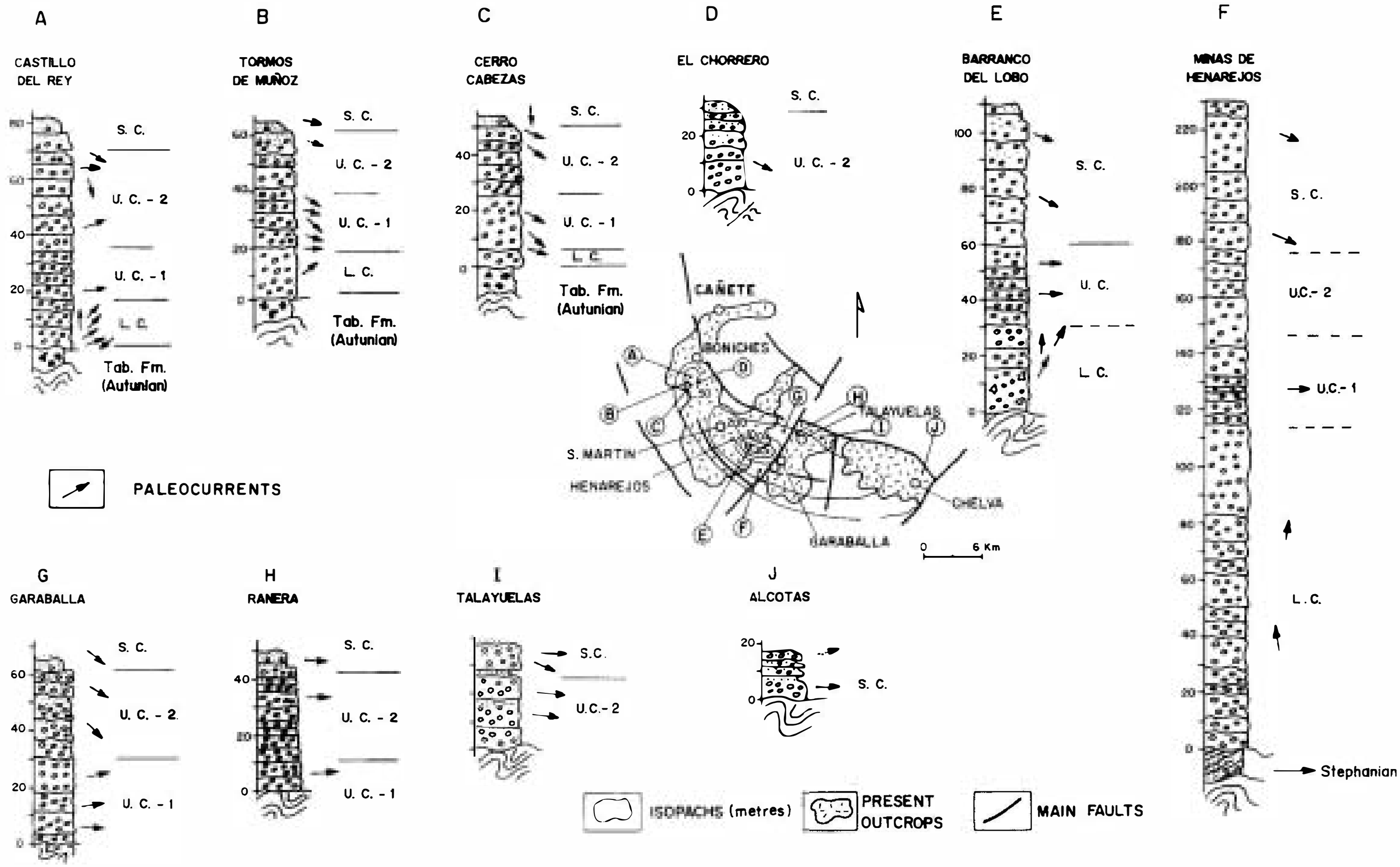


Fig. 6. Logs showing vertical evolution of the palaeocurrent trends and isopachs for the Boniches Fm. Members: *L.C.* = Lower Conglomerates, *U.C.-1* = Upper Conglomerates-1, *U.C.-2* = Upper Conglomerates-2, *S.C.* = Sandy Conglomerates. See Figs. 1 and 5 for more detailed geographical location. Arrows represent individual palaeocurrent measurements.

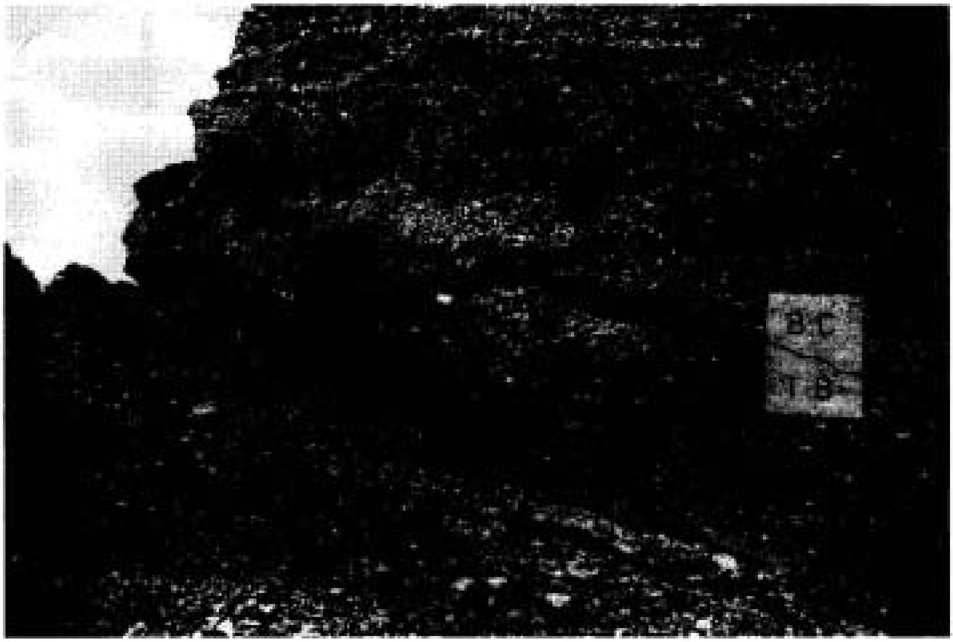


Fig. 7. Unconformity between the Boniches (*BC*) (Upper Permian) and Tabarreña (*TB*) (Autunian?) Fms. 2 km south of Boniches village (see Fig. 5 for location). Note-book in the centre of the picture measures 18 cm.

Fig. 8. General view of the Boniches Conglomerate Fm. in the Castillo del Rey section (see Fig. 6 for location). The formation consists of conglomerate packets (3–4 m thick) separated by thin (less than 0.6 m thick) sandstone layers. The picture was taken from south to north. The width of the road is 6.5 m.

a clear and progressive decrease and pyrophyllite disappears.

3.2. Facies description

Few sedimentary structures have been observed in the Boniches Fm. Low- and high-angle planar cross-stratifications are most abundant with a reduced number of trough cross-stratification, imbrications and reactivation surfaces. Planar laminations and current ripples appear in the intercalated sandstones.

A total of 238 palaeocurrents have been measured (Fig. 6) mainly from imbrications (13%), cross-bedding (61%), channels and scours (17%) and parting lineation (9%). A clear N45°–65°E direction towards the base of the formation, evolving sharply upwards to N 80°–90°E and then to N130°–175°S towards the top of the formation (Figs. 5 and 6) may be observed.

The lithology, sedimentary structures and palaeocurrents differentiate four members: Lower (LC), Upper-1 (UC-1), Upper-2 (UC-2) and Sandy (SC) conglomerates from bottom to top respectively (Fig. 11). Each one is separated from the following member by a clearly defined major boundary surface (MBS): MBS-1, 2 and 3 from bottom to top respectively. The MBS do not only separate these members but also indicate an overall, gentle change in the dip of each member.

The packets of each member are composed of different thinning-upwards sequences, 24 to 52 cm thick. Coarsening-upwards and normal-reverse to thinning-upwards sequences are, in general, very scarce (Fig. 9). The lower members sometimes disappear laterally or wedge out due to marked palaeorelief (Fig. 6). However, when present, these show the same general sedimentary characteristics to the area under study.

The different facies and facies associations are defined from the main sedimentary characteristics and lithologies of each member. The terminology used to define and interpret these facies is similar to that used by Miall (1977, 1978) and Rust (1979). The main sedimentary characteristics of the facies in the Boniches Fm., including fabric, sorting, distribution and sequence type are summarized in Table 1 and Fig. 12.

