Coarse Alluvial Deposits

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INTRODUCTION

Alluvial conglomerates are minor components of the stratigraphic record, but their tectonic and paleoclimatic significance give them an importance far greater than their abundance implies. They are indicators of the sharp terrestrial relief resulting from lithospheric uplift at continental margins and from intra-cratonic faulting. They are also indicative of climatic extremes, for the production of large lithic fragments is maximized on steep slopes in semi-arid or paraglacial/alpine settings (Wilson, 1973). The study of alluvial conglomerates can, therefore, reveal important tectonic or paleoclimatic influences on sedimentation and basin evolution.

Coarse-grained alluvial deposits also have economic importance, notably the Witwatersrand placer gold and uranium ores of South Africa (Minter, 1978; Smith and Minter, 1980) and the similar uraniferous conglomerates of the Blind River-Elliot Lake area, Canada (Pienaar, 1963). Robertson *et al.* (1978) noted that uranium placer deposits are confined to rocks between 3.0 and 2.2 billion years old, because their formation ceased when the atmosphere became oxygenic. Thick, laterally impersistent coals are associated with intermontane alluvial deposits, some conglomeratic, as described by Heward (1978) and Long (1981).

Compared with studies of sandy fluvial systems, those on alluvial gravels are hampered by problems of scale in flume work, and by the high energy and rarity of natural flows capable of transporting large clasts. In addition, clast size is not necessarily a function of flow competence alone; availability from the source terrane may also be a factor. For these reasons, experimental studies have not contributed greatly to gravel models, although notable exceptions are the work of Koster (1978b) and Southard *et al.* (1984).Studies of modern gravel systems are mainly geomorphic, because of the difficulty of observing active gravel transport, and of coring or trenching gravel. Another problem is the strong influence of Quaternary glaciation on present-day alluvial gravel transport in many parts of the world, an influence present only intermittently in the past. The recognition and interpretation of structures in gravels and conglomerates requires extensive, good quality exposure, which is rare in modern gravels. Both gravels and conglomerates are hard to interpret from cores, and commonly cannot be distinguished from sandstones using borehole logs (Cant, "Subsurface Facies Analysis", this volume).

From the discussion above it is evident that there are abundant data on the geomorphic features of alluvial gravels, but we rely heavily on the ancient record for evidence of stratal type and stratification sequence. This means that coarse alluvial facies models have rather limited use for hydrodynamic interpretation (Walker, 1979). Their function as guides and predictors relates to variations in external factors, largely climatic and tectonic. Recent reviews which provide useful insights are those of Miall (1977), Collinson (1978), Nilsen (1982) and Chapter 6 of Harms *et al.* (1982). Symposium volumes edited by Miall (1978a), Collinson and Lewin (1983) and Koster and Steel (1984) include additional reviews, case histories and discussions of alluvial models.

TERMINOLOGY

The facies terminology used here (Table 1) is that of Miall (1978b). We restrict the term coarse-grained to successions that contain at least 50% gravel, which are therefore dominated by facies prefixed G in Table 1. Sand facies are also present, but in subordinate amounts. In effect, this limits the discussion to braided alluvium, characterised by multiple, low-sinuosity, relatively unstable channels (Rust, 1978a). Various authors, for example McGowen and Garner (1970) and Jackson (1976, 1978) have described meandering-fluvial deposits containing gravel. However, the coarse sediment is restricted to lag accumulations within channels, constituting less than half the total succession. Exceptions are the deposits of streams like the Little Wind River (Jackson, 1978) and the Jarama River, Spain (Arche, 1983), which contains gravel in large-scale cross-strata formed by lateral migration of meander bars. Smith and Smith (1980) reported gravel-filled channels in the anastomosing Columbia River, but Smith (1983, p. 161) showed that these channel sediments are mainly coarse sand and granules. The valley fill is dominated by finer overbank deposits,

Table 1
Facies typical of fans and braidplain deposits (Miall, 1977; as modified by Miall, 1978 and Rust, 1978).

