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Alluvial fan and lacustrine sediments from the Stephanian A and B (La Magdalena, Ciñera—Matallana and Sabero) coalfields, northern Spain

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ABSTRACT

Vertical sequence analysis within 1500–2500 m thick coarse-grained coalfield successions allows six sedimentary associations to be distinguished. These are interpreted in terms of depositional environments on, or related to alluvial fans which fringed a fault bounded source region. (i) Topographic valley and fanhead canyon fills: occurring at the bases of the coalfield successions and comprising sporadically reddened, scree, conglomeratic thinning and fining upward sequences, and fine-grained coal-bearing sediments. (ii) Alluvial fan channels: conglomerate and sandstone filled. (iii) Mid-fan conglomeratic and sandstone lobes: laterally extensive, thickly bedded (1–25 m) and varying from structureless coarse conglomerates and pebbly sandstones, to stratified fine conglomerates and cross-bedded sandstones. (iv) Interlobe and interchannel: siltstones, fine-grained sheet sandstones, abundant floras, thin coals and upright trees. (v) Distal fan: 10 cm–1·5 m thick sheet sandstones which preserve numerous upright trees, separated by siltstones and mudstones with abundant floras, and coal seams. The sheet sandstones and normally arranged in sequences of beds which become thicker and coarser or thinner and finer upwards. These trends also occur in combination. (vi) Lacustrine: coals, limestones, and fine-grained, low-energy, regressive, coarsening upward sequences.

Proximal fan sediments are only preserved in certain basal deposits of these coalfields. The majority of the successions comprise mid and distal alluvial fan and lacustrine sediments. Mid-fan depositional processes consisted of debris flows and turbulent streamflows, whilst sheetfloods dominated active distal areas. A tropical and seasonal climate allowed vegetation to colonize abandoned fan surfaces and perhaps resulted in localized diagenetic reddening. Worked coals, from 10s cm–20 m thick, occur in the distal fan and lacustrine environments.

These alluvial fan deposits infill 'California-like' basins developed and preserved along major structural zones. In many of their characteristics, in particular the occurrence of thinning and fining, and thickening and coarsening upward sequences and megasequences, these sediments have similarities to documented ancient submarine fan deposits.

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INTRODUCTION

'An alluvial fan is a body of detrital sediments built up by a mountain stream at the base of a mountain front' and commonly having the shape of a segment of a cone (Blissenbach, 1954, p. 176). Sedimentation is characterized by an accumulation of debris within a drainage basin and its sporadic transference to the mountain front (Beaty, 1963, 1970, 1974; Bull, 1964a, b; Denny, 1965, 1967; Hooke, 1967, 1968). Deposition results from deceleration due to the increase in flow width and decrease in flow depth as floods emerge from the confines of the feeder canyon or fanhead channel (Bull, 1964a; Denny, 1965). The locus of deposition on a fan surface depends on the presence of channels. Over a period of time the cutting, infilling, migration and abandonment of channels results in fairly even fan sedimentation (Beaty, 1963, 1970, 1974; Denny, 1965, 1967; Lustig, 1965; Hooke, 1967, 1968; Bull, 1972). At any time much of the fan surface is inactive, being the site of weathering, pedogenesis and erosion (Bluck, 1964; Denny, 1965, 1967; Lustig, 1965; Hooke, 1967, 1968, 1972).

Modern fans have been described most frequently from arid and semi-arid climatic settings (e.g. Blissenbach, 1954; Bull, 1964a, b, 1972; Lustig, 1965; Denny, 1965, 1967; Hooke, 1967; Williams, 1970; Meckel, 1975), and ancient fan sediments interpreted almost exclusively so (e.g. Allen, 1965a; Laming, 1966; Bluck, 1967; Miall, 1970; Groat, 1972; Steel, 1974, 1976; Steel & Wilson, 1975; cf. McGowen & Groat, 1971; Hubert, Reed & Carey, 1976). However, modern fans also occur in other climatic regimes, their occurrence being primarily a function of topography and sediment supply (e.g. Winder, 1965; Curry, 1966; Legget, Brown & Johnson, 1966; Murata, 1966; Broscoe & Thomson, 1969; Johnson & Rahn, 1970; Wasson, 1977a).

The purpose of this paper is to describe coarse-grained coal-bearing alluvial fan and lacustrine sediments which probably accumulated under a tropical and ?seasonal climate. These ancient fan sediments are viewed in terms of processes and these related to depositional environment, whilst bearing in mind that climate, vegetation and processes, themselves interrelated, have evolved (Schumm, 1968).*

SETTING

The La Magdalena, Matallana (Ciñera–Matallana) and Sabero coalfields are located on the southern flank of the Cantabrian Mountains, in the Province of León, Northern Spain (Fig. 1). Thick coal-bearing Stephanian successions rest unconformably on folded Precambrian–Namurian strata. These coalfields occur within a belt of small, isolated Stephanian A–C basins (5–175 km^2 in size), in which sedimentation began progressively later from Sabero westwards. Thick conglomerates, poorly sorted lithic sandstones, lacustrine shales and coals typify these deposits.

Previous work, stratigraphy and structure

Previous work in La Magdalena, Matallana and Sabero has been almost entirely of a stratigraphical nature (van Amerom & van Dillewijn, 1963; Helmig, 1965; Wagner,

* Since this paper was completed considerable additional data on alluvial fans has been published by Bull (1977) and Wasson (1977b).

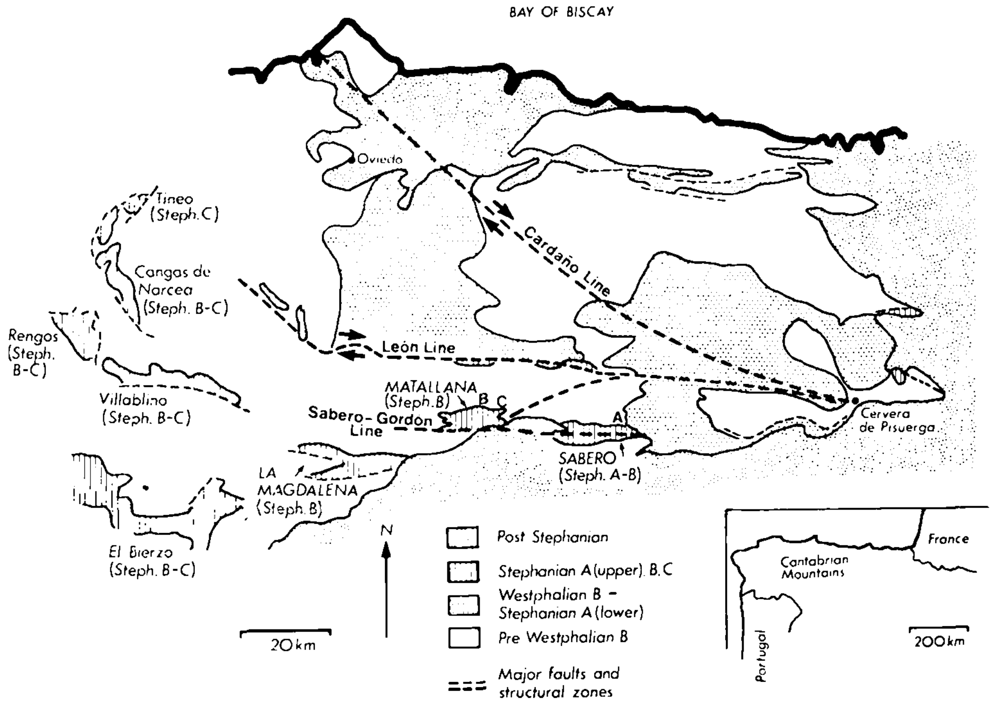


Fig. 1. Geological map of the Cantabrian Mountains, Northern Spain. Stratigraphic ages (based on floras) for the Stephanian coalfields, from Wagner (1970) and Knight (1975). A = Alejico, B = Bardaya, C = Correcillas, refer to locations mentioned in the text.

1966, 1971b; Evers, 1967; van den Bosch, 1969; Wagner & Artieda, 1970; Knight, 1971, 1974, 1975; van Staalduinen, 1973). Terms such as continental, limnic and paralo-limnic have been used to describe these deposits.

The stratigraphies of the studied coalfields are illustrated in Fig. 2. Those of Matallana and Sabero are well established following the mapping of Wagner (1971b) and Knight (1975). The La Magdalena coalfield has not yet been mapped stratigraphically and the succession of Fig. 2 represents a well exposed road section measured by the author (La Magdalena–Mora de Luna).

Inter-coalfield correlation exists at a general level only (Wagner, 1970, 1971b), although Knight has attempted several correlations of Sabero and Matallana whose outcrops are separated by only 10 km (Knight, in Wagner, 1971a; Knight, 1974, 1975).

Structurally the three basins are similar, being broadly synclinal, with sediments striking E–W. A well preserved, though faulted and sometimes tectonically repeated northern limb, contrasts with a highly tectonized, dissected and shortened southern limb.

Extensive deep mining continues in the coalfields of Matallana and Sabero.

General characteristics of the deposits

Thick, coarse conglomerates occur in the basal formations of the coalfields and are prominent to varying levels in the overlying successions. Well-rounded clasts are

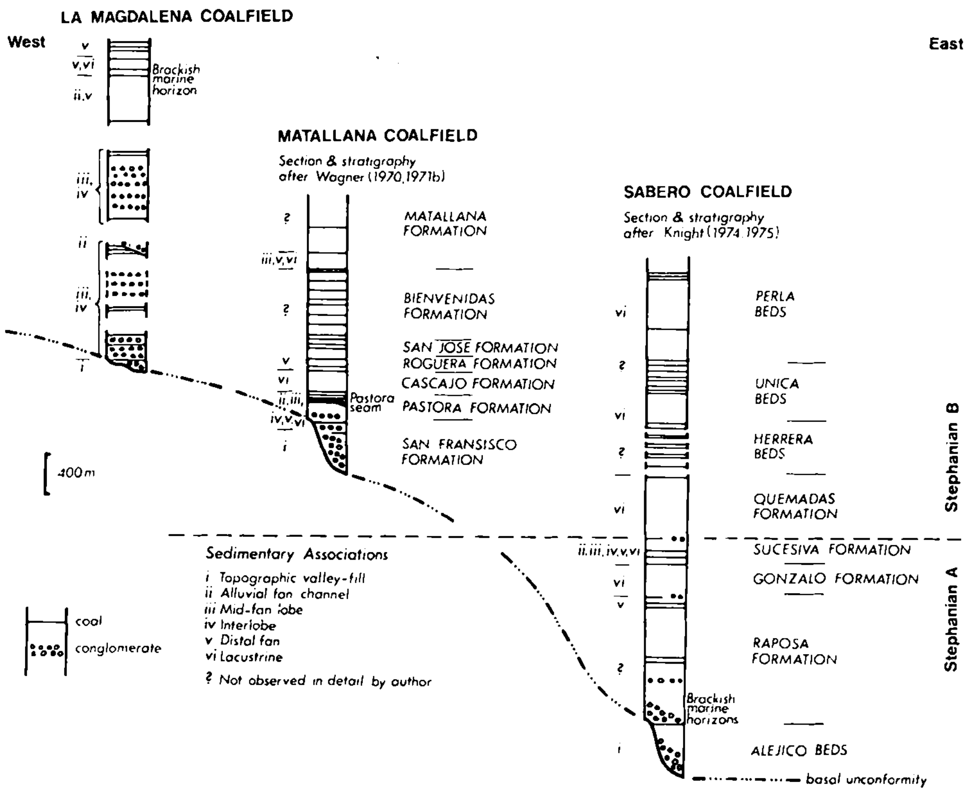


Fig. 2. Stratigraphies and the generalised occurrence of the six sedimentary associations within the coalfield successions. Correlations based on Wagner (1970) and Knight (1974, 1975).

ubiquitous in all Carboniferous and Stephanian conglomerates in the Cantabrian Mountains, irrespective of environment of deposition. Roundness does not appear to result from recycling, because an extensive conglomeratic source formation is lacking (van Loon, 1972) and there appear to be no multi-cycle clasts or half round pebbles (Tanner, 1976). Rounding may have resulted from rapid weathering under a tropical climate (Tricart, 1972; Thomas, 1974), from transport in highly concentrated debris/turbulent flows (Winder, 1965; Scott & Gravlee, 1968), or from abrasion in place (Schumm & Stevens, 1973).

Texturally, sandstones are poorly sorted and composed of angular to sub-angular grains. They are predominantly lithic or sub-lithic, arenites or greywackes (Pettijohn, Potter & Siever, 1973). Sedimentary rock fragments of chert, quartzite and shale abound. Sandstone petrographies and compositions of conglomerate clasts indicate a predominantly sedimentary source area.

Fresh-water faunas typify the lacustrine intervals of the coalfields (Eagar & Weir, 1971; Wagner, 1971b; Knight, 1975; Heward, 1976). However, a few localized horizons yielding brackish-marine faunas have also been recorded (Fig. 2; Knight, 1971, 1974, 1975; Heward, 1976). Fossil floras abound within the alluvial fan sediments and have been the subject of several publications (Wagner, 1966, 1971b; Wagner & Artieda, 1970; Knight, 1974, 1975).

Vertical sequences and sedimentary associations are readily distinguishable in the field. Vertical sequences can be observed on several scales and normally change progressively. They range from individual beds (cm–m thick), sequences of related beds (m–10s m thick), to megasequences, consisting of arrangements of sequences and beds (10s–100s m thick). Sedimentary associations consist of vertical sequences and may themselves be arranged into megasequences. The characteristics of beds, vertical sequences and sedimentary associations enable reconstruction of depositional processes, depositional environments and long-term behaviour of depositional systems.

Methods of study

Well-exposed, though isolated, road and stream sections were measured in detail, particular attention being paid to the nature of the individual beds (lithology, sedimentary structures, flora and fauna), grain size variations, bed contacts, the lateral extent of beds and their relative palaeocurrents. The latter, with the exception of long axes clast orientations, were difficult to obtain.

Grain size of shale to sand grade sediments was estimated visually in the field. An average maximum clast size was measured for conglomerates from the longest axes of the twenty-five largest clasts. These were taken 1–5 m either side of the section line and at intervals normally not greater than 1 m.

SEDIMENTARY ASSOCIATIONS

Within the La Magdalena, Matallana and Sabero coalfield successions six sedimentary associations can be identified: topographic valley and ?fanhead canyon fills, alluvial fan channels, mid-fan conglomeratic and sandstone lobes, interlobe and ?interchannel, distal fan, and lacustrine.

Topographic valley and ?fanhead canyon fill association

Description

At the bases of the coalfield successions localized accumulations of conglomerates, sandstones, shales and coals occur confined within palaeo-hollows or valleys of the underlying surface.

In the La Magdalena coalfield small (100s m wide and 10s m deep), conglomerate filled palaeo-valleys are cut into folded and cleaved Precambrian turbidites (van den Bosch, 1969; Heward, 1976). These conglomerates contain locally derived, angular fragments of shale and sandstone, up to 50 cm. They are polymodal, unstratified, lack fabric and are matrix supported, the matrix consisting of smaller rock fragments. The top few metres of underlying Precambrian and finer-grained horizons within the conglomerates are commonly reddened.

Basal deposits from the northern margin of the Matallana coalfield include a 2 km wide and 300 m deep conglomerate filled valley at Correcillas (C on Fig. 1), and a smaller fine grained accumulation at Bardaya (B on Fig. 1) containing several thick coal seams.