4. Depositional environment interpretation

Many of the textural and sedimentary structural features of the Boniches Fm. described above have been previously described for both modern (Bull, 1964; Ore, 1964; Boothroyd and Ashley, 1975; Hein and Walker, 1977) and ancient (McGowen and Groat, 1971; Bull, 1972; Larsen and Steel, 1978; Bluck, 1980; Middleton and Trujillo, 1984) alluvial fan–braided stream settings. Recently, Blair and McPherson (1994a) have described what they consider to be basic characteristics to differentiate alluvial fan deposits from those of fluvial origin. These criteria are based on sedimentary processes, facies associations, hydraulic processes and morphology.

The present study of the sedimentary processes in the Boniches Fm. is based on the differentiation and interpretation of associations of the facies mentioned above.

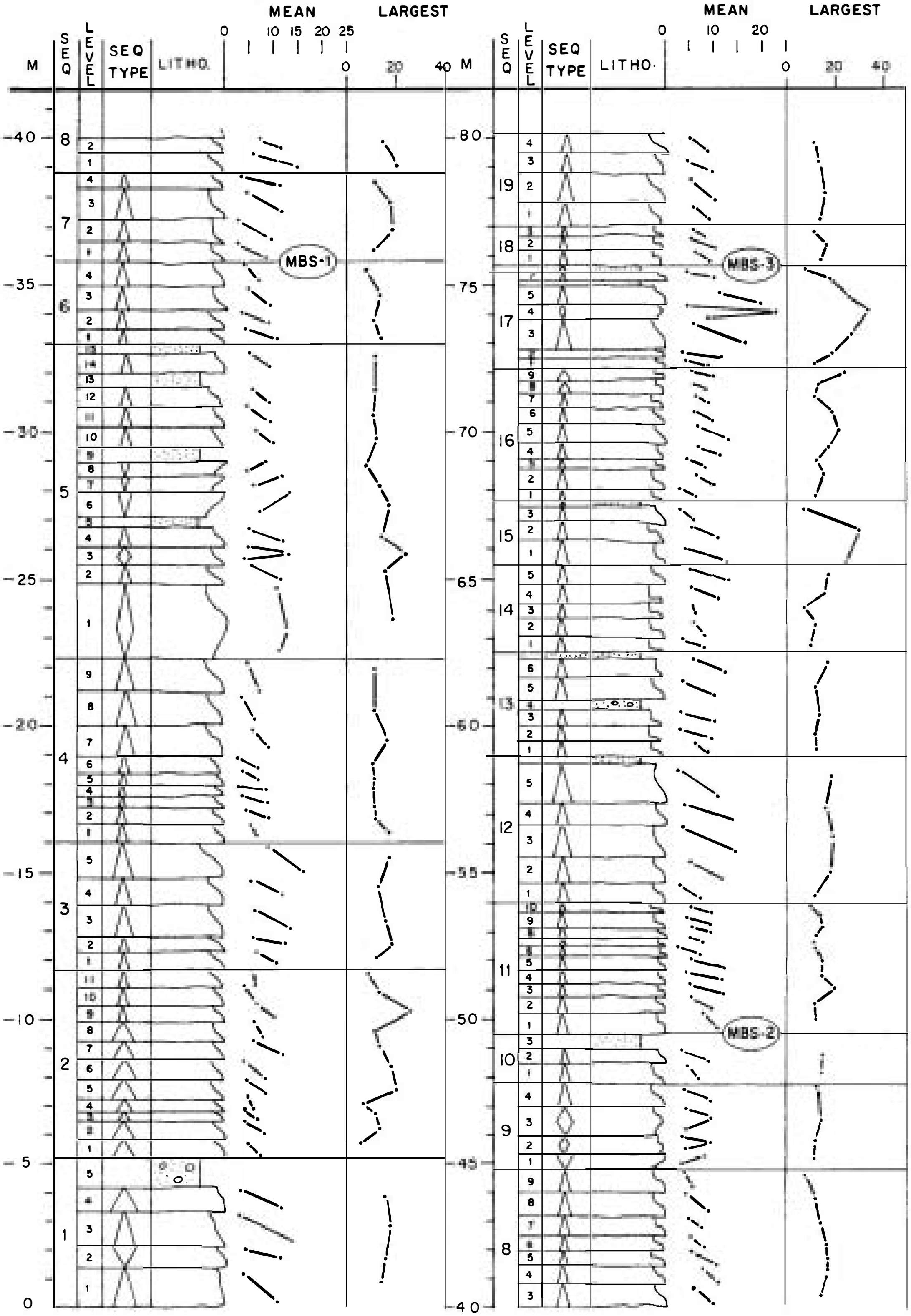
4.1. Facies associations

Six vertical facies associations were observed in the Boniches Fm. (I–VI). These appear vertically distributed between the formation members and are generally incompletely preserved. Fig. 13 summarizes these facies associations and their main characteristics.

4.2. Depositional environments

According to facies and facies association analysis, the Boniches Fm. shows basic sedimentary characteristics that could be classed as having been deposited within alluvial fan and braided fluvial systems. Alluvial fan systems have been observed in the lower part of the LC member and in the upper parts of the LC member deposits. In contrast, braided fluvial systems are seen in the upper LC and UC-1, UC-2 and SC members. In view of the change in the general sedimentary characteristics observed above and below the MBS-1 level (Fig. 14), the transition from the alluvial fan to the fluvial environment is thought to have occurred in a relatively short period of time.

Each MBS (1, 2 and 3) represents general changes in sedimentary style that include palaeocurrents (Figs. 6 and 7), clast features (Fig. 9), petrologic


M
SEQ
LEVEL
SEQ TYPE
LITHO.
MEAN
0 10 15 20 25
LARGEST
0 20 40
MBS-1
MBS-2
MBS-3
-40
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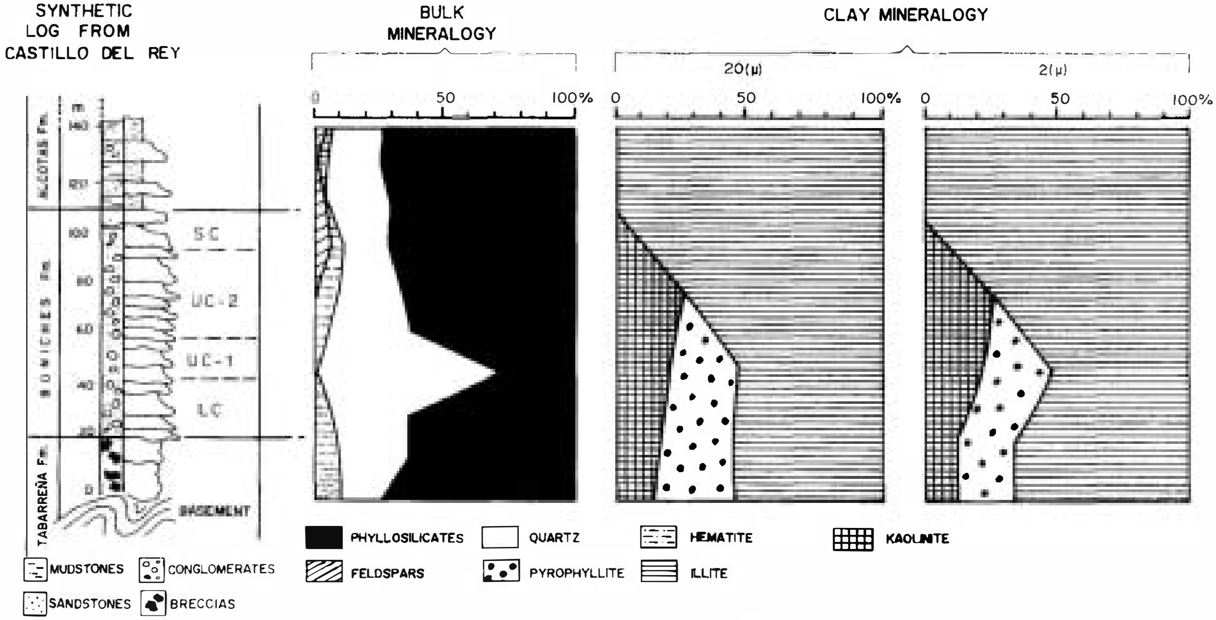


Fig. 10. Bulk and clay mineralogical vertical evolution of the Boniches Fm. including part of the lower and upper units. Synthetic log from Castillo del Rey (see Figs. 5 and 6 for geographical location).

and clay mineralogy content (Fig. 10) and sedimentary structures (Fig. 12).