Major facies —	Gm:	Clast-supported, commonly imbricate gravel with poorly defined sub-horizontal bedding.
	Gms:	Muddy matrix-supported gravel without imbrication or internal stratification
	Gt:	Trough cross-bedded clast-supported gravel
	Gp:	Planar cross-bedded gravel, transitional from clast-supported gravel through sand matrix-supported gravel to sand (Sp)
Minor facies —	Sh:	Horizontally stratified sand
	St:	Trough cross-stratified sand
	Sp:	Planar cross-stratified sand
	Fm:	Massive fine sandy mud or mud
	Fl:	Laminated or cross-laminated very fine sand, silt or mud
	P:	Pedogenic concretionary carbonate

Table 2
Descriptive parameters for gravels/conglomerates

MATRIX
- size, sorting
- mineralogy
- pedogenic modification

COARSE FRACTION
- size, sorting
- shape, sorting

  textural maturity
- fabric
- lithotypes and compositional maturity

- clast or matrix-supported
- diagenetic changes
- porosity and permeability

- maximum clast size vs. bed thickness relationship

INDIVIDUAL BEDS
- boundaries
- distribution and thickness
- preserved bedforms, stratification
- grading
- fossil content

SUCCESSION
- temporal trends in bed character
- stratigraphic relationships with associated facies

Figure 1
Planar cross-stratified conglomerate (facies Gp) in the Middle Devonian Malbaie Formation, Pte. St-Pierre, Quebec. Notebook 19 cm long. Note sorting on cross-strata and sparry calcite cement filling voids in openwork conglomerate (arrowed). See Rust (in press, b).

so that the overall proportion of gravel is small (Smith, 1983, Fig. 5).

An important descriptive parameter for gravels and conglomerates is the relationship between framework (clasts greater than 2 mm in diameter) and matrix (sand- and mud-sized particles) (Table 2). Framework-supported gravel results from deposition of gravel bedload by an energetic aqueous flow that keeps sand in suspension. As flow velocity decreases, the sand infiltrates the spaces between the framework particles (Smith, 1974; Eynon and Walker, 1974; Beschta and Jackson, 1979). Openwork gravel is less common, and results from incomplete matrix infiltration, which ocurs mostly during the rapid accumulation of gravel on cross-strata (Fig. 1). There are two types of matrix-supported gravel: those with stratified sand matrix, and those with unstratified matrix, commonly of muddy sand. The former type indicates aqueous transport, but at an energy level lower than for framework gravel, so that sand and fine gravel are deposited together. The second type of matrix-supported gravel is typified by facies Gms (Table 1), which, in the alluvial context, forms mainly by debris flow deposition.

Other descriptive parameters include particle shape and fabric (Koster *et al.*, 1980) and stratification and stratal sequence (Table 2 and Harms *et al.*, 1982). Aqueous deposition commonly forms a fabric in which maximum projection *(ab)* planes dip upstream at moderate angles, and *a* axes are perpendicular to flow, due to rolling on the bed (Rust 1972b, 1975). Fabrics with *a* parallel to flow are less common, and apparently result from more energetic aqueous transport, in which elongate pebbles saltate longitudinally (Johansson, 1965). Stratification boundaries are commonly gradational, but may be abrupt or erosional. In contrast, debris flow deposits normally lack internal stratification and fabric.

DEPOSITIONAL ENVIRONMENTS

Alluvial gravels accumulate in two related depositional environments: 1) *fans*, and 2) *braided rivers and braidplains.*

Alluvial fans form where streams confined by narrow valleys emerge onto a plain or major trunk valley (Fig. 2). Related gravel-bearing landforms are the steep talus cones that accumulate below mountain gullies (Church *et al.*,

Figure 2
Block diagram of alluvial fans tributary to a braided river in a trunk valley. D) debris flows.

1979; White, 1981), and pediment mantles. Pediments are sloping surfaces cut on bedrock by streams emerging from mountain valleys, which are normally covered by a thin alluvial mantle (Denny, 1967; Twidale, 1979). Sedimentation under these conditions, particularly alluvial fan development, occurs in response to a sharp decrease in transport efficiency as the stream emerges from its confined valley. A semi-conical landform is built, with slopes and transport directions radiating from the mouth of the source valley. Grain size decreases rapidly down fan (Figs. 3 and 4), and roundness of gravels increases, whereas the proportion of finer facies increases distally (Fig. 3). Conditions on the steep valley slopes adjacent to alluvial fans commonly give rise to debris flows, particularly in proximal fan reaches (Fig. 2).