At Correcillas, the palaeo-valley eroded in folded Palaeozoic formations is infilled by thick unstratified coarse conglomerates (Figs 3–5). Clasts are well rounded,

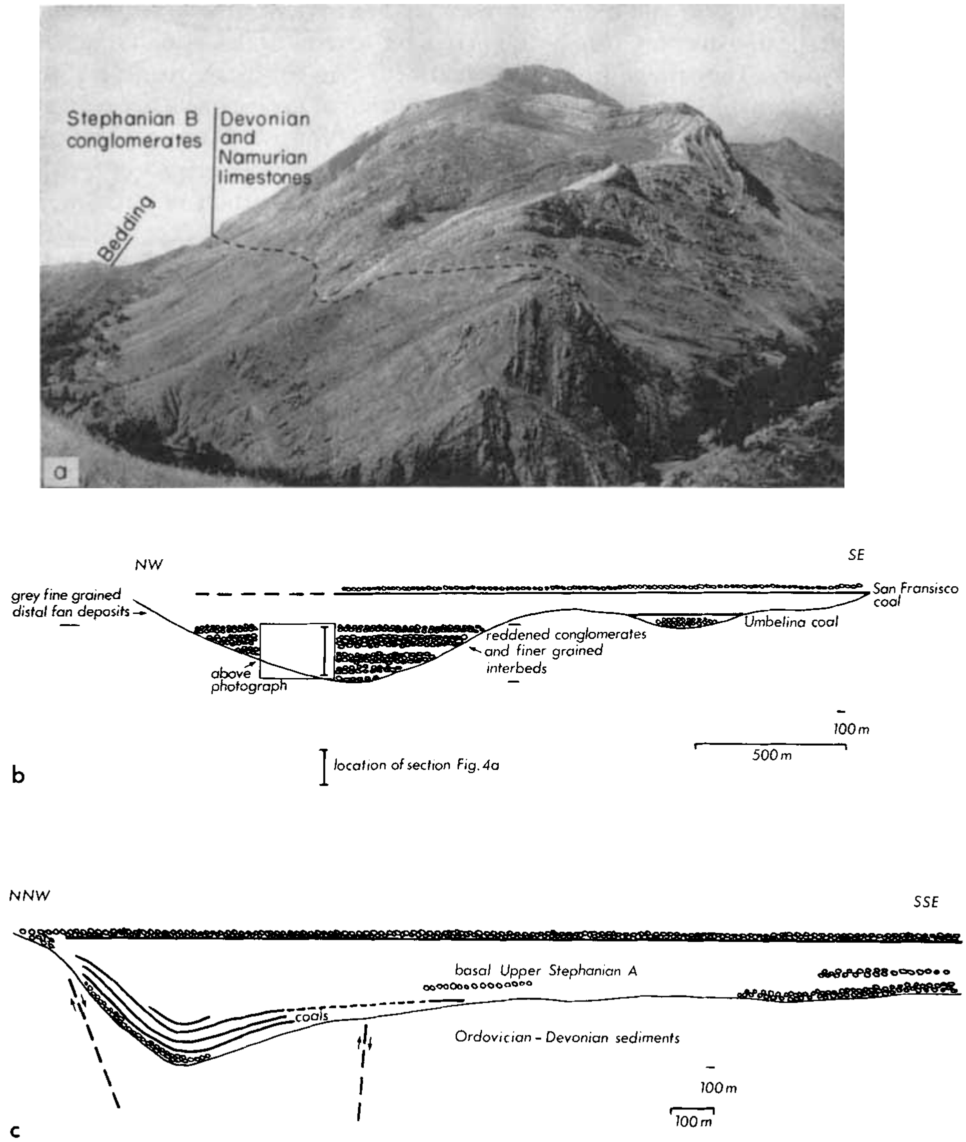


Fig. 3. Palaeotopographic valley-fills. (a) View to NW across margin of valley-fill at Correcillas, Matallana coalfield, where folded Devonian and Namurian limestones are overlain by Stephanian B conglomerates. Younging to middle left. (b) Reconstruction of Correcillas palaeo-valley; after Wagner (1971b). (c) Reconstruction of valley-fill at Alejico, Sabero coalfield; after Knight (1975).

polymodal and consist predominantly of quartzite and limestone (Fig. 5a). Conglomerates vary from clast to matrix supported and have a red coarse sandstone–granule-sized matrix. Individual beds, 10s cm–20 m thick (Fig. 4a), defined by differences in clast size, or clast/matrix support, are separated by fine-grained interbeds and are laterally continuous across the valley fill (Fig. 5b). Trough cross-bedding in reddened fine-grained sandstone interbeds indicates transport to the North. Red and red-green mottled rootlet beds, of siltstone or mondstone, occur at several horizons.

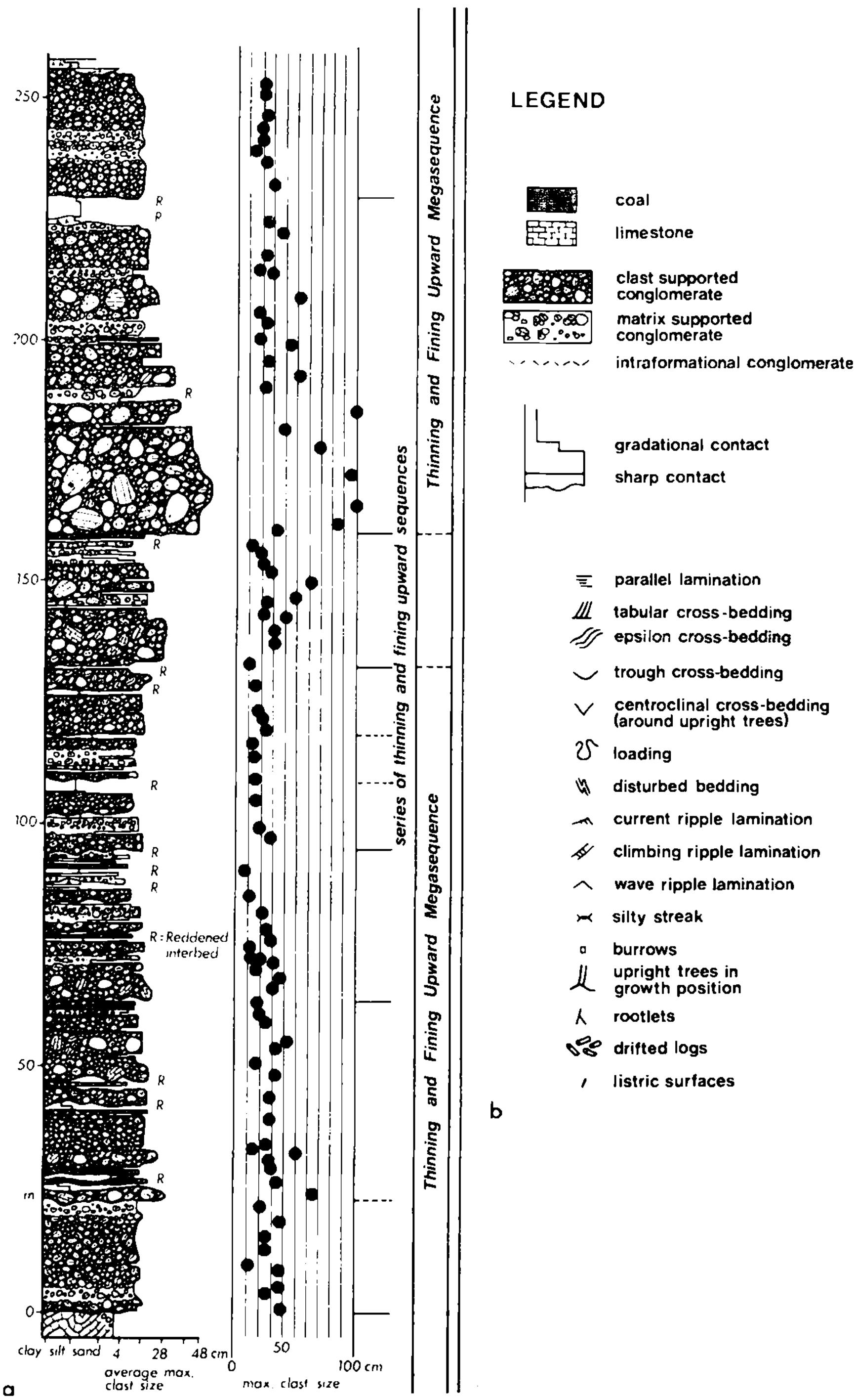


Fig. 4. (a) Section through conglomeratic part of valley-fill at Correcillas, Matallana coalfield; see Fig. 3b for location. (b) Legend to figures in this paper.

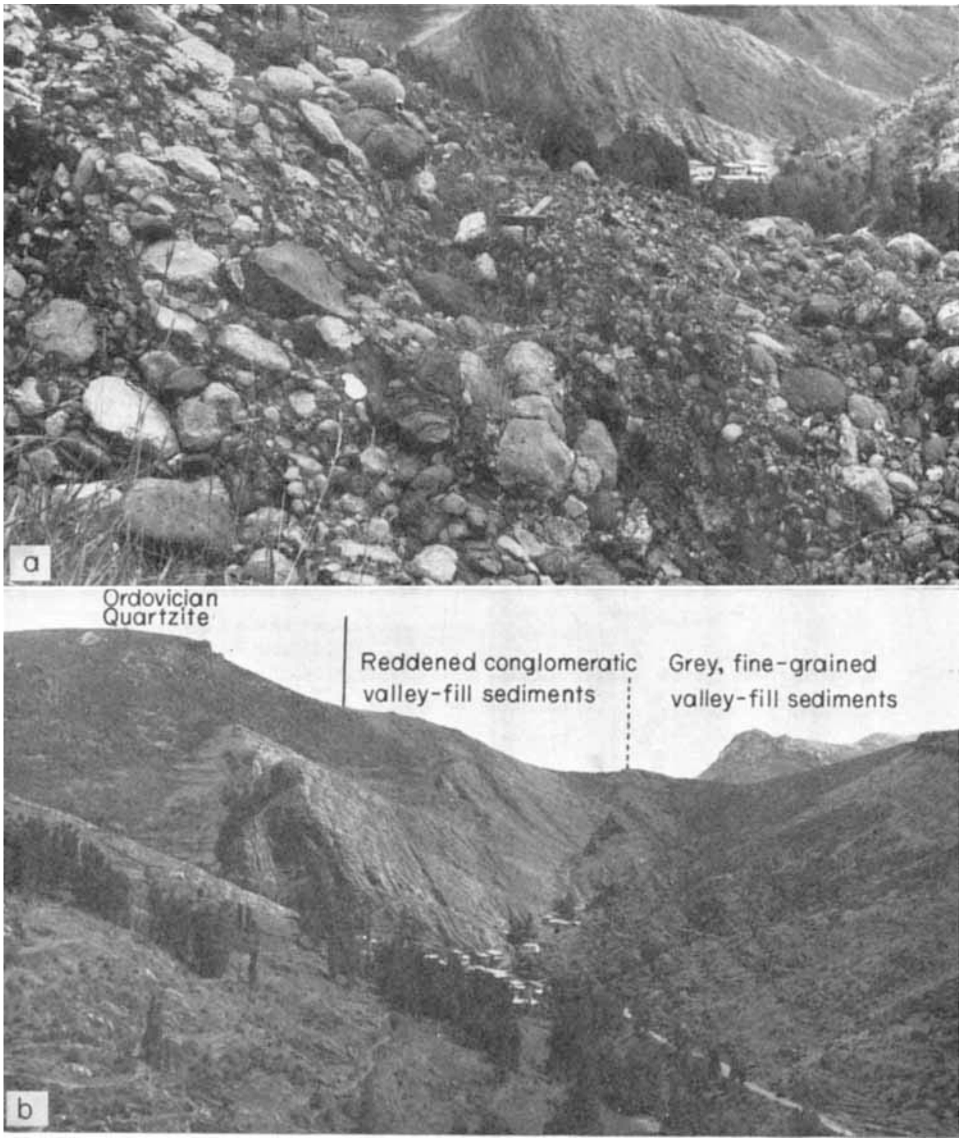


Fig. 5. Valley-fill sediments at Correcillas, Matallana coalfield. (a) Polymodal, clast supported, bedded though unstratified pebble and boulder conglomerates, comprising sub rounded–well rounded limestone quartzite and sandstone clasts. Younging to top right; hammer handle 30 cm long. (b) View to East illustrating the lateral continuity of the individual conglomerate beds and sequences of Figs 4a and 5a. Younging to top right.

The laterally extensive conglomerate beds appear to be crudely organized into sequences, 15–65 m thick, in which bed thickness, maximum clast size and overall clast size decreases upward, and matrix support becomes more prominent upwards (Fig. 4a, thinning and fining upward sequences). These sequences are themselves broadly organized into two thinning and fining upward megasequences (Fig. 4a).

These reddened conglomerates are abruptly overlain by grey, coal-bearing, finer sediments, which still occur within the valley-fill (Fig. 3b).

In the Sabero coalfield (data from Knight, 1975), locally derived conglomerates and coal-bearing sediments occur within a Northeast–Southwest graben feature near Alejico (A on Fig. 1; Alejico Beds, Figs 2 and 3c). During the deposition of the lower formations of this coalfield, thicker successions always accumulated over the syn-sedimentary Alejico graben feature.

Interpretation

These localized basal accumulations infill palaeotopography or developing basins and are similar to deposits described by Reinemund (1955), Melton (1965), Selley (1965), McGowen & Groat (1971) and Stephenson (1972). Scree and/or colluvial debris (Leopold, Wolman & Miller, 1964; Costello & Walker, 1972) appear to be important constituents of the La Magdalena and Sabero accumulations.

The coarse grain size, lack of channelling, lateral extent, presence of clast and matrix support, and the unstratified nature of the conglomerates at Correcillas, suggest that they were probably transported by some form of mass-flow (Johnson, 1970; Fisher, 1971; Middleton & Hampton, 1973; Walker, 1975a; Lowe, 1976; Rodine & Johnson, 1976; Enos, 1977). The 15–65 m thick thinning and fining upward sequences (Fig. 4a) are perhaps comparable to submarine fan sequences of similar style, normally considered to have accumulated within major channels (Mutti & Ricci-Lucchi, 1972; Walker & Mutti, 1973; Mutti, 1974; Ricci-Lucchi, 1975; Walker, 1975b, c, 1977; van Vliet, 1978).

The infilling and burial of these palaeotopographic depressions implies that source areas were uplifted relative to basins. Coals require a high water table for their preservation, which is of significance when the underlying bedrock was commonly limestone. The reddened Precambrian surface in La Magdalena suggests that the localized reddening of these deposits is Stephanian. The nature of the reddening, its sporadic occurrence and the red-green mottled rootlet beds at Correcillas appear compatible with a diagenetic origin (van Houten, 1964; Walker, 1967, 1974).

Alluvial fan channel association

Description

Twenty to thirty channels were observed cutting into sediments of the mid-fan lobe, interlobe and distal fan associations (Figs 6 and 7). Width thickness ratios vary from 4 – 25 for channels filled with clast supported conglomerate, to 9 – 38 for channels filled by sandstone or pebbly sandstone. Fills are massive or cross-bedded and in most cases infill appears to have been rapid. A few large conglomerate filled features may have been supply channels to down-fan areas (Fig. 6a). However, the absence of lag conglomerates, lack of sorting, rare stratification and the overall nature of many others suggests they result from major erosive floods rather than prolonged channel occupation (Fig. 7a). The orientations of channels and their internal sedimentary structures are similar to palaeocurrents from adjacent sediments, suggesting that they paralleled the general direction of sediment dispersal (Fig. 7b).

Interpretation

The interpretation of the described examples as alluvial fan channels depends on

Fig. 6. Alluvial fan channels. (a) Clast supported, congomerate filled channel, 150 m wide and 60 m deep, cut into finer-grained distal fan sediments. Younging to top right. Correcillas, Matallana coalfield. (b) Channellized, matrix supported conglomerates and coarse sandstones eroded into finer-grained distal fan sheet sandstones. Younging to top right. Aq = aqueduct. Vegacervera, Matallana coalfield.