A set containing vertical sequences of *Gt* facies may indicate gradual channel filling. In general, the absence of planar cross-stratified conglomerates, accompanied by sets smaller than 1.5 m, indicates that flow was considerably more shallow in facies association III in comparison to facies association II. These are clearly separated by MBS-1 (Fig. 13). A new increase in energy was detected above the MBS-2 since facies association IV contained sets with thicker *Gp* facies in addition to the reappearance of *Gm* facies (facies association V). Finally, the MBS-3 separates facies association VI at the top of the Boniches Fm., where sets composed of *Gp* and *Gt* facies are of least thickness with a very gentle angle (sometimes with transition into horizontally bedded units). Furthermore, there is a high content of sandstone indicated by the *St* and *Sp* facies which suggests that deposition is near the transition to upper stage plane beds (Røe, 1987) bearing forms that indicate episodes of cut-and-fill in shallow scours (Smith, 1990).

As previously stated, facies *Gms* and *Gm* were mainly included in the LC member and were very close to one of the main synsedimentary faults (Figs. 5 and 15, I). These facies probably defined the fan perimeter and the influence of proximal braided systems generated by the migration of longitudinal bars which indicate a high-energy fluvial system (Fig. 16). Palaeocurrents were to the northeast, perpendicular to the cited main fault.

An increase in deposits, interpreted to represent transverse or linguoid bars, and the increasing amounts of coarse-grained sand towards the top of the Boniches Fm., suggest vertical change from a proximal to a more distal alluvial setting. UC-1, UC-2 and SC members clearly correspond to an abrupt change in palaeocurrents (Fig. 15, III). Palaeocurrents at the base of the LC member could

Fig. 9. Clast vertical evolution in the Boniches Fm. including largest and mean (in cm) for the levels and elementary sequences differentiated in the Castillo del Rey outcrop (see Fig. 6A for location). No represented lithology in the log (in white) indicates conglomerates and dotted levels indicate sandstones. Sequence type is fining-upward when arrow points upward and coarsening-upward when arrow points downward.

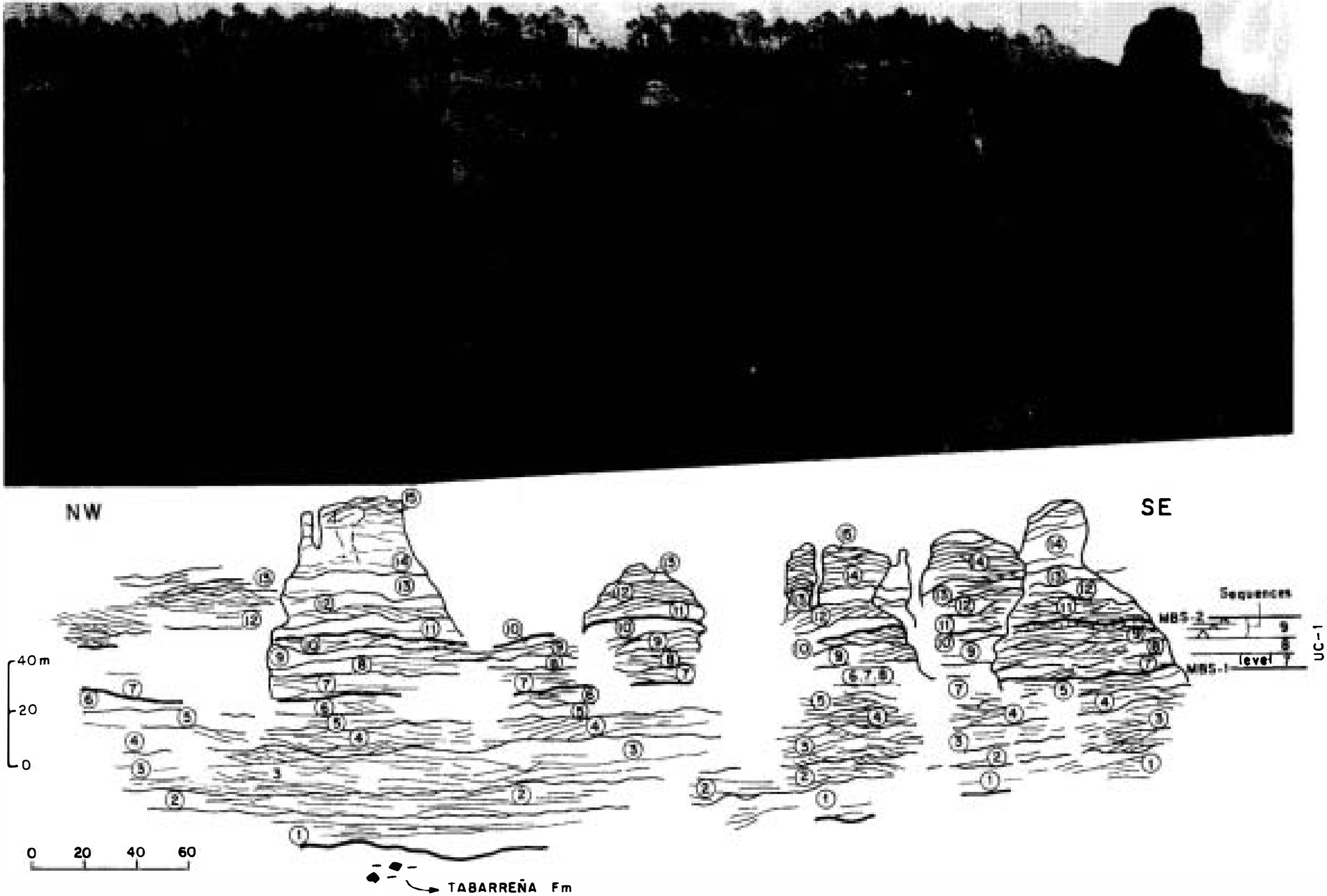


Fig. 11. General view and architectural reconstruction of the Boniches Fm. in the Castillo del Rey outcrop (see Fig. 5A for geographical location). Wider lines indicate major bounding surfaces (MBS) that separate members composed by different levels represented by numbers in this figure. Each of these levels is composed of centimetric sequences as shown on the right side of the figure (see this detail also in Fig. 9). The Tabarreña Fm. appears unconformably below on the left side.

Table 1
Summary of the main sedimentary characteristics of the facies observed in the Boniches Fm

Facies	General characteristics	Characteristics in the Boniches Fm.	Interpretation	Refs.
Gms	Massive or crudely horizontal stratification, matrix to clast-supported conglomerates.	Appears in the LC member. Grading almost absent.	Mass flows. Deposition from highly concentrated sediments with very small dispersion.	Miall (1978), Rust (1979), Allen (1982), Todd (1989).
Gm	Massive or crudely bedded, bimodal to polimodal clast-supported conglomerate	Appears in the LC and UC-2 members. Show good vertical organization. Normal grading in almost every bed.	Longitudinal bars and diffuse gravel sheets. Presence of waning flows and flashy hydrological regime.	Steel and Thompson (1983), Nemec and Steel (1984).
Gt	Through cross-stratified conglomerate	Although not very abundant it appears all along the Fm. Troughs up to few metres wide.	Channel fill. Migration of transverse bars with curved crest lines	Rust (1979), DeCelles et al. (1991), Miall (1985)
Gp	Planar cross-stratified conglomerate.	Very common in the whole of the Fm. Sets can be followed for more than 45 m. Commonly overlain by sandstones	Linguoid or transverse bars. Falling stage modification of the downstream margin of longitudinal bars.	Whiting et al. (1988), Allen (1983), Miall (1978), Smith (1990), Rust (1978).
St	Trough cross-stratified sandstone.	Appears in UC-2 and SC members. Constitute cosets up to 80 cm thick and cosets up to 45 cm thick.	Dune migration.	Miall (1978), Allen (1983), Røe (1987), Smith (1990), Southard (1971).
Sp	Planar–tabular cross-stratified sandstone.	Appears only in the SC member. Moderate sorting	Linguoid bars and dunes migration.	Miall (1978) Miall (1996), Bluck (1971).
Sh	Horizontally stratified sandstone.	Individual horizontally stratified sets are less than 8 cm thick. Lateral extent is on the order of 8 m.	Planar bed flow in upper regime	Allen (1968), Harms et al. (1982), Røe (1987).