In contrast, ***braided rivers and braidplains*** (Allen, 1975) have two-dimensional depositional surfaces with lower slopes. Drainage patterns are essentially parallel, although they may radiate or converge locally due to increasing or decreasing space at the margins of the river or braidplain (Fig. 5). Downslope decrease in grain size and attendant facies changes occur over a considerable distance, generally an order of magnitude greater than that required for equivalent facies changes on alluvial fans (Fig. 4). Debris flows are rarely deposited, and if so, are unlikely to survive reworking by aqueous flows.

Some authors have extended the term fan to what are regarded here as braidplains, for example the Scott fan of Boothroyd and Ashley (1975). Boothroyd and Nummedal (1978) referred to coastal outwash plains in Iceland as alluvial fans. These landforms are morphologically unlike fans, and their sediment dispersal patterns and facies fit the braidplain model.

Alluvial fans that are tributary to braided rivers enter them perpendicularly, have significantly higher slopes and are readily distinguished from them (Fig. 5). For example, Spring Creek fan is one of the larger tributary fans of the Donjek River, Yukon, and has a slope of 0.019, whereas that of the trunk river at the same locality is 0.006 (Rust, 1972b). In contrast, a series of laterally contiguous fans formed adjacent to a mountain front may be transitional downslope to a braidplain on which the radiating flow

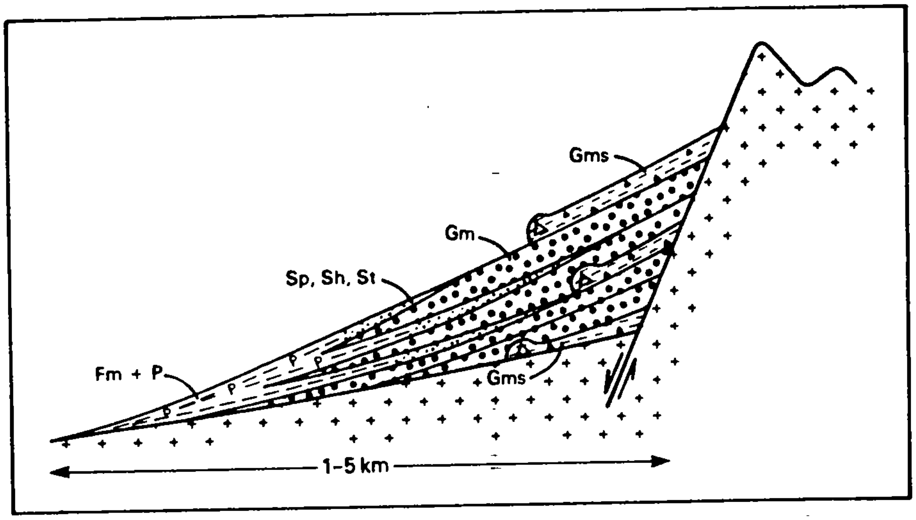

Figure 3
Diagrammatic cross-section of an alluvial fan, showing proximal-distal facies variation. See Table 1 and text for explanation of facies codes.

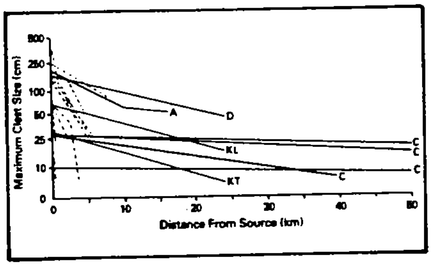

Figure 4
Variation in maximum grain size (i.e., mean of ten largest clasts at each site) versus distance downslope for various alluvial gravels. Modified after Figure 11 of Wilson (1970) and Figure 19 of Schultheis and Mountjoy (1978). Dashed lines are trends on alluvial fans, solid lines are trends on braided rivers and braidplains: A: Arroyo Seco (Krumbein, 1942), D: Donjek River (Rust, 1982a), KL: Knik River, lag gravel (Bradley et al., 1972), KT: Knik River, transported gravel, C: Cadomin Formation (McLean, 1977).

Figure 5
Vertical air photograph (A15517-19) of upper reach of Slims River, Yukon (61°55'N, 138°38'W), showing marked contrast between tributary alluvial fans and braided trunk river. Note the entrenchment features of the lower left fan (see Bull, 1977, Fig. 20b), and the constriction of the river by fans. Dark areas on fans are vegetated. Original photo supplied by the Surveys and Mapping Branch, Department of Energy, Mines and Resources, Canada. Width of view about 7.5 km, north toward top of photograph. Flow in trunk river left to right.