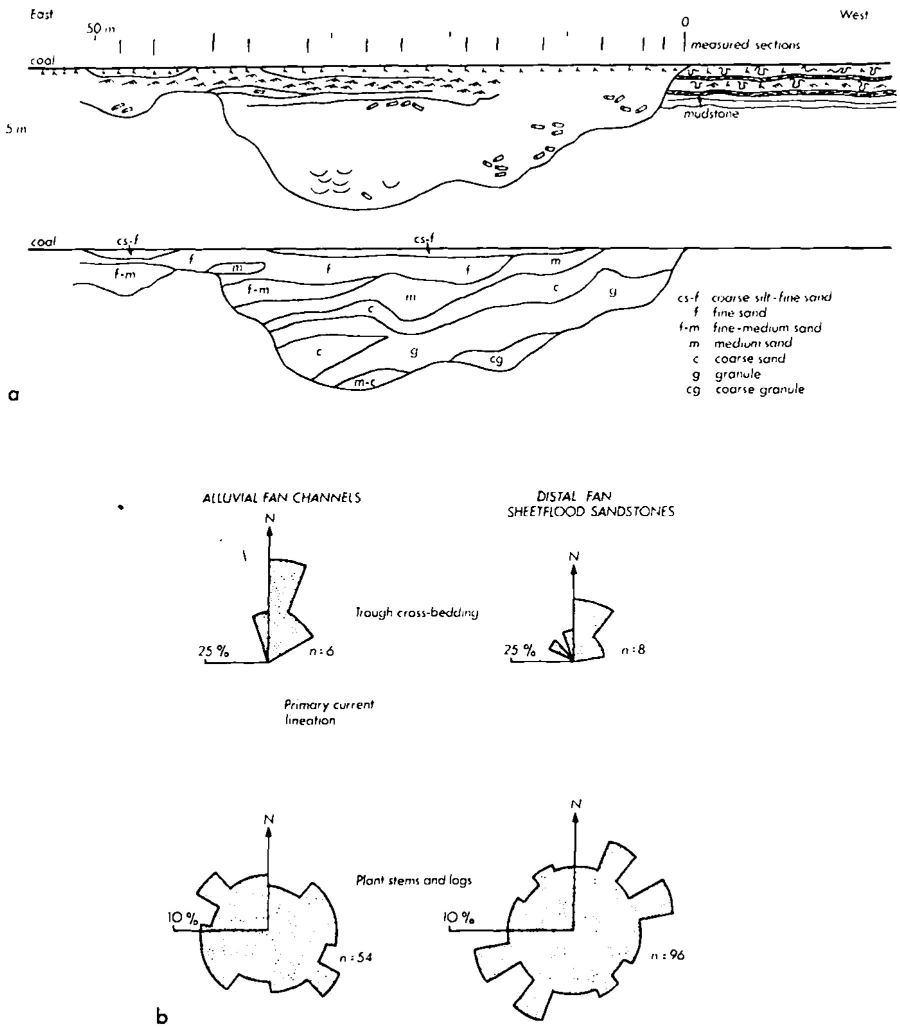


Fig. 7. Alluvial fan channels. (a) Internal structures and grain size distribution within a sand-filled channel. Near La Magdalena, La Magdalena-Mora de Luna road. (b) Comparison of the palaeocurrents from two sand filled channels with those from adjacent distal fan sheetflood sandstones. Location as above.

their occurrence within a series of sedimentary associations which are most readily explained in the context of alluvial fans. The coarseness, rapid variation in grain size, lack of sorting, mode of infill and the described palaeocurrent pattern may be typical of alluvial fan channel deposits (cf. Hunt & Mabey, 1966; Bull, 1972).

Mid-fan conglomeratic and sandstone lobe association

Description

Thickly-bedded (1–25 m), coarse sandstones, pebbly sandstones and conglomerates occur as laterally extensive units from 100s m–km. The considerable variation within this association can be viewed in terms of four specific facies, unstratified conglomerates, stratified conglomerates, pebbly sandstones and cross-bedded sandstones

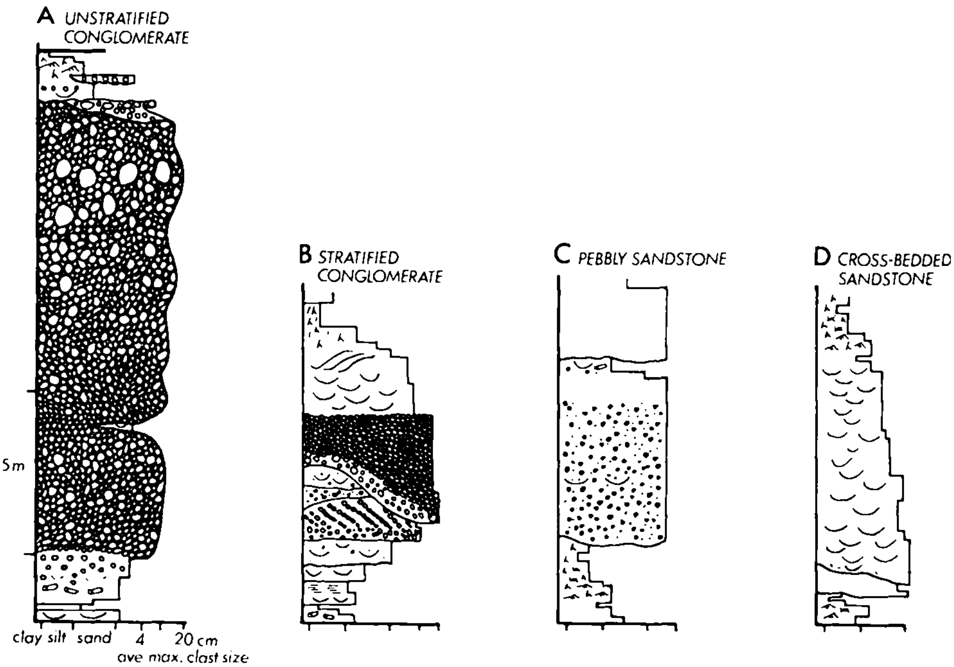


Fig. 8. Examples of the four facies which can occur singly or combined within mid-fan lobe deposits. Sections adjacent to La Magdalena-Mora de Luna road.

(Fig. 8). Lobe sequences may comprise a single or combination of facies which may have sharp or gradational contacts with one another both vertically and laterally. The thickness of these deposits and their lateral extent indicate that large volumes of sediment were involved in their accumulation. Broad patterns of occurrence and the interbedding and lateral gradation of the different facies implies that these deposits, whilst differing in processes of transport and accumulation are related to the same sort of depositional event.

Individual lobe sequences are separated by finer-grained (interlobe) sediments, siltstones, rootlet beds and thin coals (Figs 13 and 14). Lobe sequences are sharp based, marked by a dramatic increase in grain size and show only minor evidence of erosion, some rest without erosion on thin interlobe coal seams.

Unstratified conglomerates (Figs 8A and 9) are well rounded, polymodal and are commonly clast supported. Clast size varies up to 50+ cm and the average clast size is normally in excess of 5–10 cm. Clast support occurs most frequently with coarser grained conglomerates. Unstratified conglomerate beds (1–25 m thick) are laterally extensive over 100s m (Fig. 14b) up to 5 km. They are composed of relatively homogeneous conglomerate (Fig. 9a), but contain occasional cross-bedded sandstone lenses. Vertical trends in clast size illustrate that sand lenses separate depositional events, or pulses of sedimentation within an event (Fig. 10a), and also indicate the common presence of inverse and normal grading (Walker, 1975a). In Fig. 10b it is of interest to note the occurrence of inverse grading in sections where the clast supported conglomerate is thickest and the passage laterally into normally graded conglomerate as the bed thins to the East.

Fig. 9. Mid-fan lobe. (a) Coarse-grained, clast supported unstratified conglomerates, comprising well rounded quartzite clasts. Younging to top left; red mini-van 3·2 m long. La Magdalena-Mora de Luna road, north of Garaño. (b) As above, conglomerate considered to be the product of a debris flow event. The overlying fine conglomerates and cross-bedded sandstones possibly being declining floodwater deposits. Younging to top right; pick handle 75 cm long. Location as above.

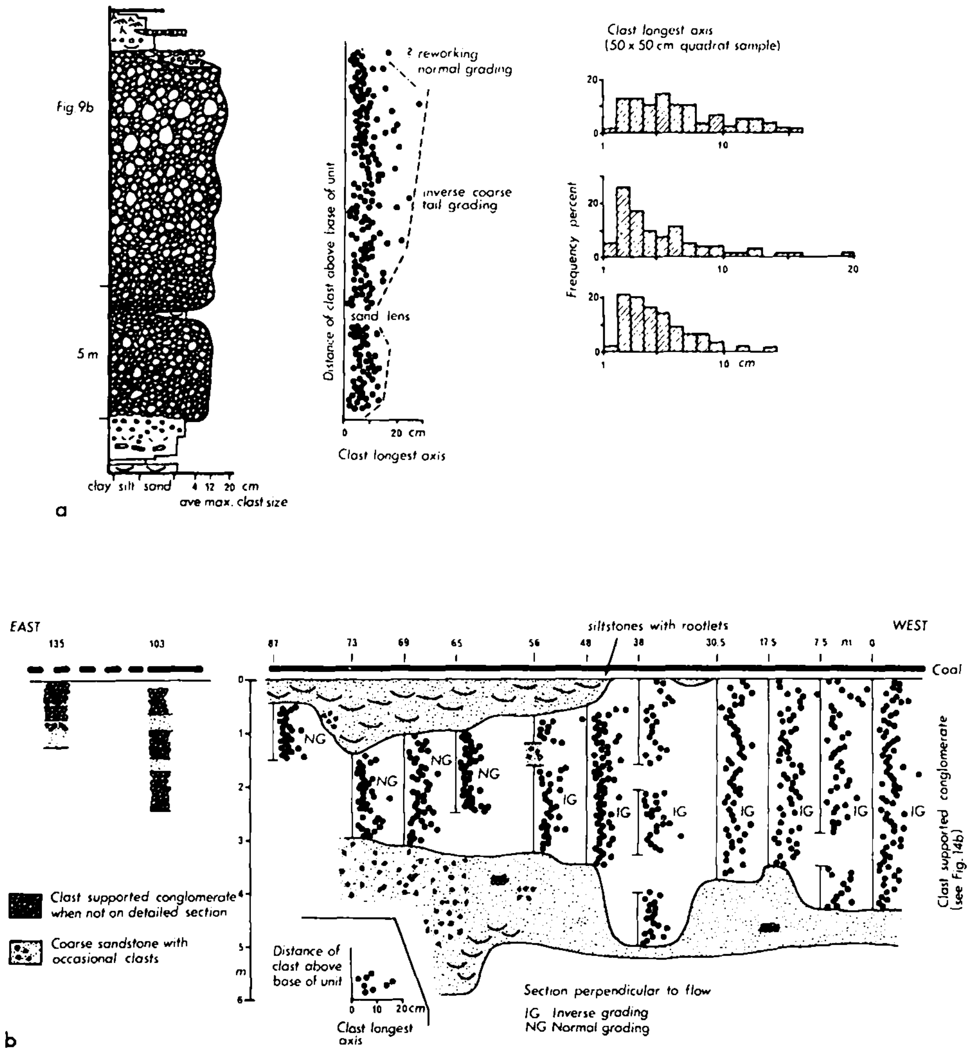


Fig. 10. Trends in clast size across mid-fan unstratified conglomerates. La Magdalena-Mora de Luna road, north of Garaño.

A thin horizon of coarse pebbly sandstone occurs at the base (Figs 8A, 10b and 14b) and the uppermost few cm–m of these conglomerates are normally graded and may be overlain by finer-grained matrix supported conglomerate and/or a discontinuous horizon of cross-bedded sandstone (Fig. 9b).

Imbrication is occasionally directly observed and is frequently indicated by clast long axes orientations (Fig. 11). The clast fabric consists of an imbricate 'a' long axis parallel to flow, as indicated by adjacent cross-bedding measurements, and the intermediate 'b' axis transverse to flow. This type of fabric is particularly common in the resedimented submarine conglomerates of Davies & Walker (1974) and Walker (1975a, d, 1977) who suggest it results from clast deposition from suspension. It contrasts with an 'a' axis transverse to flow and imbricate 'b' axis fabric considered to

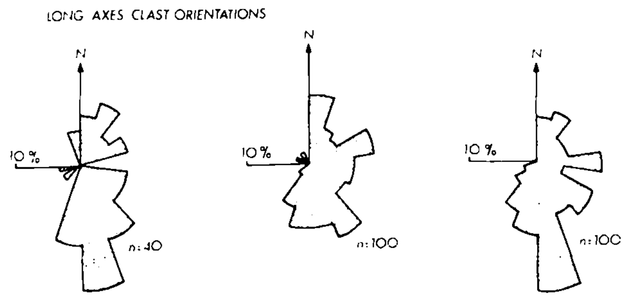


Fig. 11. Three examples of clast fabrics from mid-fan unstratified conglomerates illustrating the general occurrence of an 'a' axis imbrication (parallelling palaeoflow, the latter derived from adjacent cross-bedding). La Magdalena-Mora de Luna road, north of Garaño.

result from bedload rolling (Rust, 1972; see also Enos, 1977, for discussion of conglomerate fabrics).

Stratified conglomerates (Figs 8B and 12) are considerably less common and occur as beds 1–5 m thick. They consist of clast, or more rarely, matrix supported fine conglomerates (clast size is normally less than 5 cm). Minor channelling, tabular cross-bedding and parallel stratification occur (Fig. 12).

Pebbly sandstones (Fig. 8C) occur in units 1–13 m thick which are massive or

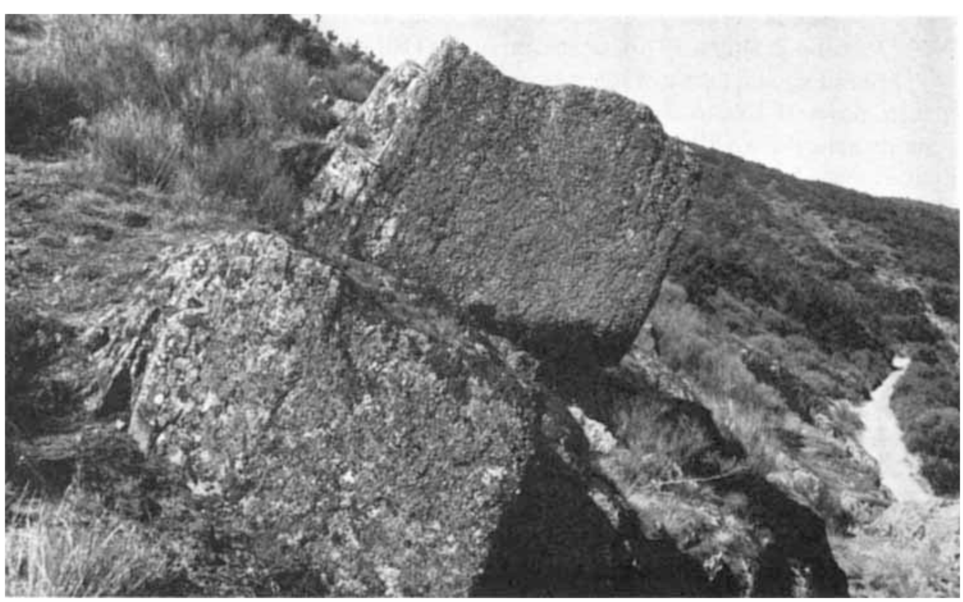


Fig. 12. Fine-grained, faintly parallel stratified mid-fan conglomerate overlain by a trough cross-bedded coarse sandstone. Younging to top left; hammer handle 40 cm long. West of Garaño, La Magdalena coalfield.

cross-bedded. Clasts are sparse, generally 1–3 cm long (max. ca. 10 cm). Drifted tree trunks are abundant.

Cross-bedded sandstones (Fig. 8D) occur in units 1–7 m thick which vary irregularly from coarse to fine-grained. Trough cross-bedding predominates, although parallel bedding and irregularly bedded sandstones containing abundant drifted tree trunks also occur. Water escape structures are common.

The relative occurrence of unstratified conglomerates, stratified conglomerates, pebbly sandstones and cross-bedded sandstones is illustrated in the basal part of the La Magdalena succession (Fig. 13), where both thinning and fining, and thickening and coarsening upward megasequences occur. In the thinning and fining upward megasequence (Fig. 13A), the decrease in bed thickness and grain size is parallelled by an overall change in the predominant type of lobe facies from unstratified conglomerate to stratified conglomerate to pebbly sandstone to cross-bedded sandstone. A reverse pattern occurs in the coarsening upward megasequences (Fig. 13B, C). Finer-grained coal-bearing interlobe deposits occur interbedded throughout.

Interpretation

The unstratified conglomerates could be interpreted as debris flow deposits, reworked debris flow deposits, or be the deposits of powerful streams. The sharp non-erosive bases, occurrence in well-defined relatively thick units, absence of stratification (although in coarse conglomerates the latter may not occur), lack of sorting, presence of inverse and normal grading, presence of imbrication, and the nature of the fabric are all in accord with transportation and deposition by a debris flow mechanism (Beaty, 1963, 1970, 1974; Bull, 1964a, 1972; Hooke, 1967; Johnson, 1970; Fisher, 1971; Middleton & Hampton, 1973; Walker, 1975a; Lowe, 1976; Enos, 1977), and argue against a reworked debris flow (Beaty, 1963; Hooke, 1967; Broscoe & Thomson, 1969; Johnson & Rahn, 1970), or stream origin (Nilsen, 1969, Vaeroy Conglomerate).