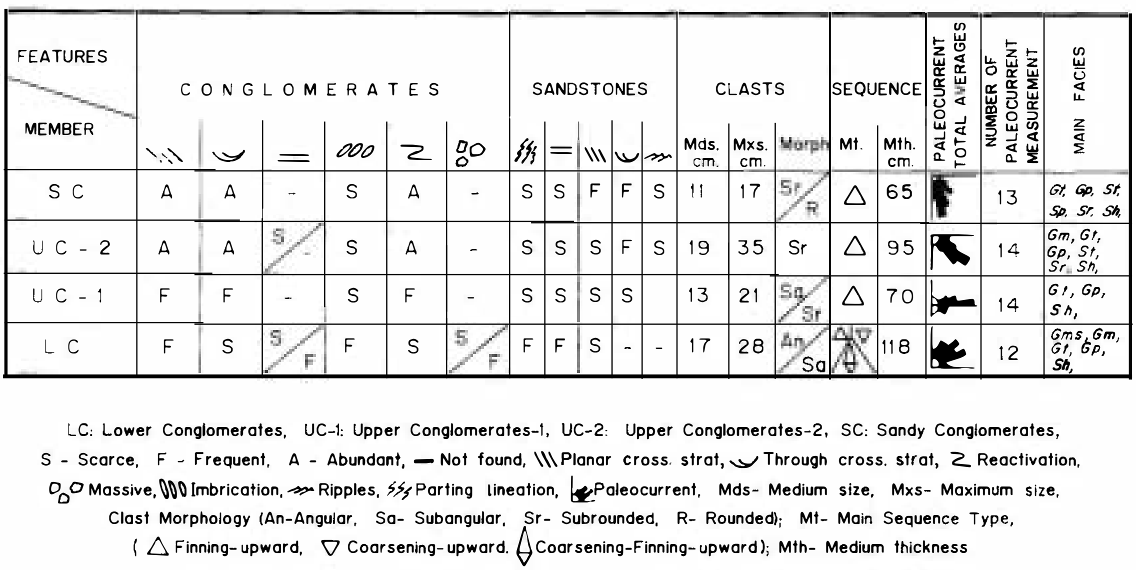
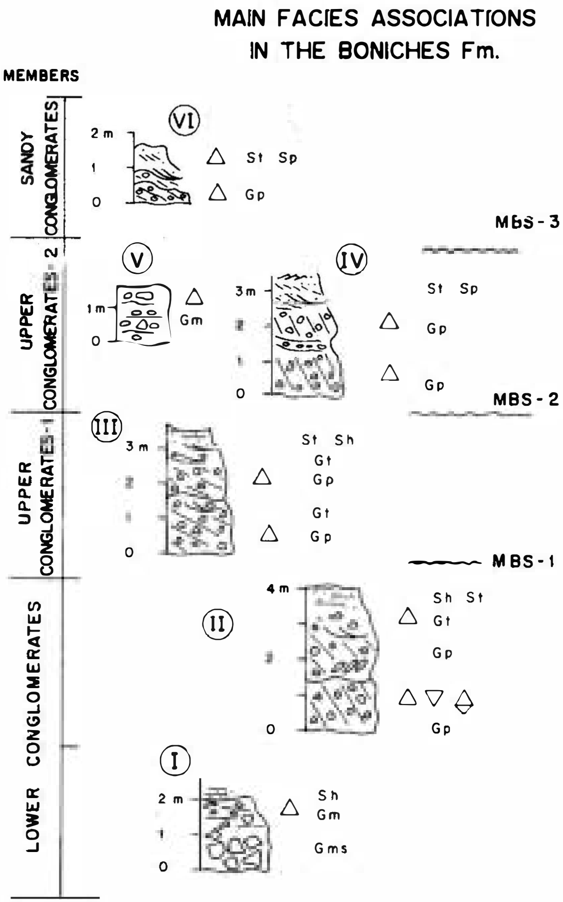


Fig. 12. Main sedimentological features of the conglomerates and sandstones and main features of the clasts, sequences and palaeocurrents of the Boniches Fm. for each of the four differentiated members. For more details of palaeocurrents see also Figs. 5 and 6.



SOME MAIN FEATURES	PARTIAL INTERPRETATION	GENERAL INTERPRETATION	REFERENCES
Very low angle cross-lamination. High percentage of sandstones.	Deposition near the transition to upper stage plane beds. Cut and -fill in shallow scours. Dunes, linguoid-transverse bars and sand waves.	Medium to distal alluvial braided system reaches.	Kraus (1984), Miall, (1996), Roe (1987), Smith (1990), Southard (1971)
Flat or irregular erosional surfaces between bar sets. General sedimentary structures features indicating an increase of energy with respect to III.	Cut banks due to migrating channels. Mid-channel bars with cross-stratified bar platform deposits caped by horizontally bedded supra-bar gravels.	Medium to proximal alluvial braided system reaches (evidence of reactivation with respect to III).	Miall (1985), Steel, and Thompson (1983), Bluck (1971), Kraus (1984)
Planar-cross-stratification, angle of dip smaller than those of II and IV. Planar-cross-stratification is frequently absent at the top of the sequences.	Migration of transverse bars with curved crest lines. Flow depth relatively shallow at the top of the sequences in comparison with II.	Proximal alluvial braided system reaches to very distal fan.	Rust (1978), Miall (1985, 1996), Kraus (1984), Steel, and Thompson (1983).
Sequences of gravels subdivided by erosion surfaces. Planar-tabular cross-stratified sets up to 210cm in thickness. Foresets dips up to 35°.	Deposition in channels during normal and wanning flow stages. Filling of minor channels that could debouch into pools. Superimposed longitudinal bar deposits.	Distal fan to proximal alluvial braided system reaches.	Rust (1978), Decelles, and others (1991), Massari (1983), Boothroyd, and Ashley (1975).
Textural inmaturity. Grading and internal sedimentary structures are almost absent. Diffuse gravel sheets.	Transport unable to winnow fines and sorting clasts. Active bedload system. Sediments forming broad sheet-like bodies. High-water stages and waning-flow conditions.	Low-viscosity debris or mass-flow deposits in distal areas of alluvial fans associated with water-laid deposits of a braided fluvial origin with flow perpendicular to the fans.	Middleton, and Trujillo (1984), Bull (1964,1972), Miall (!970, 1985), Nemec, and Filipov (1989), Nemec, and Postma (1993).

Fig. 13. Sketch showing the main facies associations differentiated for each of the four members of the Boniches Fm. and their interpretation. Symbols of the sequences taken from Miall (1978). *MBS* = major boundary surfaces (see also Fig. 11). References: Bluck (1971), Boothroyd and Ashley (1975), Bull (1964, 1972), DeCelles et al. (1991), Kraus (1984), Massari (1983), Miall (1970, 1985, 1996), Middleton and Trujillo (1984), Nemec and Filipov (1989), Nemec and Postma (1993), Røe (1987), Rust (1978), Smith (1990), Steel and Thompson (1983), Southard (1971).

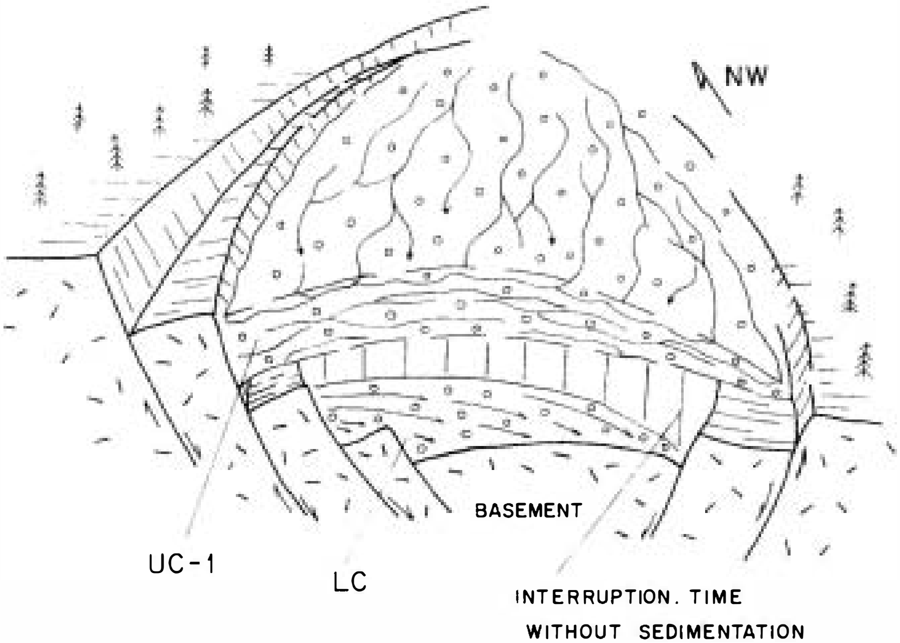


Fig. 14. Hypothetical cross-section of the study basin showing the relationship between longitudinal faults and LC and LC-1 members. During the time of interruption of the sedimentation, reorganization in the basin took place favouring the evolution from alluvial fan to fluvial system environments perpendicular to the fans. The hypothetical cross-section represents the area around Barranco del Lobo (see Fig. 5 for location).

still be clearly controlled by the Ordovician basement where the Boniches Fm. pinches out against the older palaeovalleys (Figs. 16 and 17). This resembles examples described by Trujillo et al. (1983) in the Upper Proterozoic of Central Arizona. When palaeovalleys were overstepped, palaeocurrents spread and turned toward the east and southeast (Fig. 15, II and III), coinciding with the transition stage between the distal alluvial fan and the fluvial system.