Figure 6
Block diagram of alluvial fans transitional downslope to a braidplain as the fans coalesce and lose their morphological identity. D) debris flow.

Figure 7
Horizontally stratified conglomerate (facies Gm) in Middle Devonian Malbaie Formation, Paradise Cove, Quebec. Notebook (arrowed) 19 cm long.

Figure 8
Bedding-plane view of imbricate, horizontally stratified conglomerate in Malbaie Formation, Belle Anse, Quebec. Scale 30 cm.

patterns of the individual fans are lost, but the mean drainage direction is the same (Fig. 6). The distinction between a braided river and a braidplain is one of confinement by a valley in the former case (Kraus, 1984). However, the width of the river is normally sufficient that the influence of the valley walls is minimal, so that the processes and sediments of braided rivers and braidplains are essentially identical.

ALLUVIAL FAN SEDIMENTATION

Modern Alluvial Fans

The classic descriptions of modern alluvial fans are mostly from the mountainous semi-arid regions of the southwestern United States (Bull, 1963, 1964, 1972, 1977; Hooke 1967). Fans of this type are uncommon in Canada, but paraglacial fans (those associated with retreat of valley glaciers) are relatively abundant (Ryder, 1981a,b; Church and Ryder, 1972). In each case the fans form adjacent to regions of high relief, which are rapidly denuded to provide the sediment which builds the fans. In semi-arid environments the relief is commonly a faulted mountain front, and denudation is promoted by sparse vegetation and occasional intense rainfall. Paraglacial fans form where tributary valleys enter a major glaciated valley (Figs. 2 and 5), in which case sediment production is promoted by seasonal temperature fluctuations and the high spring runoff. According to Ryder (1971b), paraglacial fans differ from arid-region fans by having steeper gradients and weaker correlations between fan and basin parameters. This is because their deposits derive from earlier glacially-eroded detritus, in contrast to the concurrent nature of denudation and sedimentation in tectonically-controlled systems. Fans in humid tropical settings are less common, because the climate induces chemical weathering rather than mechanical production of coarse detritus, and dense vegetation protects slopes. However, tropical storms in alpine areas can cause catastrophic mass movements, as illustrated by Bell's (1976) study of the effects of Cyclone Allison on South Island, New Zealand.

Most fans are dominated by water-laid deposits, predominantly facies Gm (horizontally stratified gravel, commonly imbricate) in proximal reaches (Figs. 7 and 8). Bull (1972, p. 66-9) divided water-laid gravels into stream channel, seive and sheetflood deposits, the latter defined in more detail by Hogg (1982). Sheetflood and stream channel deposits can be considered intergradational, for the surfaces on which sheetflood deposits accumulate are in fact composed of numerous shallow channels and bars. Sieve deposits are comparatively rare, forming as gravel lobes that receive little sand or mud from their source areas (Bull, 1977, Fig. 7). The broad, shallow channels on alluvial fans of humid climates commonly contain periodic accumulations of coarse, imbricate gravel, known as transverse ribs. They are interpreted as antidune bedforms, and can be used to estimate paleodepth, velocity and Froude number (Koster, 1978a). Rust and Gostin (1981) recognised fossil transverse ribs in Holocene fan gravels in semi-arid South Australia, and showed how paleohydraulic parameters could be estimated, using equations given by Koster (1978a).

On many fans the main channel is entrenched in the fanhead (proximal) region, but reaches the general level at a location downfan known as the intersection point (Hooke, 1967). Some authors attribute fanhead entrenchment to external causes such as climatic change (Lustig, 1965) or faulting (Bull, 1965), but others regard it as an intrinsic part of fan development. Wasson (1977b) suggested that both circumstances may prevail. Downcutting that contributes sediment to a lower part of the fan is part of fan construction, whereas down-cutting that results in sedimentation beyond, but not on the fan, constitutes destruction by external causes.