The grading and fabric of these unstratified conglomerates indicate that clasts were free to move relative to one another. Inverse grading is a common feature of highly concentrated flows (Middleton, 1970; Walker, 1975a, b, c). Whether these coarse-grained mass-flows relied primarily on a matrix phase of water and clay, clast dispersive pressure, or turbulence for their continued motion is debatable, however, their deposits are more closely analogous to the turbulent resedimented conglomerates of Davies & Walker (1974), Walker (1975a, c, 1977) and Hendry (1976), than to Walker's (1975a) predicted characteristics for subaerial debris flows. The non-erosive bases of the described examples imply limited turbulence, and flow was most probably in a laminar fashion (Johnson, 1970). The rarely occurring matrix supported conglomerates correspond more closely to Walker's (1975a) characteristics and to ancient sediments interpreted as subaerial mudflows or debris flows (Bluck, 1967; Miall, 1970; Steel, 1974; Steel & Wilson, 1975). These matrix supported conglomerates and some unstratified pebbly sandstones may be viewed as the product of more viscous or more dilute mass flows, occurring as separate events, or laterally to, or downflow from, clast supported conglomerates (Beaty, 1963, Figs 2–4).

Unstratified conglomerate units may represent a single depositional event, a series of pulses within an event (cf. Sharp & Nobles, 1953; Beaty, 1963; Bull, 1964a; Johnson, 1970; Johnson & Rahn, 1970; Wasson, 1974), or several different periods of accumulation. Generally they exhibit a single inverse trend in clast size, suggestive of a

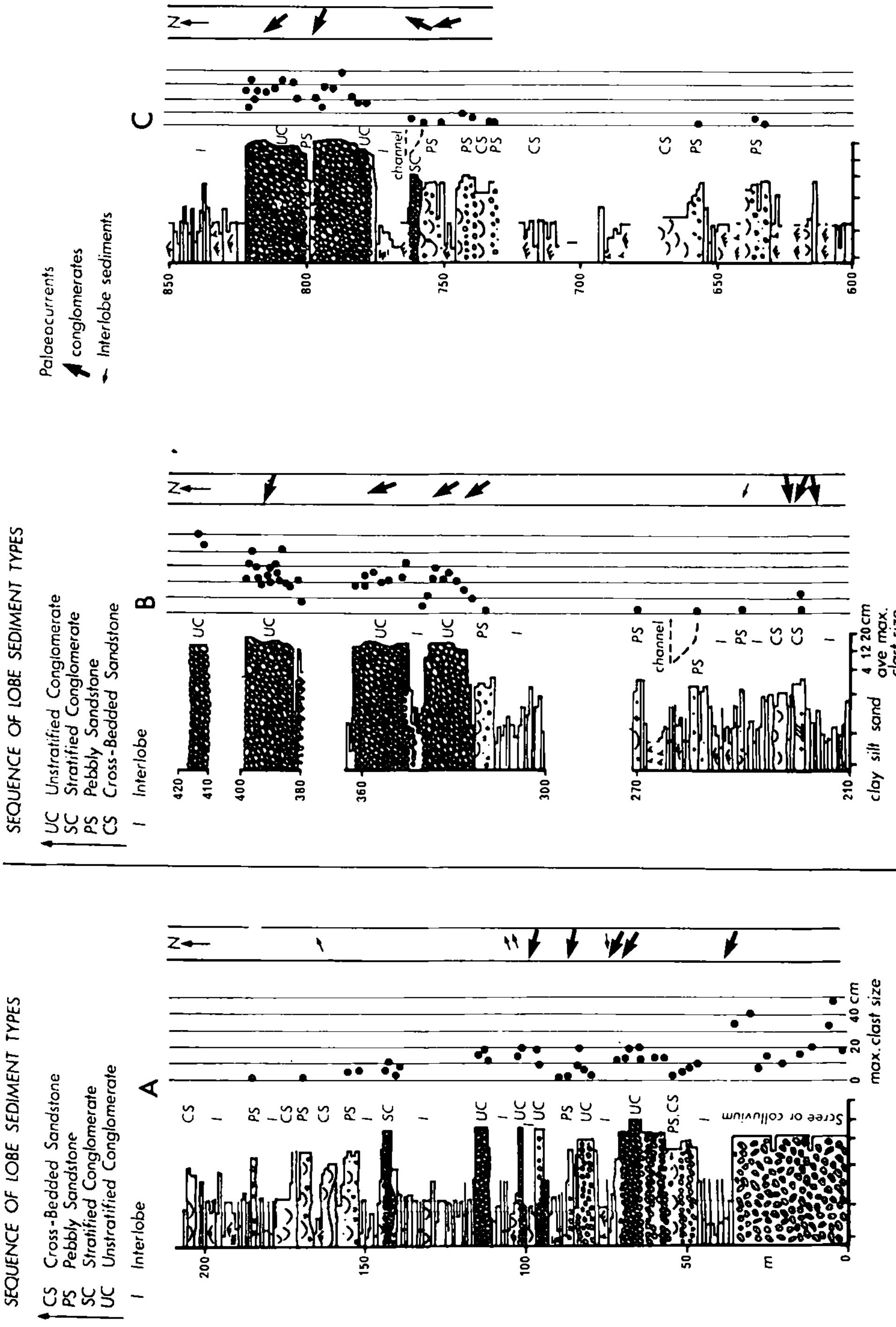


Fig. 13. The occurrence of the four types of mid-fan facies within the alluvial fan megasequences of the basal La Magdalena succession. La Magdalena-Mora de Luna road.

single phase of accumulation (Fig. 10b). Other conglomerate units may be the product of at least two phases of accumulation whose timing is uncertain (Fig. 10a). In comparison with the dimensions of recent debris flows (Beaty, 1963, 1974; Hooke, 1967; Johnson, 1970; Johnson & Rahn, 1970; Rodine & Johnson, 1976) it appears that most of these unstratified conglomerates accumulated as the result of very large flood events.

The cross-bedded sandstone lenses which separate conglomerates and the discontinuous sandstones which cap conglomerate beds are interpreted to be deposits of the declining floodwater stage known to accompany and in particular succeed debris flows (Chawner, 1935; Sharp & Nobles, 1953; Beaty, 1963, 1974; Wasson, 1974; probable ancient examples: Bluck, 1967; Steel, 1974).

Stratified conglomerates are finer-grained and better sorted than the debris flow deposits, which combined with their stratification and associated minor channelling, suggests deposition from turbulent water. They compare closely to the streamflood deposits of Bluck (1967), Steel (1974) and Steel & Wilson (1975).

In the pebbly sandstones and cross-bedded sandstones, the common occurrence of stratification and cross-stratification implies that tractional activity of turbulent streamflows was important in their deposition. The prominence of dewatering structures may result from rapid accumulation.

The thickness and relative coarseness of the previously described deposits suggest they occupy a comparatively proximal fan position and hence are termed 'mid-fan lobe deposits'. The exact geometry of mid-fan lobe deposits (whether convex-upward or convex-downward in cross-section) remains to be established, however, their lateral extent indicates accumulation on topographically smooth surfaces lacking channels that might concentrate deposition (Beaty, 1963, 1974; Lustig, 1965). The occurrences of thin coals within the interbedded (interlobe) deposits implies that major depositional events were separated by considerable periods of time. Palaeocurrents for lobe deposits in each of the coalfields suggest sediment sources to the South and Southeast (Figs 11 and 13; Heward, 1976).

The distribution of the four basic types of mid-fan facies in the megasequences of Fig. 13 can be interpreted in terms of increasing or decreasing proximality of flood deposits. A depositional model can be envisaged of proximal coarse unstratified conglomerates (debris flows), passing downfan into fine stratified conglomerates (turbulent streamflows), in turn passing into pebbly sandstones, or cross-bedded sandstones (turbulent streamflows). During the progradation or gradual abandonment of a fan segment increasingly proximal or distal flood deposits accumulated (Fig. 13), as suggested elsewhere by Bluck (1967), Steel (1974) and Steel & Wilson (1975).

On modern alluvial fans grain size decreases downfan and downflow (Eckis, 1928; Sharp & Nobles, 1953; Beaty, 1963; Bluck, 1964; Denny, 1965, 1967; Lustig, 1965; Hunt & Mabey, 1966; Bull, 1972; Meckel, 1975; Tanner, 1976). With regard to the downflow change in process, the transition debris flow–turbulent flow can result from dilution in sub-aqueous environments (Hampton, 1972), subaerially such a transition may be questioned. However, on modern semi-arid fans, sedimentation near the fan apex is commonly the result of debris flows or mud flows (Beaty, 1963, 1974; Hooke, 1967). On the lower portions of fans, sediments are normally water borne, by floods either accompanying proximal mass-flows, or by lesser storms reworking these proximal sediments (Chawner, 1935; Beaty, 1963; Denny, 1965, 1967; Hooke, 1967; Rahn, 1967; Johnson & Rahn, 1970).

Interlobe and ?interchannel association

Description

Massive siltstones, fine-grained rippled sandstones, rootlet beds and thin coals occur as 2·5–26 m interbeds (mean 10·9 m) between mid-fan lobe deposits (Fig. 14). Individual beds are normally cm–m in thickness and laterally continuous over 10s m of outcrop. Well preserved plants abound (Fig. 14a), and dewatering structures and upright and tilted tree trunks are characteristic (Fig. 14d). Sand grade sediments around these trees are frequently centroclinally cross-bedded (Underwood & Lambert, 1974). Sparse palaeocurrents parallel and also diverge from those of adjacent lobe accumulations (Fig. 13).

Interpretation

These sediments were deposited in the intervals between, or lateral to, lobe depositional events. Many of their characteristics suggest periodic rapid deposition (cf. Elliott, 1968; Broadhurst & Loring, 1970; Lowe, 1975). The centroclinal cross-bedding results from sediment accumulation in scours around upright *Calamites* and Sigillarians. Periods of non-deposition and high water tables allowed peats (coals) to form and be preserved. The absence of siderite nodules, normally abundant in fine-grained coal-bearing deposits, may result from better drainage conditions.

It is suggested that these interlobe deposits are the result of minor floods. The laterally extensive and rapidly accumulated, massive siltstones and rippled sheet sandstones, are probably sheetflood deposits (McGee, 1897; Rahn, 1967; Bull, 1972; Thorbecke, 1973). The majority of the occurrences of this association are demonstratively of 'interlobe type'. Similar sediments might, however, accumulate on the interfluves between, or levees of, relatively permanent fan channels (Sharp, 1942; Hooke, 1967).

Distal fan association

Description

These sediments are characteristically fine-grained, varying from mudstones to fine sandstones, although occasional coarser sandstones also occur. Sandstone beds, 10 cm–1·5 m thick, are laterally continuous across outcrops 10s–100s m wide (Fig. 16a) and channelling is only rarely observed (Figs 6b and 16a). These sheet sandstones are sharply based, occasionally sole marked (grooves) and individual beds fine upwards. Palaeocurrents, though sparse, continue to indicate a source to the South (Fig. 7b; Heward, 1976). Intraformational conglomerates at the base of beds are overlain by parallel laminated, cross-laminated, or massive and irregularly bedded sandstones. Drifted logs are common in some of these sheet sandstones and yet absent from others. Subsequent to deposition these beds have been deformed by loading (Figs 15 and 16b, which is almost ubiquitous), or by water escape.

Sandstone beds are separated by siltstones and mudstones which vary in thickness from a few cm (Fig. 16b) up to m (Fig. 16a). Interbeds of carbonaceous mudstones, thin coals and workable coals also occur, with or without underlying rootlet beds. Well preserved plants occur within the sandstones, but particularly in the siltstones and mudstones. Upright and tilted tree trunks abound (Fig. 16b; Wagner & Artieda, 1970, their Fig. 22; Knight, 1971, his '*Calamites* forest bed').

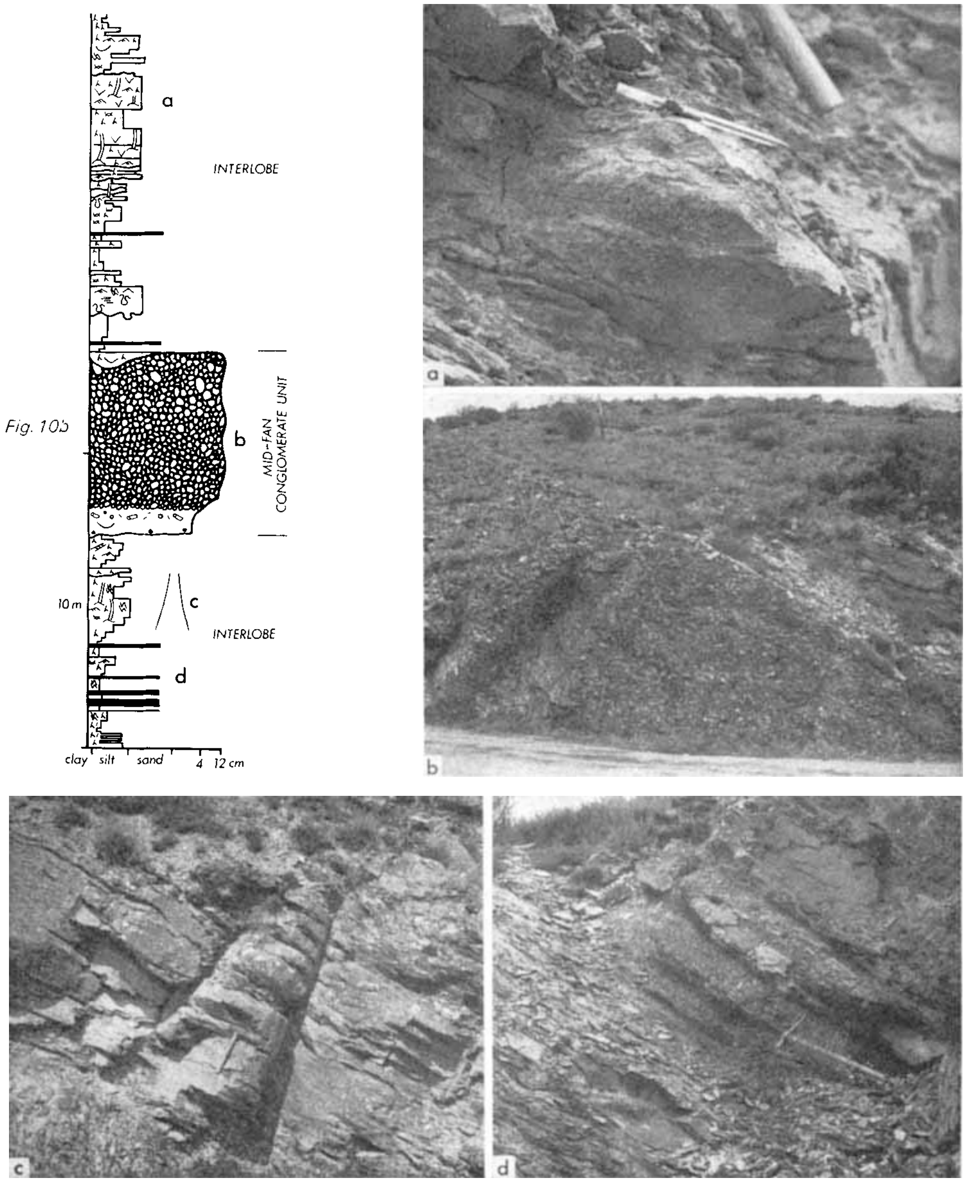


Fig. 14. Interlobe and mid-fan lobe deposits on the La Magdalena-Mora de Luna roadside. (a) Perfectly preserved fern frond lying obliquely to bedding; the latter indicated by biro, 14·5 cm long. (b) Inversely graded, laterally extensive, clast supported, mid-fan unstratified conglomerate. Younging to top right; pick handle 75 cm long. (c) Upright tree (decorticated Sigillarian) within rapidly accumulated interlobe siltstones; hammer handle 30 cm long. (d) Typical interlobe sediments: structureless siltstones (with well preserved floras), rootlet beds and thin coals. Younging to top right; pick handle 75 cm long.