Lithological differences between alluvial fan sediments from palaeovalleys and from those outside the valley corresponding to the more mature fluvial sediments, were clearly marked by the pyrophyllite content (Fig. 10). This mineral was found to be abundant in the basement and therefore served to indicate the distance from the source area.

5. Morphological characteristics

Many of the morphological characteristics of alluvial fans in ancient sediments are very difficult to recognize. However, these may represent fundamental criteria in the differentiation of alluvial fans from fluvial systems. The present study investigates the characteristics of the LC member by detailed mapping and by structural and sediment dispersion analysis.

The sediments of the LC member related to the alluvial fan system, originated in the active fault front located in the SW (Fig. 15, I and II). These were dispersed more or less perpendicularly to that margin and showed a clear reduction in energy and thickness during their flow towards the northeast. Eventually they disappeared within a radius of less than 9 km (Figs. 5, 15 and 16) in a similar way to that described by Anstey (1966) in Pakistan and in the United States, and Blair (1987) in the Jurassic–Cretaceous transit of the Chiapas region, Mexico. The sediment dispersion showed two main characteristics. Each of the two main outcrop groups (Boniches and Henarejos) showed a particular area of origin, although both these areas come from the same scarp-fault of curvilinear disposition (Fig. 5). The sediment dispersion for both groups also shows how the palaeocurrents disperse in a fan-like manner, with a general northeast trend, for the lower part of the LC member. Mapping, log distribution

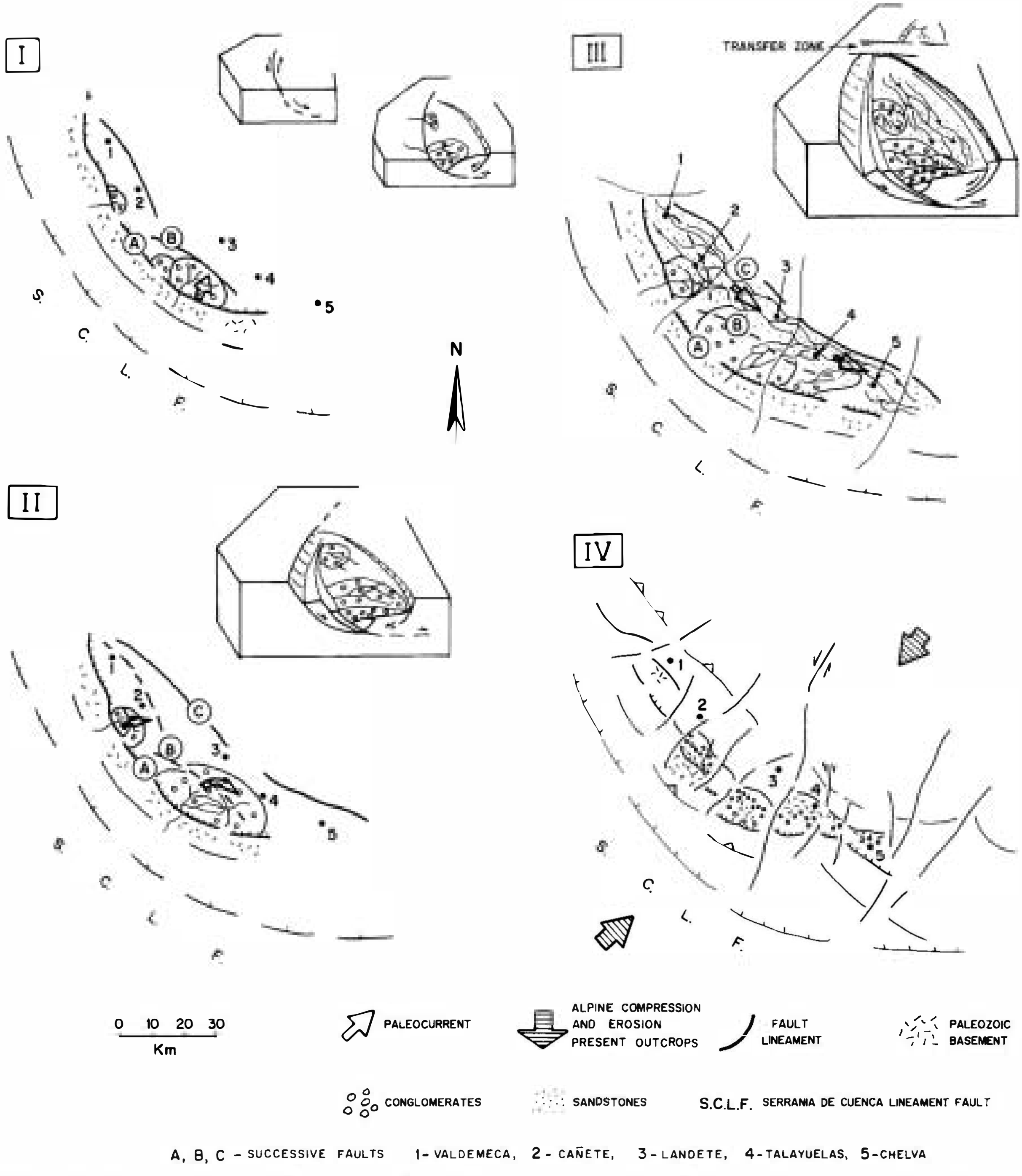


Fig. 15. Hypothetical evolution, in different stages, of the infill of the basin in relation with the general tectonic evolution of the basin. Secondary NE–SW faults separate the two main alluvial fan systems (Boniches and Henarejos) in stage II. An elevated transfer zone towards the north-northwest represented the provenance area for the fluvial sediments perpendicular to the fan systems in stage III. Stage IV represents the present situation of the Boniches Fm. outcrops after alpine compression and erosion.

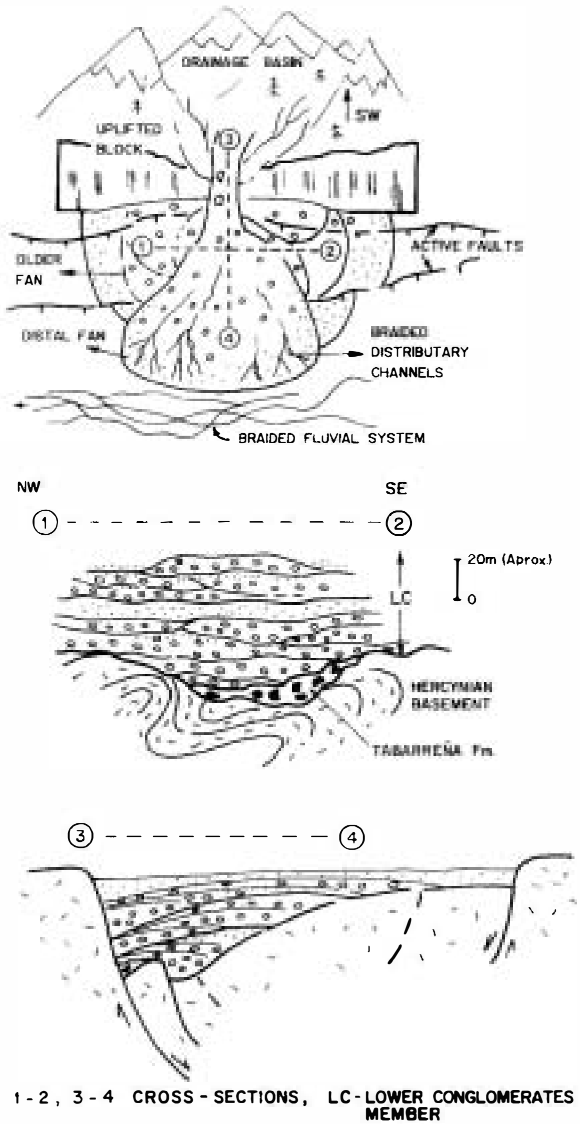


Fig. 16. Hypothetical representation of the Boniches fan system during the Lower Conglomerate (LC) member sedimentation with parallel (*1–2*) and perpendicular (*3–4*) cross-sections to the principal scarp.

and palaeocurrents (Figs. 5 and 6) differentiate two main alluvial fan systems (Boniches and Henarejos) (Fig. 5) with associated minor systems.