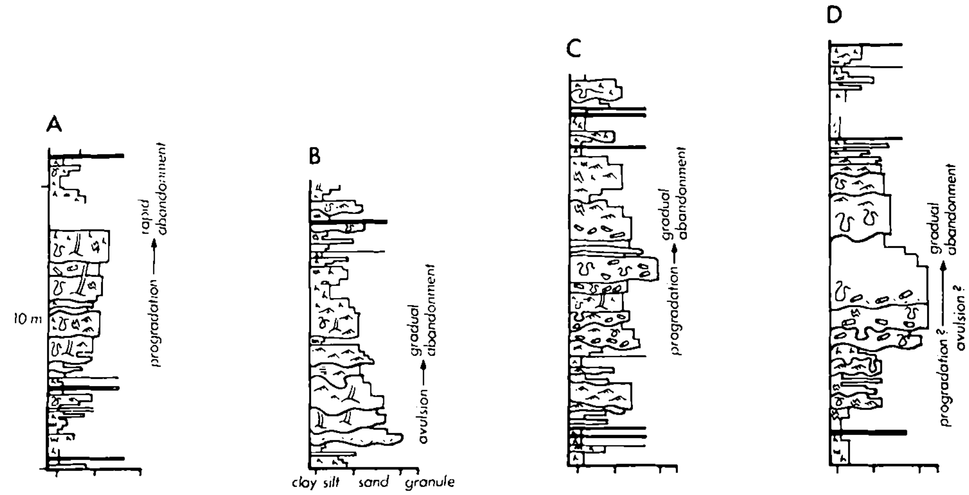


Fig. 15. Examples of distal fan sheetflood sandstone sequences, interbedded shales, rootlet beds and coals. A—asymmetric thickening and coarsening upward sequence; B—asymmetric thinning and fining upward sequence; C,D—symmetric thickening and coarsening, and thinning and fining upward sequences. Near La Magdalena, La Magdalena-Mora de Luna road.

Sandstone beds are normally arranged in packets or sequences (1·5–10 m thick), separated by coals, lacustrine sediments, or prominent rootlet horizons. Sequences of beds may be asymmetrical and generally, thicken and coarsen upward (Figs 15A and 16a), or thin and fine upward (Fig. 15B), or may be symmetrical and consist of the superimposition of the two (Figs 15C, D and 16a). Some of the thickening and coarsening upward sequences directly overlie lacustrine shales (Fig. 17D).

Interpretation

Similar accumulations of solemarked sheet sandstones occurring in coal bearing successions and containing upright trees have been described by Stanley (1968), Way (1968) and Duff & Walton (1973). They were interpreted as crevasse splays (Stanley, 1968; Duff & Walton, 1973) and the deposits of meandering streams (Way, 1968).

In the described sediments a crevasse splay origin is considered unlikely owing to the lateral continuity of sandstone beds, the failure of at least some beds to pinch out within the substantial outcrops (cf. Leeder, 1974, his Fig. 2), the vertical persistence of this type of sedimentation for 100s m, the absence of adjacent vertically stacked channel complexes, and the general parallelism of palaeocurrents with those of other associations and with the orientations of minor channels.

Laterally extensive, sharply based sandstones, which fine upwards, might be interpreted as shallow meandering stream deposits (Allen, 1964, 1965b, 1970). There are few differences in thickness or character between these sheet sandstones and some interpreted meandering stream sequences. However, the absence of epsilon cross-stratification and the abundance of upright trees and well-preserved plants argues against a meandering stream origin.

In contrast a sheetflood origin provides a depositional mechanism capable of explaining the characteristics of these sheet sandstones (McGee, 1897; Rich, 1935; Davis, 1938; Bull, 1964a, 1972; Rahn, 1967; Thorbecke, 1973; for descriptions of

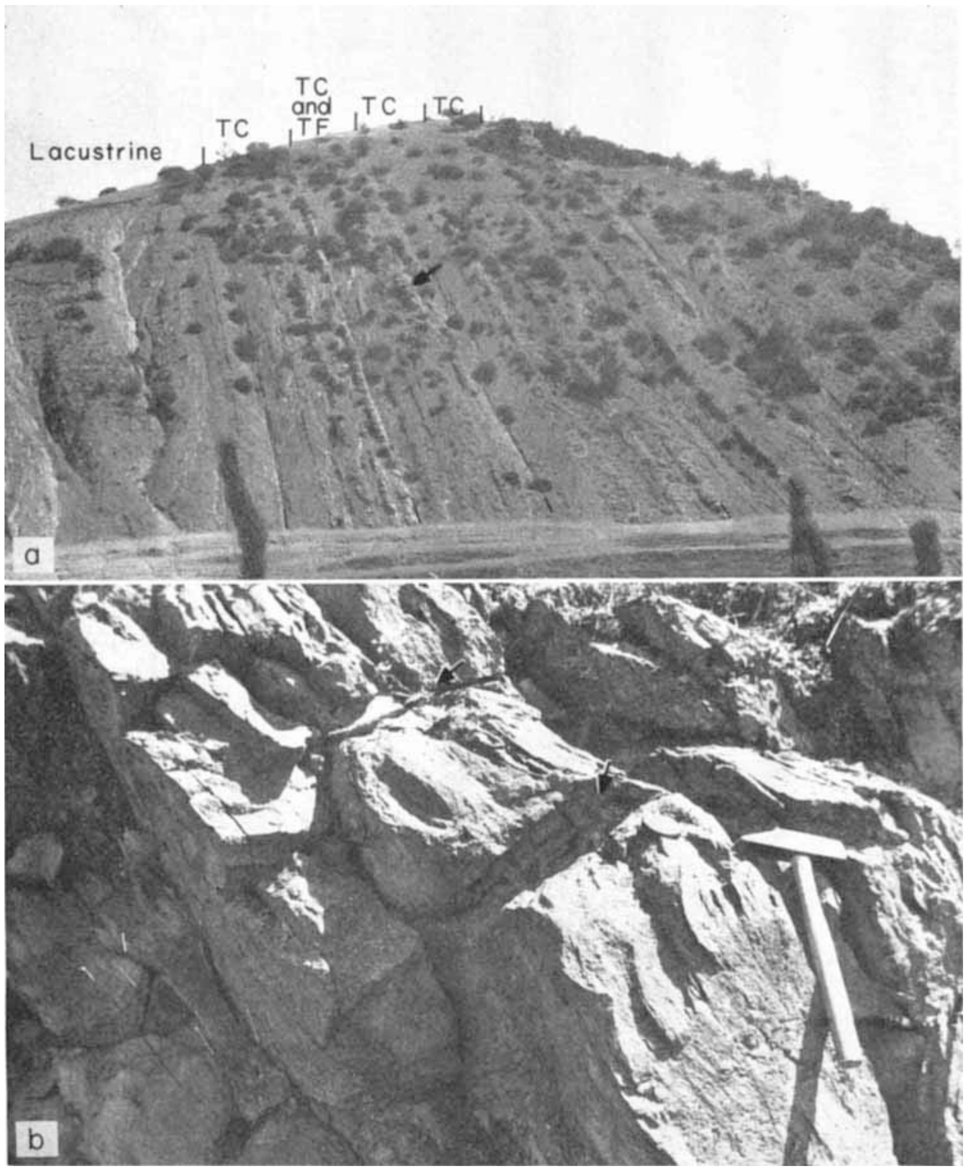


Fig. 16. Distal fan. (a) Sheetflood sandstone sequences: TC=thickening and coarsening upward, TF=thinning and fining upward. 1·5 m deep sand filled channel arrowed. Younging to top right. North of Saelices, Sabero coalfield. (b) Upright and tilted *Calamites* (arrowed) passing through a series of loaded sheetflood sandstones separated by thin shales. Younging to top right; hammer handle 30 cm long. Near La Magdalena, La Magdalena-Mora de Luna road.

modern events and deposits, and Cummins, 1958; Laming, 1966; for interpreted ancient deposits).

Sediments of this association occur interbedded with those of the lacustrine association and also with the distal representatives of the mid-fan lobe association (Heward, 1976 for detailed sections). Periodic sheetfloods are considered to have led to the rapid accumulation of sheet sandstones, as suggested by the presence of upright trees and the abundance of dewatering structures (Broadhurst & Loring, 1970; Lowe, 1975). Minor or waning floods may be represented by the interbeds of siltstone and mudstone. Individual sheetflood events were normally separated by sufficient time to allow the colonization and growth of plants to considerable size on the surface of previous deposits. Longer breaks in sedimentation allowed plant debris to accumulate, resulting in carbonaceous mudstones, thin coals and coals of workable thickness (20 cm–1·5+ m).

The thickening and coarsening upward, and thinning and fining upward sequences of sheetflood sandstones (Figs 15 and 16a) may be analogous to outer fan and fan fringe turbidite sequences of similar style (Mutti & Ricci-Lucchi, 1972; Walker & Mutti, 1973; Mutti, 1974, 1977; Ricci-Lucchi, 1975; van Vliet, 1978). The organization of these sandstones into sequences suggests that the sheetfloods are distal representatives of mid-fan lobes undergoing progradation or abandonment, rather than the of variable storm events reworking older proximal fan deposits. Thus, the style of the sequences reflect the gradual or abrupt, initiation and termination of sedimentation within a depositional segment (Figs 15 and 16a). The minor channels occasionally observed in this association (Figs 6b and 16a) probably resulted from obstructions to sheetflow (McGee, 1897), or were eroded during more turbulent flood events.

Lacustrine association

Description

Lacustrine coarsening upward sequences, 5–140 m thick, are prominently developed in each of the coalfields (Figs 17 and 18). They are of two types, defined by thickness and lateral extent.

Large-scale sequences (15–140 m thick) coarsen upward from bioturbated black faunal mudstones, through grey shales with thin solemarked sandstones and into fine-grained sandstones (Fig. 17A, B). These fine-grained sandstones are parallel laminated (at times with primary current lineation), cross-laminated, and tabular or trough cross-bedded. The upper boundary of sequences is delimited by the first evidence of emergence and plant colonization. These thick sequences comprise the prominent mappable shale formations of the coalfields (e.g. Cascajo Formation of Matallana, Gonzalo and Quemadas Formations of Sabero, Fig. 2). Northward sediment transport paths continue to predominate within this association.

Small-scale coarsening upward sequences (5–20 m thick) are typically less extensive than their large-scale counterparts (Figs 17C, D and 18). Parallel laminated or bioturbated faunal grey shales are normally succeeded by laminated and cross-laminated siltstones and fine-grained sandstones. Commonly, in the upper parts of these small-scale sequences, distal fan sheet sandstones occur (Fig. 17D). In the sequence illustrated by Fig. 18, individual beds, characterized by degree of cementation, rippling, wave rippled top surfaces, or loading, were found to be laterally extensive across the outcrop (120 m). Thin ostracod and *Spirorbis* bearing limestones (5–20 cm) occur

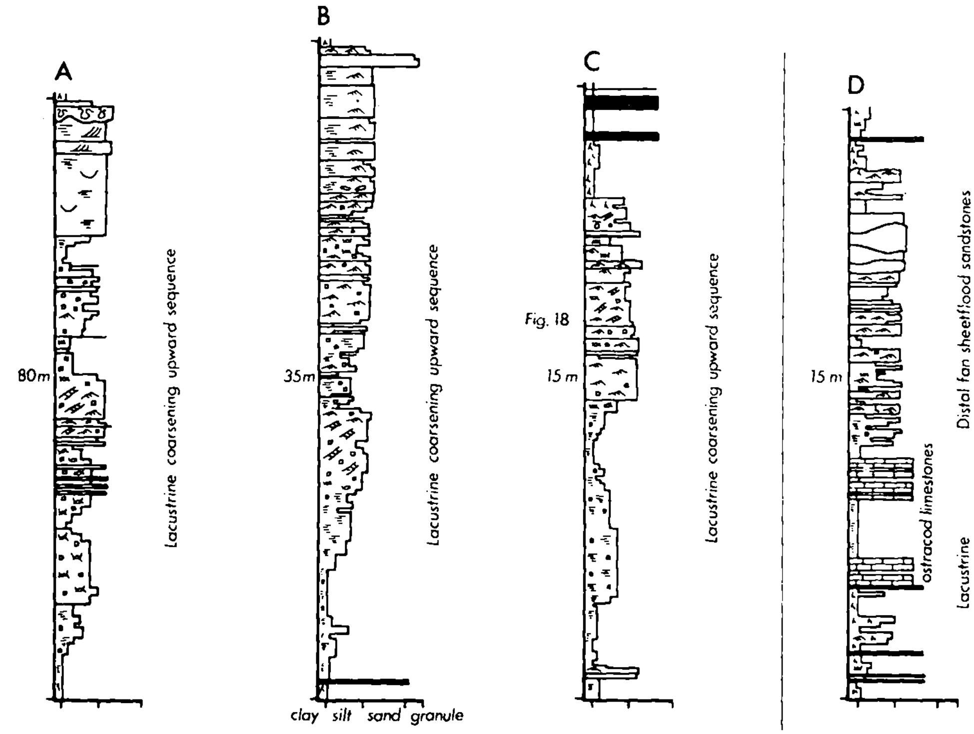


Fig. 17. Examples of lacustrine coarsening upward sequences (note differing scales). A—north of Saelices, Sabero coalfield; B—near La Magdalena, La Magdalena-Mora de Luna road; C and D—Vegacervera, Matallana coalfield.

interbedded with grey shales at the base of several of these sequences in the Pastora Formation of the Matallana coalfield (Figs 2 and 17D). These limestones consist of smooth, thin shelled ostracods (*Carbonita*), and *Spirorbis*, in a calcitic matrix containing only minor amounts of detrital clay.

Fresh-water faunas typify the finer-grained portions of both types of coarsening upward sequence and consist of the phyllopods *Leaia* and *Estheria*, the smooth shelled ostracod *Carbonita* and the non-marine bivalves *Anthraconauta* and *Anthraconaia* (Wagner, 1971b; Knight, 1971, 1974, 1975; Eagar & Weir, 1971; Heward, 1976). Slightly brackish Niaditids have also been recorded by Knight (personal communication) and the limited occurrences of brackish-marine faunas have been mentioned previously.

Some of the thickest coals of the Matallana and Sabero coalfields occur, in association with, or immediately succeeding lacustrine deposits. Fig. 19 illustrates the Pastora seam of Matallana which attains untectonized thicknesses in excess of 20 m. This seam represents the combination of thinner coals to the West and passes quite abruptly into a basin centre lacustrine shale lens (Wagner, 1971b). Wagner suggested a Northwest-Southeast lake with a marginal swamp facies, the coal forming from the accumulation of *in situ* vegetation and drifted plant remains.

Interpretation

These deposits, consisting predominantly of fresh-water faunal shales, have previously been regarded as lacustrine (Evers, 1967; Wagner & Artieda, 1970; Wagner,

Fig. 18. Small-scale coarsening upward sequence (see Fig. 17C) and lacustrine-distal fan sequences. L = lacustrine, TC = thickening and coarsening upward sheetflood sandstones, Aq = aqueduct. Younging to top right. Vegacervera, Matallana coalfield.

1971b; Knight, 1971, 1974, 1975). They have many features considered indicative of lacustrine sediments (Visher, 1965; Picard & High, 1972) and are closely comparable with specific ancient lacustrine deposits (Klein, 1962; Belt, 1968; Duff & Walton, 1973; van de Kamp, 1973; Hubert *et al.*, 1976).

Studies of lacustrine sedimentation suggest that lakes can infill in at least two ways; by peripheral accretion, including simple progradation of the shoreline or the outbuilding of lacustrine deltas, or by the rather uniform deposition of silts and clays over the entire lake area (Visher, 1965; Picard & High, 1972; van de Kamp, 1973).

The described sequences, with their apparent lack of channels, which might be indicative of lacustrine deltas (McEwen, 1969; Butzer, 1971; Stephen & Gorsline, 1975), suggest gradual shoreline progradation into a low-energy lake. Furthest out in the lake only suspended sediment accumulated, whilst near the shore, downslope directed tractional currents and sporadic reworking occurred. With the possible exception of granule sized beds of lithic fragments in some La Magdalena sequences (Fig. 17B) there seems no evidence of lacustrine beach deposits (Butzer, 1971; Hooke, 1972; van de Kamp, 1973; Wasson, 1974). A model may be envisaged of an alluvial shoreline building out during flood events, which extended to, and beyond, the fan base (Butzer, 1971, Fig. 2.34).

Apart from one exception (distal representative, cross-bedded sandstone, of a mid-fan lobe deposit), these lacustrine deposits were observed interbedded with sediments of the distal fan association. These lacustrine intervals imply the development of a lake covering, what was formerly, part of the distal fan. Many of the small-scale sequences of variable extent could be the product of changes in lake level, a feature characteristic of modern lakes (Butzer, 1971; Picard & High, 1972; Coventry, 1976). Others could result from the infilling of lagoons which might typify some areas of fan shoreline

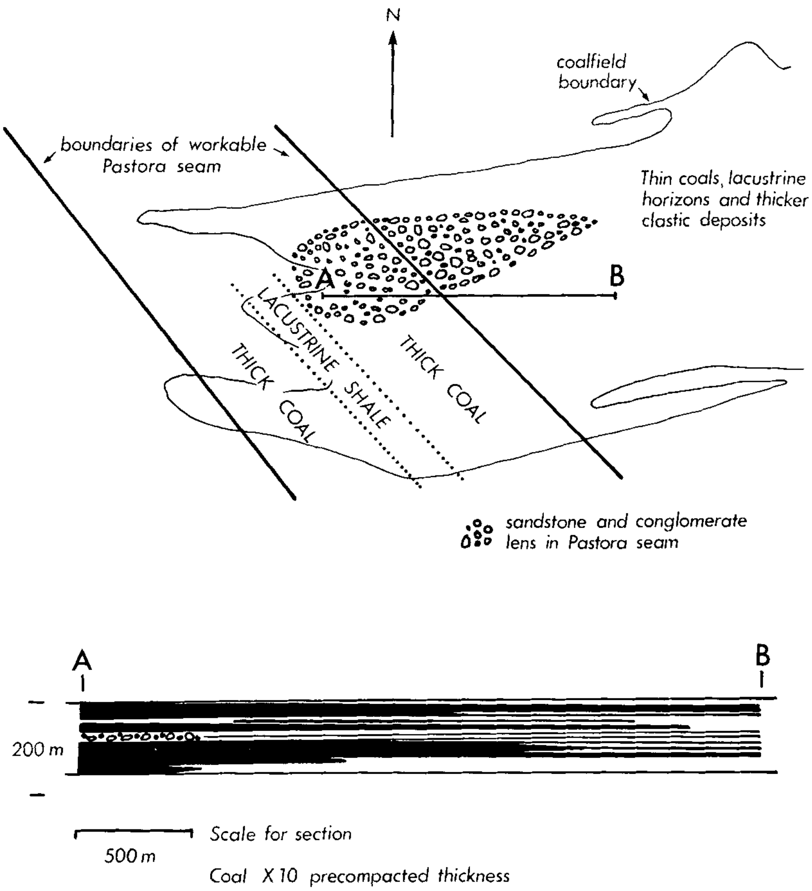


Fig. 19. Thickness and facies changes within the Pastora coal seam, Matallana coalfield; after Wagner (1971b).

(Butzer, 1971, Fig. 2.34). Other small-scale sequences and their larger counterparts, probably result from the abandonment and subsidence of depositional fan segments, or from tectonic readjustments affecting the depositional basin (Hooke, 1972).

The occurrence of very thick coals is common in lacustrine settings (Hacquebard & Donaldson, 1969). In addition to the area being totally removed from clastic sediment supply, rates of subsidence and plant accumulation must have been similar to producc thick coals. The development of a basin centre shale lens in the Pastora seam (Fig. 19) compares with an example described by Bouroz (1960) from the Dauphiné Basin, France, and is in contrast to the basin centre clean coal and marginal shale reported by Hacquebard & Donaldson (1969).

THE OCCURRENCE OF THE ASSOCIATIONS WITHIN THE LA MAGDALENA, MATALLANA AND SABERO COALFIELDS

The broad distribution of the six associations within the observed parts of the coalfield successions is illustrated in Fig. 2. The probable predominant palaeo-locations of these three successions, in terms of an alluvial fan model (to be described), are indicated on Fig. 20a. These represent only probable palaeo-locations, as adjacent fans, subject to the same climatic conditions, can have different grain size distributions and clast compositions reflecting differing drainage basin characteristics (Bull, 1964b; Denny, 1965; Hooke, 1967; Meckel, 1975). Likewise, fans in adjacent sedimentary basins may be predominantly sandy or conglomeratic as the probable consequence of differing tectonic settings (Steel, 1976).

In the La Magdalena coalfield succession the lower 850 m (along the La Magdalena-Mora de Luna road) consists predominantly of conglomerates which overlie a basal scree accumulation. The conglomerates occur in three fan megasequences, the lowest thinning and fining upward, and the subsequent two, thickening and coarsening upward (Fig. 13). The decrease in bed thickness and grain size in the lowest megasequence (Fig. 13A) is parallelled by a progressive change from proximal to distal mid-fan lobe deposits. Such megasequences probably indicate declining sediment supply, resulting from scarp retreat and denudation of topography, or perhaps from the gradual abandonment of a fan segment (Bluck, 1967; Williams, 1969; Deegan, 1973; Steel, 1974; Steel & Wilson, 1975). The 200 m thickness of the described example may indicate the latter to be unlikely.

The two thickening and coarsening upward megasequences (Fig. 13B, C; 210 and 220 m) are accompanied by a progressive change from distal to proximal mid-fan lobe deposits. They probably result from progradation of a fan segment or of the fan itself, their scale indicating major progradational phases. Such phases are probably tectonic in origin resulting from the relative uplift of the highland source area (Deegan, 1973; Steel & Wilson, 1975; Steel, 1976).

The scale of these three fan megasequences, their stacked occurrence and the constancy of conglomerate maximum clast size probably indicate periodic tectonism of a nearby basin margin.

Overlying these conglomeratic megasequences, fine-grained, distal fan and lacustrine sediments complete the observed succession. The abrupt termination of the supply of conglomerate to the basin may also reflect basin margin faulting. Distal fan sheetflood sequences suggest periods of avulsion or progradation followed by gradual or rapid abandonment (Fig. 15). These small-scale sequences (1·5–10 m) probably result from phases of entrenchment, avulsion or lateral migration of channels feeding depositional lobes. However, such sequences could also be distal representatives of extensive and prolonged proximal or mid-fan accumulations.

In the Matallana coalfield, the 10–65 m thick thinning and fining upward sequences of mass-flow deposits at Correcillas may represent gradual fan segment abandonment, or may be comparable to sequences of similar style described from submarine fan deposits, considered to result from gradual channel abandonment (Mutti & Ricci-Lucchi, 1972; Mutti, 1974; Ricci-Lucchi, 1975), decreasing sediment supply from the source area (Walker, 1975b, 1977), or accumulation on very low angle point bars (van Vliet, 1978).

The thinning and fining upward sequences are broadly organized into two thinning and fining upward megasequences, the upper one being abruptly overlain by fine-grained coal bearing sediments (Figs 3b, 4a and 5b). These two megasequences (Fig. 4a, 140 and 110 m) can be interpreted as reflecting scarp retreat and consequent reduction in the grade and amount of sediment supply. However, their scale, stacked occurrence and the dramatic increase in clast size accompanying the second megasequence may preclude a simple wearing back of an initial fault or erosional scarp (as in e.g. Bluck, 1967, his Fig. 14) and imply a phase of uplift prior to the second megasequence. These coarse conglomeratic deposits at Correcillas may represent the infill of an alluvial fan feeder canyon.

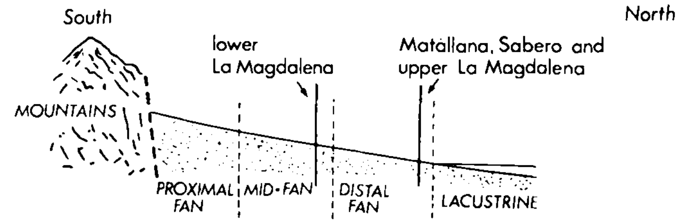
With the exception of the coarse localized basal 260 m, the Matallana succession is composed almost entirely of distal fan and lacustrine sediments (Fig. 2; author's observations and author's interpretation of Wagner, 1971b). Distal fan sediments of the San Francisco, Pastora and Roguera Formations of Fig. 2 are similar to those of Raposa Formation of Sabero, but differ from those of La Magdalena and also those of the Sucesiva Formation of Sabero (cf. Figs 6b and 16a). In the former, channellized, fine-grained, matrix-supported, cross-stratified conglomerates occur. Whilst the overall Matallana succession is finer-grained than La Magdalena, these fine conglomerates could be supplied to all the observed distal fan environments. These channellized fine conglomerates are probably the product of major floods which could extend into distal fan and even lacustrine environments (Fig. 19). They occur interbedded with the fine-grained sheetflood sandstones, shales and coals which are typical of La Magdalena and the Sucesiva Formation of Sabero.

The Sabero coalfield, like Matallana, consists almost entirely of distal fan and lacustrine sediments (Fig. 2; Knight, 1971, 1974, 1975 and personal communication). The detailed work of Knight allows important advances in the understanding of these coal-bearing deposits. As in La Magdalena and Matallana, the transport direction for the Sabero deposits was predominantly from the South. Differences occur between outcrops on the southern (upfan) and northern (downfan) flanks of the coalfield. The lower formations on the northern flank are finer-grained, show greater lacustrine influence, and contain fewer and thinner workable coals. Sediments of the southern flank are coarser-grained, show less lacustrine influence and have a greater number of thicker workable coals. The interaction of rates of sediment supply, subsidence and compaction, and plant growth, appear to have been most favourable for coal accumulation in the southern (upfan) area. On the northern flank a similar pattern emerges of a western area of lesser subsidence and a few workable coals, which split and become unworkable when traced eastward into the higher subsidence Alejico Beds graben feature (Fig. 3b).

Heward (in press) presents a more detailed account of the possible causes of the fan sequences, megasequences, and basin-fill sequences (successions) occurring in these coalfields, in terms of present-day and hypothetical alluvial fan behaviour.

DEPOSITIONAL MODEL

The modes of occurrence, nature, and consistent petrographies and palaeocurrents of the six sedimentary associations, suggest they are related and can be integrated into a depositional model. The earliest sedimentation consisted of the infilling of palaeotopography by scree, mass-flow deposits, or finer-grained coal-bearing accumulations. Overlying deposits are interpreted to be the product of debris flows, sheetfloods and the infill of rare channels. The assemblage of interpreted processes and organization of the deposits appear compatible with an alluvial fan origin (Blissenbach, 1954; Beaty,



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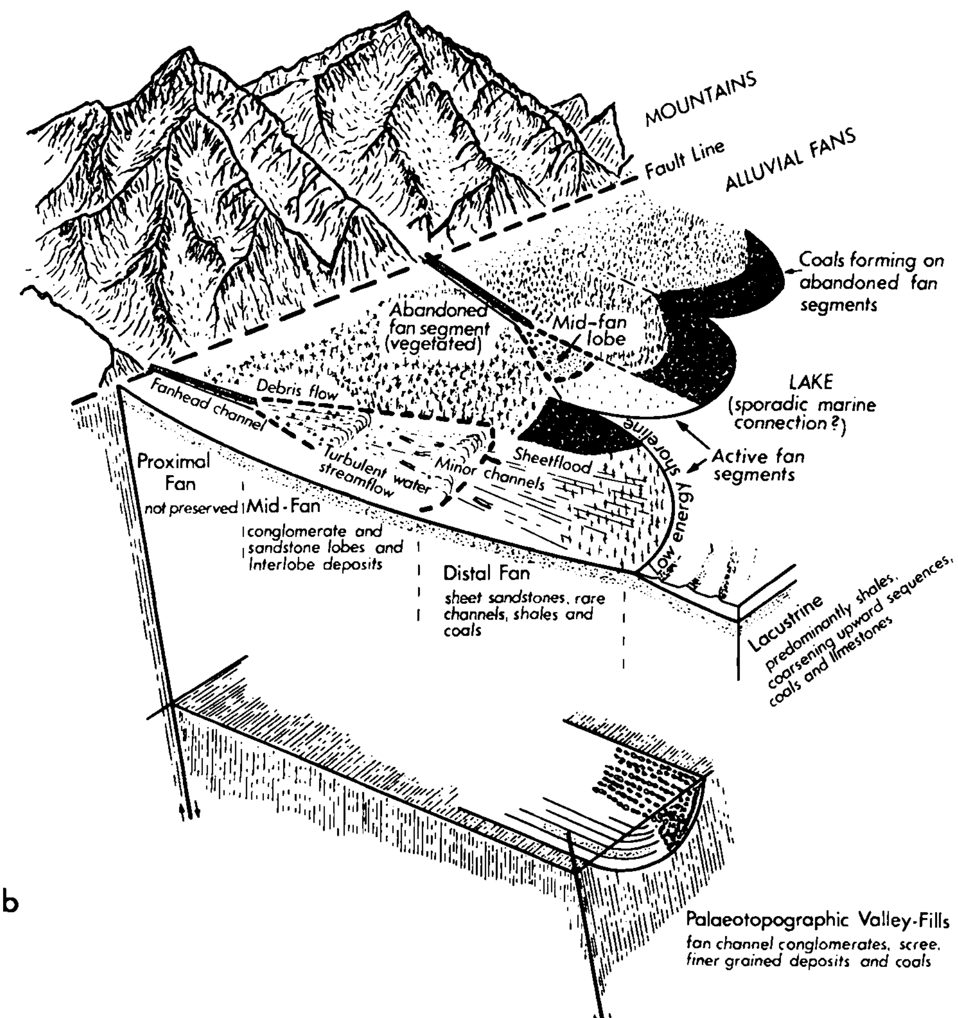

b

Fig. 20. (a) Predominant palaeo-locations of the coalfield successions in terms of the alluvial fan model. (b) Depositional model for the Stephanian A and B sediments of the La Magdalena, Matallana and Sabero coalfields.

1963, 1970, 1974; Bull, 1964a, b, 1972; Bluck, 1964; Denny, 1965, 1976; Lustig, 1965; Hunt & Mabey, 1966; Hooke, 1967, 1968, 1972; Wasson, 1977). A depositional model for the described sediments can now be proposed (Fig. 20b).

Alluvial fans developed along a single or series of fault lines which bounded a southerly sedimentary source area. The fault bounded nature of the basin(s) is suggested by the thicknesses of successions (1500–2500 m accumulating in a time period of less than a Stephanian stage—7 m.y.), by the thicknesses of alluvial fan deposits (Denny, 1965, p. 58; Bull, 1972, p. 79) and by the occurrence, scale and stacked nature of fan megasequences. By analogy with the dimensions of modern alluvial fans (Bull, 1964a; Denny, 1965; Lustig, 1965; Hunt & Mabey, 1966; Hooke, 1967; Beaty, 1970, 1974) it is unlikely that these sediments accumulated more than a few kilometres from a fault scarp, even though, through progressive back-faulting, initial sediments may lie at a considerable distance from the eventual basin margin (Steel & Wilson, 1975; Steel, 1976).

Locally developed basal deposits indicate relative topography (for their infill), a high water table (for the accumulation and preservation of coals), some syn-sedimentary basin development, and a tropical ?seasonal climate for their sporadic diagenetic reddening. These basal accumulations may be abruptly overlain by fine grained distal fan sediments, suggesting rapid development of the depositional basin. A situation on a separate fault block as illustrated in Fig. 20b may be envisaged.

Laterally extensive sediment accumulations typify these alluvial fans rather than channel-fills (cf. Bull, 1972, p. 66; Beaty, 1963, 1974). During a major flood, conglomeratic debris flows probably passed or were reworked downfan into turbulent streamflows, which finally passed into sheetfloods (Fig. 20b). Between, or lateral to, major events, lesser floods led to the deposition of rapidly accumulated silts and fine-grained sheet sandstones. Long periods of non-deposition, between flood events, or on inactive areas of the fan surface, allowed plant debris to accumulate and coals to form. Commonly, growing vegetation was surrounded by rapidly introduced sediment. The occurrence of thin coals in the interlobe deposits, suggests that coals could form and be preserved on the fan surface even in ?mid-fan environments. The development and preservation of these plant accumulations on the fan surface requires the maintenance of a high water table, perhaps by an abundant rainfall (cf. Anderson, 1964). The absence of siderite concretions from interlobe sediments and their abundance within distal fan and lacustrine deposits, may indicate slightly better drainage conditions at higher fan levels. Thicker coals occur interbedded with the distal fan and lacustrine sediments. The development of thick coal seams reflects a critical interaction of subsidence and rate of plant accumulation (drifted or *in situ*), in the absence of clastic sediment supply.

The minor contrasts in distal fan sediments between those comprising solely sheet sandstones (Fig. 16a) and those which also include channellized stratified fine conglomerates (Fig. 6b), probably reflect minor differences in fan size or drainage basin characteristics. Similar differences are known from adjacent modern fans (Beaty, 1963; Bull, 1964a, b; Hooke, 1967) and should be expected in ancient fan deposits.

These alluvial fans appear to have prograded into a single, or series of, low-energy lake(s). Faunas suggest predominantly fresh-water lakes with only occasional brackish or brackish-marine conditions. Restricted areas may have undergone evaporation, or a sporadic link to the sea established. Loaded horizons commonly occur near the top of both small and large scale lacustrine sequences. In the fault bounded basinal setting suggested, some of these may correspond to earthquake shocks and so prove chronostratigraphic markers within diachronous? lacustrine formations (Sims, 1975).