If we reconstruct the original position of these systems before the more recent alpine movements (Fig. 15, I–IV), it is easy to observe the curvilinear fault border that defined both fan head systems on the southwest side. If each log is then located (Fig. 6) and joined by an imaginary line between the upper and lower points for both systems (Boniches and Henarejos), the resulting cross-profiles display clear semiconical forms with an irregular base, caused by palaeorelief infill (Fig. 17) and restricted radial length. This is the consequence of the transfer of sediment-charged flows from an upland drainage basin to the fan site through a point source located where the feeder channel intersects the mountain front.

The curvilinear border described above is complex and was composed of two subparallel lines of faults (Figs. 5, 15 and 16), clearly shown in the mapping and log distributions. The fault synsedimentary activity created blocks linked by the faults that conditioned the thickness of the sediments, concentrating a major accumulation basinward rather than towards the border (Fig. 15, II). A similar process can be deduced from the repeated back-faulting of the basin margin as described by Steel and Wilson (1975) in the North Minch Basin.

The facies association analysis outlined above would suggest that the change or transit from an alluvial fan environment to a generalized fluvial one was produced in the MBS-1, that is, between the LC and UC-1 members. However, morphology, sediment thickness and dispersion, palaeocurrents and mineralogical analysis indicate that this change may have occurred in the lower part of the LC member. This point will be discussed later.

6. Controls over general alluvial evolution

In a field study of small alluvial fans in northwest England, Wells and Harvey (1987) showed that the spatial variation of the type of depositional process was controlled by variables other than tectonism or climatic change. Climatic and tectonic factors are the two most important factors causing changes in erosional energy. This was shown by Lecce (1990) with the reintroduction of the dimension of time in alluvial fan research. Although a steady-state balance exists between form and process, if erosional energy changes through time, then form must also change (Hack and Goodlet, 1960). In spite of these controls over non-marine rifts, alluvial fans may be important. The details of how this sedimentary environment and its facies react to changes in the rate and type of tectonic movement and climate are still

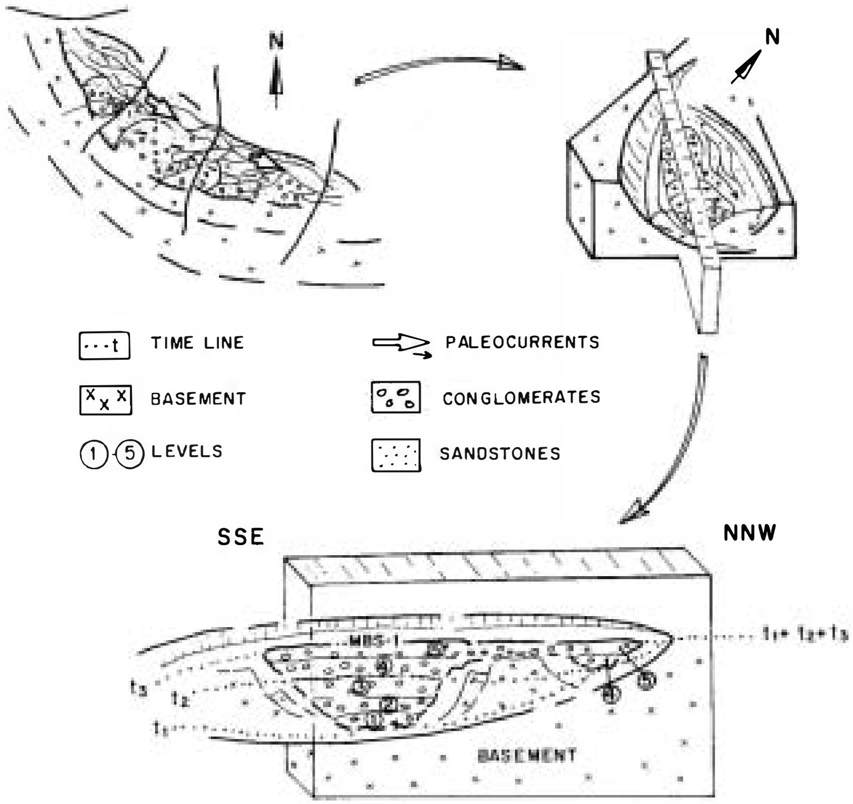


Fig. 17. Hypothetical longitudinal cross-section of the northern half of the study basin during the sedimentation of the LC member showing the relationship between deposits, palaeorelief and time-lines.

poorly understood (Frostick and Steel, 1993; Ritter et al., 1995).

6.1. Climatic factors

The climate of the study area during the deposition of the Boniches Fm. was considered to be generally humid. This theory is supported by the lack of significant indicators of arid environments in the sediments, such as the presence of desert varnish on pebbles (Lustig, 1965), the absence of calcic soils and evaporites and the scarce amounts of potassium feldspar, biotite and ferric oxide are suggestive criteria of non-arid conditions (Fig. 10). In contrast, kaolinite is relatively abundant which could represent kaolinitic saprolites of the Hercynian basement in a humid or seasonally humid source area. The internal sedimentary structures of the conglomerates also indicate transport and deposition by running water along the Boniches Fm.

Semi-arid alluvial fans characteristically have abundant debris-flow deposits and few systematic sorting patterns (Bull, 1972). Very few debris-flow deposits (*Gms* facies) have been observed in the Boniches Fm. despite the fact that the bed-rock lithology and the morphology of the drainage basin suggest that conditions are favourable. On the other hand, the relative frequency of facies *Gp* in sets averaging 1 m in thickness and their high preservation in the conglomerate association of the Boniches Fm. is an indication of consistently high discharge in a humid climate. This brings to mind Rust's description of the Devonian Malbaie Conglomerates Fm. (Rust, 1984) in Gaspé, Canada.

There are no marked changes in the evolution of clast size between consecutive sequences within the same member in the Boniches Fm. (Fig. 9). This may indicate that catastrophic events related to arid or semi-arid areas without vegetative cover associated with significant reactivations of the fan head affecting clast size, were not common or did not take place. The Iberian Basin was located near the Equator during the Permian according to palaeomagnetic and palaeogeographic data (Ziegler, 1988). Today, a whole range of climates, from tropical rainforests to arid deserts are found near the Equator. In the Boniches Fm., the absence of distinctive criteria of hot-arid climates such as mass-flow deposits, deflection surfaces, dreikanters and evaporites (Miall, 1996, chapter 12) and the exclusive presence of running-water deposits indicate that it was deposited in a humid climate in the equatorial zone.

Lecce (1990) considers that climatic change influences the development of alluvial fans by inducing variability in the magnitude and frequency of fluvial processes which alter alluvial fan features. Lustig (1965) suggested that fan aggradation occurs regardless of climatic regime. Possibly, the complex response of drainage systems may not always be related to external influences (Schumm, 1977). However, it is clear that sedimentation, at least, may be conditioned by vegetation which is closely related to climate. If climatic changes are produced during a particular time interval, this could produce sufficient water discharge to initiate fan aggradation and may be repeated periodically. This is clearly seen under arid or semi-arid conditions and climatic changes exert a strong influence on the nature of fan sequences, as Frostick and Reid (1989) reported for the Pleistocene Dead Sea fans. However, under humid conditions, as in the case of the Boniches Fm., climatic factors could have affected the sediments in general, favouring a constant supply and a better selection of the clasts.

It should be taken into account that several difficulties may hinder the analysis of climatic control in this type of sediment. These include the general lack of indicators typical to coarse-grained sediments, a lack of knowledge about the timing of ancient fan deposits (Ritter et al., 1995) and also the possible overlapping of effects produced by tectonics and those of climatic origin.