Palaeomagnetic reconstructions for the Carboniferous-Permian locate Northern Spain within the tropical belt (Smith, Briden & Drewry, 1973; Turner & Tarling, 1975). Hence, these alluvial fan deposits probably accumulated under a tropical ?seasonal climate. The processes interpreted to have been active in their characterization (with the exception of vegetation growth), whilst being essentially those of modern semi-arid fans (Beaty, 1963, 1970, 1974; Bull, 1964a, b, 1972; Denny, 1965, 1967; Hooke, 1967, 1968, 1972), also typify small alpine (Curry, 1966; Broscoe & Thomson, 1969), paraglacial (Wasson, 1977), and humid fans (Winder, 1965; Johnson & Rahn, 1970). Whether similar processes affect modern tropical fans in mountainous southeast Asia, or whether extensive fluvial reworking of mass-flow deposits occurs awaits verification. It may be that the Carbo/Permian tropics were typified by processes which today occur particularly in semi-arid climates, Schumm's (1968) concepts of the influence of evolving vegetation on processes may be applicable.

GEOLOGICAL SETTING OF THESE STEPHANIAN COALFIELD ACCUMULATIONS

The location of these and other Stephanian A–C coalfields (Fig. 1) are clearly influenced by prominent structural zones. Debate has centred around whether the structural basins are approximately the same as the original depositional basins, or whether they represent the preserved fragments of much larger basins (Wagner, 1970, 1971b; Wagner & Martinez-Garcia, 1974; Knight, 1975; Heward, 1976).

Faunal evidence suggests that the basin(s) were predominantly fresh-water but were subject to occasional brackish-marine conditions. The richness of the floras and lack of endemism between coalfields suggests that deposition occurred close to the sea in a single large basin, or separate basins whose divides did not impede the spread of floral elements (Wagner, 1971b; Knight, 1975 and personal communication).

The inability to correlate adjacent coalfield successions suggests that sediments accumulated in either, separate depositional basins, or within a basin lacking basin wide phenomena (e.g. major changes in lake level). The systematic younging of the Stephanian successions westwards from Sabero (Fig. 1; Evers, 1967; Wagner, 1971a) may indicate either, progressive expansion of a single basin, or that the basins developed successively in that direction. The exact nature and setting of these basin(s) is hence uncertain.

Reading (1975 and personal communication) suggested that these coalfield accumulations may have occurred within a pull-apart basin (Crowell, 1974a, b) which developed along a sinuous portion of a strike-slip fault (León line?, Fig. 1). To the south of this line block faulting occurred along fault splays, and sediments derived from these blocks began to infill the basin (in a similar fashion to the method of fill of the Ridge Basin, California, Crowell, 1974a). The subsidence of differing fault blocks at differing times may have resulted in the progressive westward younging of the base of the Stephanian deposits, from Sabero-Villablino. Alluvial fans developed along fault lines in the South and Southeast and prograded to the North and Northwest, this major pull-apart basin being in proximity to the sea and perhaps having a sporadic marine connection (cf. Salton Sea–Gulf of California setting, van de Kamp, 1973).

Subsequent to the accumulation of alluvial fan deposits and the probable progressive backfaulting of the highland/depositional basin margin, these Stephanian sediments were folded, faulted and preserved along the still mobile major structural zones (the León line in the North and the Sabero-Gordón line in the South).

CONCLUSIONS

The described coal-bearing deposits differ from those normally regarded as of alluvial fan origin, namely coarse grained sediments which occur at the base, or close to the margins of red-bed accumulations. In detail, however, there are many similarities between the coarser conglomeratic sediments of 'typical' alluvial fan deposits (Allen, 1965a; Laming, 1966; Bluck, 1967; Miall, 1970; Steel, 1974, 1976; Steel & Wilson, 1975) and those described here. Differences lie in the prominence of obvious fan sequences on various scales, the abundance of sheetflood sandstones, the growth of vegetation and the accumulation of coals.

As has been noted, these Stephanian deposits have considerable similarities to described ancient submarine fan accumulations. The coarse-grained debris flow deposits and their downfan passage into finer stratified deposits are comparable to Walker's (1975a, d, 1977) resedimented conglomerate models for ancient submarine fans. Likewise, the thinning and fining upward conglomerate sequences, and thickening and coarsening, and thinning and fining upward sheetflood sandstone sequences appear comparable to submarine fan channel, and outer fan and fan fringe turbidite sequences. Periods of non-sedimentation on the described alluvial fans are indicated by colonization of vegetation, and longer periods by the accumulation of coals. These are equivalent to the distal turbidites and pelagic shales or limestone interbeds of submarine fans. The intercalations of lacustrine and distal alluvial fan sediments may be comparable to those of submarine fan fringe and basin plain deposits, following abandonment of an active depositional fan segment.

Sequences and megasequences of progressively changing bed thickness and grain size appear common to many submarine fan deposits, and are becoming increasingly recognized in alluvial fan successions (e.g. Bluck, 1967; Steel, 1974, 1976; Steel & Wilson, 1975; this paper). Such sequences require the gradual progradation, abandonment, or migration of depositional elements. For flood events (debris flows, turbidites, sheetfloods, etc.) to form a sequence of gradually changing properties, flood magnitude can only vary within certain narrow limits. With greater variation, sequences would be obscured by the variable size, grain size and properties of the flood deposits. Hence, the occurrence of sequences within submarine and alluvial fan successions reflects a regularity of flood magnitude, which in turn can only reflect source area control. In turbidite basins, where a series of point sediment sources occur, their interference may mask the behaviour of individual elements (e.g. Walker, 1970; Bennetts & Pilkey, 1976; Ditty *et al.*, 1977; van Vliet, 1978). Also in seismically active turbidite basins, where flood magnitude reflects seismicity, sequences may not occur. The absence of sequences from some alluvial fan successions may likewise reflect differing drainage basin and tectonic settings (Heward, in press).

From the literature, the described type of alluvial fan sedimentation does not appear unique. Sediments of similar type have been described from the French Massif Central 'limnic' coal basins by Bouroz (1960) and Vetter (1975), and the sediments of the continental coalfields of eastern North America may be comparable (Massachusetts: Reinemund, 1955; Mutch, 1968; Stanley, 1968; Connecticut: Hubert *et al.*, 1976; Atlantic coast of Canada: Belt, 1968; in particular Nova Scotia: Way, 1968; Hacquebard & Donaldson, 1969; Duff & Walton, 1973; Ferguson, 1975).

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REFERENCES

ALLEN, J.R.L. (1964) Studies in fluviatile sedimentation: six cyclothems from the Lower Old Red Sandstone, Anglo-Welsh Basin. *Sedimentology*, **3**, 89–108.

ALLEN, J.R.L. (1965a) The sedimentation and palaeogeography of the Old Red Sandstone of Anglesey, North Wales. *Proc. Yorks. geol. Soc.* **35**, 139–185.

ALLEN, J.R.L. (1965b) A review of the origin and characteristics of recent alluvial sediments. *Sedimentology*, **5**, 91–191.

ALLEN, J.R.L. (1970) Studies in fluviatile sedimentation: a comparison of finding upward cyclothems, with special reference to coarse member composition and interpretation. *J. sedim. Petrol.* **40**, 298–323.

AMEROM, H.W.J. VAN & DILLEWIJN, J. VAN (1963) Note sur le bassin houiller de Ciñera-Matallana. *Leidse geol. Med.* **29**, 303–312.

ANDERSON, J.A.R. (1964) The structure and development of the peat swamps of Sarawak and Brunei. *J. trop. Geog.* **18**, 7–16.

BEATY, C.B. (1963) Origin of alluvial fans, White Mountains, California and Nevada. *Ann. Ass. Am. Geogr.* **53**, 516–535.

BEATY, C.B. (1970) Age and estimated rate of accumulation of an alluvial fan, White Mountains, California, U.S.A. *Am. J. Sci.* **268**, 50–77.

BEATY, C.B. (1974) Debris flows, alluvial fans and a revitalised catastrophism. *Z. Geomorph.* Suppl. Bd. **21**, 39–51.

BELT, E.S. (1968) Carboniferous continental sedimentation, Atlantic Provinces, Canada. In: *Late Palaeozoic and Mesozoic Continental Sedimentation, Northwestern North America* (Ed. by G. de V. Klein). *Spec. Pap. geol. Soc. Am.* **106**, 127–176.

BENNETTS, K.R.W. & PILKEY, O.H. (1976) Characteristics of three turbidites, Hispaniola—Caicos Basin. *Bull. geol. Soc. Am.* **87**, 1291–1300.

BLISSENBACH, E. (1954) Geology of alluvial fans in semi-arid regions. *Bull. geol. Soc. Am.* **65**, 175–190.

BLUCK, B.J. (1964) Sedimentation of an alluvial fan in southern Nevada. *J. sedim. Petrol.* **34**, 395–400.

BLUCK, B.J. (1967) Deposition of some Upper Old Red Sandstone conglomerates in the Clyde area: a study in the significance of bedding. *Scott. J. Geol.* **3**, 139–167.

BOSCH, W.J. VAN DEN (1969) Geology of the Luna-Sil Region, Cantabrian Mountains (N.W. Spain). *Leidse geol. Med.* **44**, 137–225.

BOUROZ, A. (1960) La sédimentation des séries houillères dans leur contexte paléogéographique. *C.r. 4th Congr. Av. Et. Strat. Géol. Carbon., Heerlen* 1958, **1**, 65–78.

BROADHURST, F.M. & LORING, D.H. (1970) Rates of sedimentation in the Upper Carboniferous of Britain. *Lethaia*, **3**, 1–9.

BROSCOE, A.J. & THOMSON, S. (1969) Observations on an alpine mudflow, Steele Creek, Yukon. *Can. J. Earth Sci.* **6**, 219–299.

BULL, W.B. (1964a) Alluvial fans and near surface subsidence in western Fresno County, California. *Prof. Pap. U.S. geol. Surv.* **473-A.**

BULL, W.B. (1964b) Geomorphology of segmented alluvial fans in western Fresno County, California. *Prof. Pap. U.S. geol. Surv.* **352-E**, 89–129.

BULL, W.B. (1972) Recognition of alluvial fan deposits in the stratigraphic record. In: *Recognition of Ancient Sedimentary Environments* (Ed. by J. K. Rigby and W. K. Hamblin), *Spec. Publs Soc. econ. Paleont. Miner., Tulsa*, **16**, 63–83.

BULL, W.B. (1977) The alluvial fan environment. *Prog. phys. Geogr.* **1**, 222–270.

BUTZER, K.W. (1971) Recent history of an Ethiopian Delta. *Res. Pap. Geog. Dept Univ. Chicago, 136.*

CHAWNER, W.D. (1935) Alluvial fan flooding, the Montrose, California flood of 1934. *Geog. Rev.* **25**, 225–263.

COSTELLO, W.R. & WALKER, R.G. (1972) Pleistocene sedimentology, Credit River Southern Ontario: a new component of the braided stream model. *J. sedim. Petrol.* **42**, 389–400.

COVENTRY, R.J. (1976) Abandoned shorelines and the Late Quaternary history of Lake George, New South Wales. *J. Geol. Soc. Aust.* **23**, 249–273.

CROWELL, J.C. (1974a) Sedimentation along the San Andreas fault, California. In: *Modern and Ancient Geosynclinal Sedimentation* (Ed. by R. H. Dott, Jr and R. H. Shaver), *Spec. Publs Soc. econ. Paleont. Miner., Tulsa*, **19**, 292–303.

CROWELL, J.C. (1974b) Origin of late Cenozoic basins in Southern California. In: *Tectonics and Sedimentation* (Ed. by W. R. Dickinson), *Spec. Publs Soc. econ. Paleont. Miner., Tulsa*, **22**, 190–204.

CUMMINS, W.A. (1958) Some sedimentary structures from Lower Keuper sandstones. *Geol. J.* **2**, 27–43.

CURRY, R.R. (1966) Observations of alpine mudflows in the Tenmile Range, central Colorado. *Bull. geol. Soc. Am.* **77**, 771–776.

DAVIS, W.M. (1938) Sheetfloods and stream floods. *Bull. geol. Soc. Am.* **49**, 1337–1406.

DAVIES, I.C. & WALKER, R.G. (1974) Transport and deposition of resedimented conglomerates: The Cap Enrage Formation, Cambro-Ordovician, Gaspé, Quebec. *J. sedim. Petrol.* **44**, 1200–1216.

DEEGAN, C.E. (1973) Tectonic control of sedimentation at the margin of a carboniferous depositional basin in Kirkcudbrightshire. *Scott. J. Geol.* **9**, 1–28.

DENNY, C.S. (1965) Alluvial fans in the Death Valley region, California and Nevada. *Prof. Pap. U.S. geol. Surv.* **466.**

DENNY, C.S. (1967) Fans and pediments. *Am. J. Sci.* **265**, 81–105.

DITTY, P.S., HARMON, C.J., PILKEY, O.H., BALL, M.M. & RICHARDSON, E.S. (1977) Mixed terrigenous-carbonate sedimentation in the Hispaniola-Caicos turbidite basin. *Mar. Geol.* **24**, 1–20.

DUFF, P., McL.D. & WALTON, E.K. (1973) Carboniferous sediments at Joggins, Nova Scotia. *C.r. 7th Congr. Av. Et. Strat. Géol. Carbon. Krefeld* 1971, II, 365–379.

EAGAR, R.M.C. & WEIR, J. (1971) Some Spanish Upper Carboniferous non-marine bivalve faunas: a preliminary statement with emphasis on facies in Northwest Spain and in Britain. *Trab. Geol. Fac. Ci. Univ. Oviedo*, **3**, 87–98.

ECKIS, R. (1928) Alluvial fans in the Cucamonga district, southern California. *J. Geol.* **36**, 111–141.

ELLIOTT, R.E. (1968) Facies, sedimentation successions and cyclothems in productive coal measures in the East Midlands, Great Britain. *Mercian Geol.* **2**, 76–99.

ENOS, P. (1977) Flow regimes in debris flow. *Sedimentology*, **24**, 133–142.

EVERS, H.J. (1967) Geology of the Leonides between the Bernesga and Porma rivers, Cantabrian Mountains, N.W. Spain. *Leidse geol. Med.* **41**, 83–151.

FERGUSON, L. (1975) *The Joggins section: from Nova Scotia—A chip of Africa! Soc. econ. Paleont. Miner., Tulsa*, Eastern Section Field Trip Guide (formal guidebook in preparation).

FISHER, R.V. (1971) Features of coarse-grained, high-concentration fluids and their deposits. *J. sedim. Petrol.* **41**, 916–927.

GROAT, C.G. (1972) Presidio Bolson. Trans-Pecos Texas and adjacent Mexico: Geology of a desert basin aquifer system. *Rept. Invest. Bur. econ. Geol. Univ. Texas*, **76.**

HACQUEBARD, P.A. & DONALDSON, J.R. (1969) Carboniferous coal deposition associated with flood-plain and limnic environments in Nova Scotia. In: *Environments of Coal Deposition* (Ed. by E. C. Dapples and M. E. Hopkins), *Spec. Pap. geol. Soc. Am.* **114,** 143–191.

HAMPTON, M.A. (1972) The role of subaqueous debris flow in generating turbidity currents. *J. sedim. Petrol.* **42,** 775–793.

HELMIG, H.M. (1965) The geology of the Valderrueda, Tejerina, Ocejo and Sabero coal basins (Cantabrian Mountains, Spain). *Leidse geol. Med.* **22,** 75–179.

HENDRY, H.E. (1976) The orientation of discoidal clasts in resedimented conglomerates, Cambro-Ordovician, Gaspe, eastern Quebec. *J. sedim. Petrol.* **46,** 48–55.

HEWARD, A.P. (1976) *Sedimentation patterns in coal bearing strata, Northern Spain and Great Britain.* Unpublished D.Phil. Thesis, Univ. Oxford.

HEWARD, A.P. (1978) Alluvial fan sequence and megasequence models: with examples from Westphalian D—Stephanian B coalfields, Northern Spain. In: *Fluvial Sedimentology* (Ed. by A. B. Miall). *Can. Soc. Petrol. Geol. Memoirs.* (In press.)

HOOKE, R. LeB. (1967) Processes on arid-region alluvial fans. *J. Geol.* **75,** 438–460.

HOOKE, R. LeB. (1968) Steady-state relationships on arid-region alluvial fans in closed basins. *Am. J. Sci.* **266,** 609–629.

HOOKE, R. LeB. (1972) Geomorphic evidence for Late-Wisconsin and Holocene tectonic deformation, Death Valley, California. *Bull. geol. Soc. Am.* **83,** 2073–2098.

HOUTEN, F.B. VAN (1964) Origin of red beds—some unsolved problems. In: *Problems of Palaeoclimatology* (Ed. by A. E. M. Nairn), pp. 647–659. Interscience, London.

HUBERT, J.F., REED, A.A. & CAREY, P.J. (1976) Palaeogeography of the East Berlin Formation, Newark Group, Connecticut Valley. *Am. J. Sci.* **276,** 1183–1207.

HUNT, C.B. & MABEY, D.R. (1966) Stratigraphy and structure, Death Valley, California. *Prof. Pap. U.S. geol. Surv.* **494-A.**

JOHNSON, A.M. (1970) *Physical Processes in Geology.* Freeman, Cooper and Co., San Francisco.

JOHNSON, A.M. & RAHN, P.H. (1970) Mobilization of debris flows. In: *New Contributions to Slope Evolution. Z. Geomorph.* Suppl. Bd. **9,** 168–186.

KAMP, P.C. VAN DE (1973) Holocene continental sedimentation in the Salton Basin, California: a reconnaissance. *Bull. geol. Soc. Am.* **84,** 827–848.

KLEIN, G. DE V. (1962) Triassic sedimentation, Maritime Provinces, Canada. *Bull. geol. Soc. Am.* **83,** 1127–1146.

KNIGHT, J.A. (1971) The sequence and stratigraphy of the eastern end of the Sabero coalfield (León, N.W. Spain). *Trab. Geol. Fac. Ci. Univ. Oviedo,* **3,** 193–229.

KNIGHT, J.A. (1974) The Stephanian A–B flora and stratigraphy of the Sabero coalfield (León, N.W. Spain). *C.r. 7th Congr. Av. Strat. Géol. Carbon., Krefeld* 1971, **111,** 283–306.

KNIGHT, J.A. (1975) *The systematics and stratigraphic aspects of the Stephanian flora of the Sabero coalfield.* Unpublished Ph.D. Thesis, Univ. Sheffield.

LAMING, D.J.C. (1966) Imbrication, palaeocurrents and other sedimentary features in the Lower New Red Sandstone, Devonshire, England. *J. sedim. Petrol.* **36,** 940–959.

LEEDER, M.R. (1974) Lower Border Group (Tournaisian) fluvio-deltaic sedimentation and palaeogeography of the Northumberland Basin. *Proc. Yorks. geol. Soc.* **40,** 129–180.

LEGGET, R.F., BROWN, R.J.E. & JOHNSON, G.H. (1966) Alluvial fan formation near Aklavik, North West Territories, Canada. *Bull. geol. Soc. Am.* **77,** 15–30.

LEOPOLD, L.B., WOLMAN, M.G. & MILLER, J.P. (1964) *Fluvial Processes in Geomorphology.* W. H. Freeman and Co., San Fransisco.

LOON, A.J. VAN (1972) A prograding deltaic complex in the Upper Carboniferous of the Cantabrian Mountains (Spain): the Prioro-Tejerina basin. *Leidse geol. Med.* **48,** 1–81.

LOWE, D.R. (1975) Water escape structures in coarse-grained sediments. *Sedimentology,* **22,** 157–204.

LOWE, D.R. (1976) Grain flow and grain flow deposits. *J. sedim. Petrol.* **46,** 188–199.

LUSTIG, L.K. (1965) Clastic sedimentation in Deep Springs Valley, California. *Prof. Pap. U.S. geol. Surv.* **352-F,** 131–192.

MCEWEN, M.C. (1969) Sedimentary facies of the modern Trinity Delta. In: *Holocene Geology of the Galveston Bay Area* (Ed. by R. R. Lankford and J. J. W. Rogers), pp. 53–77. Houston geol. Soc.

MCGEE, W.J. (1897) Sheetflood erosion. *Bull. geol. Soc. Am.* **8,** 87–112.

MCGOWEN, J.H. & GROAT, C.G. (1971) Van Horn Sandstone, West Texas: an alluvial fan model for mineral exploration. *Rep. Invest. Bur. econ. Geol. Univ. Tex.* **72,** 57.

MECKEL, L.D. (1975) Holocene sand bodies in the Colorado Delta area, Northern Gulf of California. In: *Deltas Models for Exploration* (Ed. by M. L. Broussard), pp. 239–265. Houston geol. Soc.

MELTON, M.A. (1965) The geomorphic and palaeoclimatic significance of alluvial deposits in southern Arizona. *J. Geol.* **73**, 1–38.

MIALL, A.D. (1970) Devonian alluvial fans, Prince of Wales Island, Arctic Canada. *J. sedim. Petrol.* **40**, 556–571.

MIDDLETON, G.V. & HAMPTON, M.A. (1973) Sediment gravity flows: Mechanics of flow and deposition. Soc. econ. Paleont. Miner. Short Course 1, Anaheim, 1–38.

MURATA, T. (1966) A theoretical study of the forms of alluvial fans. *Geog. Rep., Tokyo Metropolitan Univ.* **1**, 33–43.

MUTCH, T.A. (1968) Pennsylvanian non-marine sediments of the Narragansett Basin, Massachusetts—Rhode Island. In: *Late Palaeozoic and Mesozoic Continental Sedimentation Northeastern North America* (Ed. by G. de V. Klein), *Spec. Pap. geol. Soc. Am.* **106**, 177–209.

MUTTI, E. (1974) Examples of ancient deep-sea fan deposits from circum-Mediterranean geosynclines. In: *Modern and Ancient Geosynclinal Sedimentation* (Ed. by R. H. Dott Jr. and R. H. Shaver), *Spec. Publs Soc. econ. Paleont. Miner., Tulsa,* **19**, 92–105.

MUTTI, E. (1977) Distinctive thin-bedded turbidite facies and related depositional environments in the Eocene Hecho Group (South-central Pyrenees, Spain). *Sedimentology,* **24**, 107–131.

MUTTI, E. & RICCI-LUCCHI, F. (1972) Le torbiditi dell 'Appennino settentrionale: introduzione all' analisi di facies. *Soc. Geol. Ital. Mem.* **11**, 161–199.

NILSEN, T.H. (1969) Old Red Sandstone sedimentation in the Buelandet-Vaerlandet Devonian district, Western Norway. *Sedim. Geol.* **3**, 35–57.

PETTIJOHN, F.J., POTTER, P.E. & SIEVER, R. (1973) *Sand and Sandstone.* Springer-Verlag, New York.

PICARD, M.D. & HIGH, L.R. Jr (1972) Criteria for recognising lacustrine rocks. In: *Recognition of Ancient Sedimentary Environments* (Ed. by J. K. Rigby and W. K. Hamblin), *Spec. Publs Soc. econ. Paleont. Miner., Tulsa,* **16**, 108–145.

RAHN, P.H. (1967) Sheetfloods, streamfloods and the formation of pediments. *Ann. Ass. Am. Geogr.* **57**, 593–604.

READING, H.G. (1975) Strike-slip fault systems; an ancient example from the Cantabrians. *IXth Int. Congr. Sedim., Nice 1975*, Theme 4, **2**, 287–292.

REINEMUND, J.A. (1955) Geology of the Deep River coalfield, North Carolina. *Prof. Pap. U.S. geol. Surv.* **246.**

RICCI-LUCCHI, F. (1975) Depositional cycles in two turbidite formations of Northern Apennines (Italy). *J. sedim. Petrol.* **45**, 3–43.

RICH, J.L. (1935) Origin and evolution of rock fans and pediments. *Bull. geol. Soc. Am.* **46**, 999–1024.

RODINE, J.D. & JOHNSON, A.M. (1976) The ability of debris, heavily freighted with coarse elastic material, to flow on gentle slopes. *Sedimentology,* **23**, 213–234.

RUST, B.R. (1972) Pebble orientation in fluvial sediments. *J. sedim. Petrol.* **42**, 384–388.

SCHUMM, S.A. (1968) Speculations concerning palaeohydrologic controls of terrestrial sedimentation. *Bull. geol. Soc. Am.* **79**, 1573–1588.

SCHUMM, S.A. & STEVENS, M.A. (1973) Abrasion in place: A mechanism for rounding and size reduction of coarser sediments in rivers. *Geology,* **1**, 37–40.

SCOTT, K.M. & GRAVLEE, G.C. Jr (1968) Flood surge of the Rubicon River, California—hydrology, hydraulics and boulder transport. *Prof. Pap. U.S. geol. Surv.* **422-M**, 40.

SELLEY, R.C. (1965) Diagnostic characteristics of fluviatile sediments of the Torridonian Formation (Precambrian) of Northwest Scotland. *J. sedim. Petrol.* **35**, 366–380.

SHARP, R.P. (1942) Mudflow levees. *J. Geomorph.* **5**, 222–227.

SHARP, R.P. & NOBLES, L.H. (1953) Mudflow of 1941 at Wrightwood, Southern California. *Bull. geol. Soc. Am.* **64**, 547–560.

SIMS, J.D. (1975) Determining earthquakes recurrence intervals from deformational structures in young lacustrine sediments. *Tectonophysics,* **29**, 141–152.

SMITH, A.G., BRIDEN, J.C. & DREWRY, G.E. (1973) Phanerozoic world maps. Organisms and continents through time, *Spec. Pap. Palaeont.* **12**, 1–42.

STAALDUINEN, C.J. VAN (1973) Geology of the area between the Luna and Torio rivers, southern Cantabrian Mountains, N.W. Spain. *Leidse geol. Med.* **49**, 167–205.

STANLEY, D.J. (1968) Graded bedding—sole marking—graywacke assemblage and related sedimentary structures in some Carboniferous flood deposits, eastern Massachusetts. In: *Late Palaeozoic* *and Mesozoic Continental Sedimentation, Northeastern North America* (Ed. by G. de V. Klein), *Spec. Pap. geol. Soc. Am.* **106,** 210–239.

STEEL, R.J. (1974) New Red Sandstone floodplain and piedmont sedimentation in the Hebridean province, Scotland. *J. sedim. Petrol.* **44,** 336–357.

STEEL, R.J. (1976) Devonian basins of western Norway—sedimentary response to tectonism and to varying tectonic context. *Tectonophysics,* **36,** 207–224.

STEEL, R.J. & WILSON, A.C. (1975) Sedimentation and tectonism (?Permo-Triassic) on the margin of the North Minch Basin, Lewis. *J. Geol. Soc. Lond.* **131,** 183–202.

STEPHEN, M.F. & GORSLINE, D.S. (1975) Sedimentary aspects of the New River Delta, Salton Sea, Imperial County, California. In: *Deltas Models for Exploration* (Ed. by M. L. Broussard), pp. 267–282. Houston geol. Soc.

STEPHENSON, D. (1972) Middle Old Red Sandstone alluvial fan and talus deposits at Foyers, Invernessshire. *Scott. J. Geol.* **8,** 121–127.

TANNER, W.F. (1976) Tectonically significant pebble types: sheared, pocked, and second-cycle examples. *Sedim. Geol.* **16,** 69–83.

THOMAS, M.F. (1974) *Tropical Geomorphology: A Study of Weathering and Landform Development in Warm Climates.* Macmillan, London.

THORBECKE, F. (1973) Landforms of the savanna zone with a short dry season. In: *Climatic Geomorphology* (Ed. by E. Derbyshire), pp. 96–103. Macmillan, London.

TRICART, J. (1972) *The Landforms of the Humid Tropics, Forests and Savannas.* Longmans, London.

TURNER, P. & TARLING, D.H. (1975) Implication of new palaeomagnetic results from the Carboniferous system of Britain. *J. geol. Soc. Lond.* **131,** 469–488.

UNDERWOOD, J.R. Jr & LAMBERT, W. (1974) Centroclinal cross strata, a distinctive sedimentary structure. *J. sedim. Petrol.* **44,** 1111–1113.

VETTER, P. (1975) Sedimentation continentale dans les bassins houillers et Permiens du Sud du Massif Central. Guidebook Excursion 22, *IXth Int. Congr. Sedim., Nice* 1975.

VISHER, G.S. (1965) Use of vertical profile in environmental reconstruction. *Bull. Am. Ass. Petrol. Geol.* **49,** 41–61.

VLIET, A. VAN (1978) The early Tertiary deep-water fans of Guipuzcoa. In: *Submarine Canyon and Fan Sedimentation* (Ed. by D. J. Stanley and G. Kelling). Dowden, Hutchinson and Ross (in press).

WAGNER, R.H. (1966) Palaeobotanical Dating of Upper Carboniferous Folding Phases in N.W. Spain. *Mem. Inst. Geol. Min. España,* **66** (1965), 1–169.

WAGNER, R.H. (1970) An outline of the Carboniferous stratigraphy of Northwest Spain. *Congr. Coll. Univ. Liège,* **55,** 429–463.

WAGNER, R.H. (1971a) Account of the International field meeting on the Carboniferous of the Cordillera Cantabrica, 19–26 Sept. 1970. *Trab. Geol. Fac. Ci. Univ. Oviedo,* **3,** 1–39.

WAGNER, R.H. (1971b) The stratigraphy and structure of the Ciñera-Matallana coalfield (prov. León, N.W. Spain). *Trab. Geol. Fac. Ci. Univ. Oviedo,* **4,** 385–429.

WAGNER, R.H. & ARTIEDA, J.I. (1970) *Le Cuenca Minera Ciñera-Matallana.* S.A. Hullera Vasco-Leonesa.

WAGNER, R.H. & MARTINEZ-GARCIA, E. (1974) The relationship between geosynclinal folding phases and foreland movements in Northwest Spain. *Studia Geologica,* **VII,** 131–158.

WALKER, R.G. (1970) Review of the geometry and facies organisation of turbidites and turbidite bearing basins. In: *Flysch Sedimentology in North America* (Ed. by L. Lajoie), *Spec. Pap. Geol. Ass. Can.* **7,** 219–251.

WALKER, R.G. (1975a) Conglomerate: Sedimentary structures and facies models. In: *Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences* (Ed. by J. C. Harms *et al.*), *Soc. econ. Paleont. Miner., Tulsa,* Short Course **2,** 133–161.

WALKER, R.G. (1975b) Upper Cretaceous resedimented conglomerates at Wheeler Gorge, California: description and field guide. *J. sedim. Petrol.* **45,** 105–112.

WALKER, R.G. (1975c) Nested submarine-fan channels in the Capistrano Formation, San Clemente, California. *Bull. geol. Soc. Am.* **86,** 915–924.

WALKER, R.G. (1975d) Generalised facies models for resedimented conglomerates of turbidite association. *Bull geol. Soc. Am.* **86,** 737–748.

WALKER, R.G. (1977) Deposition of upper Mesozoic resedimented conglomerates and associated turbidites in southwestern Oregon. *Bull. geol. Soc. Am.* **88,** 273–285.

WALKER, R.G. & MUTTI, E. (1973) *Turbidite Facies and Facies Associations. Soc. econ. Paleont. Miner., Tulsa,* Short Course **1**, Anaheim, 119–157.

WALKER, T.R. (1967) Formation of red beds in modern and ancient deserts. *Bull. geol. Soc. Am.* **78**, 353–368.

WALKER, T.R. (1974) Formation of red beds in moist tropical climates: a hypothesis. *Bull. geol. Soc. Am.* **85**, 633–638.

WASSON, R.J. (1974) Intersection point deposition on alluvial fans: An Australian example. *Geogr. Annlr.* **56**, 83–92.

WASSON, R.J. (1977a) Catchment processes and the evolution of alluvial fans in the lower Derwent valley, Tasmania. *Z. Geomorph.* **21**, 147–168.

WASSON, R.J. (1977b) Late-glacial alluvial fan sedimentation in the lower Derwent valley, Tasmania. *Sedimentology*, **24**, 781–799.

WAY, J.H. Jr (1968) Bed thickness analysis of some Carboniferous fluvial sedimentary rocks near Joggins, Nova Scotia. *J. sedim. Petrol.* **38**, 424–433.

WILLIAMS, G.E. (1969) Characteristics and origin of a Precambrian pediment. *J. Geol.* **77**, 183–207.

WILLIAMS, G.E. (1970) Piedmont sedimentation and late Quaternary chronology in the Biskra region of the northern Sahara. *Z. Geomorph.* **10**, 40–60.

WINDER, C.G. (1965) Alluvial cone construction by alpine mudflow in a humid temperate region. *Can. J. Earth Sci.* **2**, 270–277.

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