6.2. Tectonic factors

Although alluvial fans may form in areas where tectonic uplift is not an important factor, they are especially prominent where the uplift of mountain regions provides a continental supply of fresh debris from steep drainage basins (McPherson and Hirst, 1972; Lecce, 1990).

Mapping of the Boniches Fm. provides clear evidence that tectonism controlled sedimentation, as previously indicated. Palaeocurrents suggest two stages with different source areas. The first from the southwest, during the alluvial fan stage, and the second from the northwest, when the drainage was established parallel to the main axis of the basin (Figs. 14 and 15). Although the change in flow direction started during the LC sedimentation, the MBS-1 was identified with the definitive change and with the new reorganization of the basin. This general change could be related to the appearance of a possible transfer zone towards the northwest, where sedimentation disappeared against the outcropping basement in a topographically high area (Fig. 15, III). This has been described in many recent sedimentation studies (Ebinger et al., 1987; Ebinger, 1989a,b; Morley et al., 1990; Gibbs, 1990; Frostick and Reid, 1990; Frostick and Steel, 1993). This transfer zone separated two sub-basins of the Iberian Basin and also limited sedimentation in the Boniches Fm. (Figs. 3, 5 and 15). There was another, almost symmetrical, high area located towards the southeast that definitely isolated the basin under study during this first stage in the evolution of the Iberian rift.

The general geometry of the basin was longitudinal, approximately 75 km long and 20–26 km wide, wedge-shaped with a regionally curvilinear complex border fault and stratal packages successively onlapping either basement rocks or older sediments. This was demonstrated by the thickness of the sediments in relation to the disposition of main faults (Figs. 5 and 15) and the angular unconformities between the MBS that involve tectonic tilting during infill (Fig. 18). Similar sizes for tilted sub-basins have been described by Rogers and Rosendahl (1989). These MBS could also represent hiatuses in deposition (as shown in Fig. 14) which may be attributed to movements of the faulted margins. The influence of a combined change effect is also possible but difficult to distinguish (Frostick et al., 1991).

The distribution of sediments also show that preservation potential is particularly high in the central part of the border-fault segment in the Henarejos area (Fig. 5). This may show similarity to certain

Fig. 18. Castillo del Rey section. Prolongation towards the southwestern border (the main border of the basin during the Boniches Fm. sedimentation that was geographically located very close, as shown in Figs. 5 and 6) of the major boundary surfaces (*MBS*) and members (*LC, UC-1, UC-2* and *SC*). The progressive unconformities indicate possible block rotation during the sedimentation.

Eastern African Rift examples (Ebinger, 1989a) that decrease towards the northwest and southeast, that is, against the transfer zones. The interior part of the basin also shows that there are at least two more NE–SW faults that cross both the foot-wall and hanging-wall blocks, parallel to those comprising the transfer zones (Figs. 5 and 17). These internal faults controlled the infill of the basin, firstly isolating the two main alluvial fan systems described above and later overlapping both systems in a unique transversal fluvial system (Fig. 15, III). Finally the faults caused the widening of the basin area.

During this infill, the first stage corresponds to the LC member sedimentation, during which the Henarejos area probably had a more active faulted border with a greater accumulation of fan sediments. During the syn-rift stage, high rates of subsidence create space faster than it can be filled and coarse sediments are trapped and stored nearer to the fault scarps, as Nøttvedt et al. (1995) pointed out in their study of the northern North Sea rift basins. The more elevated areas of the interior part of the basin corresponded to the southeast extremes. These were probably never covered by fans, and only crossed by late transversal fluvial systems at the time when the rate of sediment supply resulted in over-filling of the deeper parts of the basin. This caused coarse clastic sediments to spill over into neighbouring parts when the transverse drainage system was better established. This situation appeared during the sedimentation of the UC-1, just above the MBS-1, when most of the palaeorelief of the central part of the basin was probably over-stepped (Figs. 11 and 15). This created a new situation which is also well marked by palaeocurrent data and a reduction in the content of unstable pyrophillite above the MBS-1 (Fig. 10) which indicates that the provenance of sediments could be more distant source areas already linked to the longitudinal fluvial system.

Mapping clearly shows the curvilinear main fault border of the segment under study (Figs. 5 and 6). This may suggest a listric development in depth and concave basinward morphology (Frostick and Reid, 1987). The vertical movement of the hanging-wall individual blocks of this border fault could include rotation with simultaneous subsidence. Rotation is evident in the parts of the block closest to the main border fault of the basin as in the Boniches area. This idea is supported by the progressive unconformities discussed previously and the fact that it is possible to observe how the Tabarreña Fm. appears unconformably below the Boniches Fm. with a clear wedge-shaped distribution (Figs. 7 and 16).

Block rotation during crustal extension is not uncommon in the Triassic syn-rift European basins, before a general lateral progradation of the sediments to the whole width of the basin (Frostick and Steel, 1993; Nøttvedt et al., 1995). Rotation includes re-elevation of the basinward part of the block, creating a new slope which dips against the main border fault. The unit members of the Boniches Fm. show divergent internal strata patterns, indicating continued faulting and rotation accompanying deposition. During the first stage, when alluvial fans were developed, rotation may have been more intense and led to the deposition of wedge-shaped units, while interbedded general tabular units of later stages were deposited during periods of general tectonic subsidence and minor rotation.

The separation of the effects of extension from those of rotation on sediments is difficult for many reasons. These include the fact that both rates can vary during the syn-rift stage or due to the overlapping of these effects. However, in the Boniches Fm., the decrease in rotation in favour of extension, could represent the beginning of the transition from the alluvial fan to the axial fluvial systems as the latter cover almost the whole of the study basin homogeneously, while sedimentation of the LC member does not permit the progradation of fans more than 2–3 km basinward (Figs. 5 and 15, II–III).

In spite of petrological and sedimentological similarities between the LC member and the UC-1 and UC-2 members, we interpret the first one as alluvial fan deposits because of its palaeocurrents trending normal to the Basin Boundary Fault and the presence of the slate pebbles derived from a nearby source area and the latter two as fluvial deposits by the sudden change in palaeocurrents indicating longitudinal transport and the absence of slate pebbles. The alluvial fan and fluvial deposits are separated by a regional erosive surface (MBS-1), indicating a widening of the basin and a change of regional slope after a period of tectonic activity. There is no interbedding or transition zone among the two types of sediments.

Sedimentation of the LC member was different in the two main alluvial fan systems described above. In the Henarejos sub-basin area (Figs. 5 and 6), sedimentation was faster than in the remaining areas. This resulted in an almost triple rate of sedimentation in comparison to that of the Boniches system. Although, after LC member sedimentation, sediment expansion was possible, it was always in an endorheic basin comparable to the examples described by Frostick and Reid (1987). During extension, the

Fig. 19. Roots in the uppermost part of the Tabarreña Fm. (unconformably below the Boniches Fm.) that could indicate the angle of the slope in which the Boniches Fm was deposited (see text). The largest root is 95 cm long. The compass in the circle is 12 cm long.

basin grew both wider and longer as the basin-bounding faults lengthened and displacement accumulated. The change in the rate of increase in basin volume is positive (Schlische, 1991).

In spite of the fact that during the first stages of sedimentation of the Boniches Fm., a plane dipping towards the main SW-faulted border of the basin was created by combination of rotation and extension, palaeocurrents indicate northeastern rather than southwestern flow. The latter might be expected if one considers African models (Frostick and Reid, 1987). Only the first strata in the Castillo del Rey log, indicated south-southwestern flow (Fig. 6A), but since it is a unique and isolated level, this may not be indicative. There are several possible reasons for the lack of palaeocurrents indicating southwestern transport at this stage. A simple one could be that these sediments indicating southwestern flow were not deposited, due to a possible very gentle slope, or deposited in a very reduced proportion without reaching the southwestern border. In the latter situation, vegetation covering the slope could also retain or disperse the movement of clasts (Hughton, 1989). Another argument could be that these sediments from the northeast border were initially deposited, but rapidly eroded due to the upward movement of the basinward part of the block during rotation.

During the first stage of sedimentation of the Boniches Fm., the slope could be approximately estimated. Some root levels were observed just at the top of the Tabarreña Fm., located unconformably below the Boniches Fm. (Figs. 2 and 13). These roots grew oblique to the Tabarreña Fm. stratification and just prior to the Boniches Fm. sedimentation (Fig. 19) since the conglomerates cut them. Thus, a perpendicular plane to the roots would indicate the original surface in which the alluvial fans were deposited and since the dip of the conglomerate levels is known, the original slope may be estimated as being 3 degrees. This is considered low with respect to recent alluvial fan examples (Blair and McPherson, 1994a,b) and would probably not be enough to transport clasts larger than 10 cm (Costa, 1983) (Fig. 9).

The new high, created by the relative movement (elevation–subsidence) of the footwall block, was probably more important for sediment records in the first stage of sedimentation. This created space faster than it could be infilled and trapped coarse sediments stored nearer to the main southwest fault scarps. As a consequence of the rotation, the change in the rate of increase of the volume of the basin was probably negative during uniform extension (Schlische, 1991). In a later extension of the basin due to fault growth, alluvial sediments progressively covered pre-rift rocks of the hanging-wall block when their basinward extension was restricted, as described by Blair and Bilodeau (1988). In contrast, the most highly progradational levels within clastic wedges correspond to times of minimum tectonic activity along the basin margins (Frostick and Steel, 1993). This could correspond to the upper part of the LC member in the Boniches Fm., probably also coinciding with the overlapping of the fluvial system drainage over the fans. A rift model in which axial drainage dominates and drainage across the ramp is subsidiary, was described by Leeder and Gawthorpe (1987) in ancient sediments and by Hunt and Mabey (1966) and Hooke (1972) in recent alluvial fan systems.

Sediment thickness (Fig. 6) and estimated reduced rate of subsidence for this stage and basin (Arche and López-Gómez, 1996) could indicate a general decrease in the infill of the basin probably also linked to reduced border fault movements in comparison to other classical Permo–Triassic rift basins (Frostick et al., 1988, 1991; Glennie, 1990; Nøttvedt et al., 1995).

Based on a compilation of data from publications including fan area, fan slope and drainage area, Blair and McPherson (1994b) described certain morphological characteristics in active fan systems. Following these parameters it may be estimated that if the Boniches fan system covered about 6–9 km^2 as deduced from mapping (Fig. 5), and if the estimated slope was less than 3 degrees as quoted above, the drainage area would be about 7–9 km^2. As the Henarejos fan system was larger than the Boniches system, the total estimated drainage area could be about 20–25 km^2. This dimension fits well with the ones compiled by Heward (1978) for recent humid fans.

Differentiation between minor and major sequences and the general clast evolution of the whole of the Boniches Fm. (Fig. 9) gives insight into the development of major fans and fluvial systems with respect to the type of main border fault movement, i.e. the relationship between the footwall and hanging-wall block movements. There were at least two main faults related to the footwall that conditioned sedimentation during the first stages of the sedimentation of the Boniches Fm. Fig. 9 shows that the levels that constitute each member (LC, UC-1, UC-2 and SC) were also composed of minor sequences less than 70 cm thick, of a mainly fining-upwards tendency. There was no clear vertical progressive change in mean grain size in the vertical evolution of the formation. Only level 17 showed an increase in the mean of the sequences and largest pebble size, coinciding with sheet-flood deposits, as previously suggested. Two arguments could justify this regular evolution: a lack of strong movements in the source area and/or abundant and permanent rain with intense vegetative cover.

The general decrease of bed thickness from base to top (with exception of levels 7, 15 and 17), the homogeneous petrology of clasts (more than 99% quartzite with only some slate pebbles close to the basement, in level 1), a vertical evolution of facies associations indicating an evolving fluvial environment and the fining-upward tendency of most of the minor observed sequences, all point to a reduction of the source area relief and/or scarp retreat (Heward, 1978). This retreat or formation of a second floor fault, cutting back towards the footwall as extension proceeds, could be a result of the unloading of the footwall, probably largely gravity-driven (Gibbs, 1984). The particularly thicker beds, largest pebble size increase and facies *Gm* of level 17 (Fig. 9) could indicate faulting with a history of progressively greater vertical movements (Steel and Wilson, 1975; Gloppen and Steel, 1981) in a reduced period of time.

7. Discussion and conclusions

The stratigraphical and sedimentological analysis of the Boniches Fm. allow the interpretation of its sediments as deposits that evolved from two main alluvial fan transverse systems progressively to a longitudinal braided fluvial system environment.

Sedimentation of a reduced segment of the Iberian Rift Basin occurred at the end of the Permian in an asymmetrical half graben where extension and/or rotation configured different sedimentary geometries during the first stages of refill of the basin. The progressive evolution from fan sedimentation to the axial fluvial braided system was related to the different stages and styles of the basin, where fault-controlled subsidence dominated basin geometry and facies distribution.

Climatic factors also controlled sedimentation, favouring a constant supply and better sorting of the clast. However, it is difficult to determine its effects on the sediments, especially since these were juxtaposed with those of tectonic origin and also due to the lack of palaeoclimate indicators found in coarse-grained sediments.

If an alluvial fan consists of stream deposits with a surface which forms a segment of a cone that radiates downslope from the point where the stream emerges from the mountain area (Bull, 1963, 1968), it is easy to understand that differentiation of this environment from one that is strictly fluvial, is very difficult in ancient sediments. This is particularly true if the sediments were deposited under humid conditions. The present study discusses the evolution from alluvial fan deposits to braided fluvial systems. From the mineralogical, morphological, palaeocurrent and tectonic points of view, the transition basically coincided with the MBS-1, affecting the fan stage of practically the whole LC member. However, from the sedimentological (facies analysis) point of view it is possible to locate the alluvial fan stage as being restricted to the lower part of the LC member only. Although several recent studies (see review in Blair and McPherson, 1994b) suggest that alluvial fans are a naturally unique phenomenon readily distinguishable from other sedimentary environments including gravel-bed rivers, we consider that some difficulties are still unresolved.

Miall (1977, 1996) pointed out that there is nothing unique about the depositional processes of alluvial fans; only the geometry of the fan and its deposits are distinctive. In this sense, it is easy to understand how in the literature many interpretations of fluvial or alluvial fan environments became juxtaposed (Bluck, 1967; Hooke, 1967; Harvey, 1989; Postma, 1990 and Miall, 1992). This is true especially when braided-stream processes overlap alluvial fan deposits in ancient sediments maintaining the same palaeocurrent trend or when postflood modifications (i.e. development of braided distributary channels on top of sheet flood deposits) have eliminated almost all evidence that sheetflooding was the dominant depositional process responsible for fan aggradation. This was reported by Blair (1987) for the Roaring River Fan. It is not uncommon to find comments in the literature such as "fluvial deposition dominates below the intersection point" (Hooke, 1967), taking into account that Bull (1963, 1968) considered that the alluvial fan radiates downslope precisely from that particular point. Similarly, Hoppe and Ekman (1964) pointed out that "braided streams are known to function on alluvial fan surfaces" and later on, Bluck (1967) added that "this braided stream can be seen to grade upstream into alluvial fan deposits". More recently, Selby (1994) stated that "alluvial fan processes are increasingly fluvial in nature as the depth and regularity of flow increase away from source".

Blair and McPherson (1994a) have proposed a distinction between alluvial fans and rivers based on morphology, hydraulic processes, sedimentary processes and facies assemblages. Our study of the Boniches Fm. allows us to say that there is no real distinction between the sediments of humid alluvial fans and braided river systems, a point of view sustained by authors previously mentioned, because there is not an intrinsic, exclusive process to one or other depositional system that causes characteristic sediments; this is one of the main conclusions of this work.

We consider that the only valid differentiation criteria among those cited by the previous authors in ancient records are: (1) morphology, very difficult to reconstruct; (2) palaeocurrents dispersion, large for alluvial fans and small for braided fluvial systems; and (3) orientation of the palaeocurrents with respect to the axis of the basin, transverse for most of the alluvial fans and longitudinal for the braided river systems, because of the different nature of the basin boundary faults on one or the other depositional system.

We feel that in ancient sediments in which there is an upward evolution from alluvial fan deposits to braided fluvial deposits, palaeocurrents could indicate when a fluvial system perpendicular to the fan is clearly established. This was the case of the UC-1 member with respect to the LC member in the Boniches Fm. However, dispute over the fluvial or fan nature of deposits continues to exist when in fact the two systems were most likely superimposed in the same current trend, as seen in the upper part of the LC member of the formation. This is true especially if we consider that downslope from the intersection point, the development of the proper fan (Bull, 1968) may coincide with the local aggradation and loss in competence in a lateral flow expansion. This represents the direct physical sedimentary cause of primary braiding (Ashmore, 1991).

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