The nature of water-laid deposits shows progressive change down-fan. There is an increase in the abundance of cross-stratal sets, chiefly planar (Fig. 1) with transitions from coarse gravel through clast-supported fine-grained gravel, sand matrix-supported gravel to sand (Gm to Gp to Sp). These changes reflect gradual decrease in the particle size to water depth ratio as stream competence decreases down-fan. Minor deposits of horizontally laminated sand (facies Sh) and laminated or massive mud (Fl, Fm) also increase in abundance down-fan (Fig. 3). Fans formed entirely of sand and finer sediment are not part of our topic, but they are in any case rare, because they need a high-relief source of poorly consolidated sand or finer material, which is a short-lived feature of the landscape (Legget *et al.*, 1966).

Debris flow (or mudflow) deposits are the other principal component of most alluvial fan successions in both semi-arid and paraglacial environments (Fig. 3). Middleton and Hampton (1976) pointed out that debris flows are one member of a continuous range of sediment gravity flows. According to Bull (1977, p. 236) debris flows are promoted by steep slopes, lack of vegetation, short periods of abundant water supply and a source providing debris with a muddy matrix. Johnson (1970) discussed debris flows, providing eyewitness accounts, as did Sharp and Nobles (1953), Curry (1966) and Winder (1965). The flows may be confined to channels, but commonly spread out as lobate sheets on lower reaches of fans. The lobate distal terminations are distinctive, and commonly concentrate the larger clasts at the steep outer margin of the flow, forming levees (Fig. 9). The flows lack internal stratification, but commonly show reverse or reverse-to-normal grading (Nilsen, 1982, Figs. 17 and 34C,D). In contrast with the imbricate fabric of waterlaid gravel, the clasts in debris flow deposits commonly lack an organised fabric. Bull (1963, p. 245) noted that more fluid (that is, proximal) debris flows may show subhorizontal orientation of megaclasts, whereas more viscous (distal) flows tend to have larger clasts in predominantly vertical orientations, due to matrix support. However, according to Shultz (1983), some flows of relatively low viscosity may be able to reach distal reaches of fans.

Schumm (1977, p. 246) recognized two types of alluvial fans: "... dry or mudflow fans formed by ephemeral stream flow, and wet fans formed by perennial stream flow". This implies that "wet" fans do not develop debris flows. It is true that evenly distributed rainfall favours steady erosional processes rather than mass movements, but short term fluctuation in precipitation can undoubtedly produce debris flows in humid areas (Curry, 1966; Broscoe and Thompson, 1969; Winder, 1965). Schumm (1973) suggested that initiation of debris flows requires accumulation of a threshold amount of loose detritus, a concept further elaborated by Heward (1978). Beaty (1970) estimated an average depositional rate of approximately 2400 m³/yr on a debris flow-dominated fan of 4.4 km radius on the California-Nevada border.

Figure 9
Leveed edge of debris flow on west side of Donjek Valley between Spring Creek and Donjek Glacier. Pack (mid-ground, circled) and figure (behind) give scale.

Alluvial fans prograde into lakes or seas where high coastal topography causes alluvium to be shed directly into the water (Friedman and Sanders, 1978, Fig. 10-29; Gvirtzman and Buchbinder, 1978). These fans have been termed fan-deltas by several authors (Holmes and Holmes, 1978, p. 358-9; Wescott and Ethridge, 1980). However, because of the steep alluvial slope, the typical deltaic features of break in slope and facies change at the water plane are not well developed, and the term coastal alluvial fan seems more appropriate (Hayward, 1983). Modification of coastal fans by marine processes was described by Ethridge and Wescott (1984), who noted that they form mainly along continental and island-arc collision zones where continental shelves are narrow and relatively steep.

Ancient Alluvial Fan Deposits

The principal features of modern alluvial fans - debris flow deposits and rapid downslope facies changes - are also recognisable in ancient fan successions. Many of these successions are thick, indicating formation in a tectonically-influenced setting, for example the Devonian Peel Sound Formation of Arctic Canada (Miall, 1970). The stratigraphic record also shows vertical changes in facies type. For example, when faulting gives rise to source elevation or basin subsidence, the alluvial system is rejuvenated, and the fan progrades. Areas on which proximal facies accumulate migrate downfan, so that the succession at any given location shows upward increase in grain size and bed thickness (Fig. 10a). This upward coarsening/thickening trend may be overlain by a thinner upward fining/thinning sequence (Fig. 10b) as the effects of rejuvenation wear off (Mack and Rasmussen, 1984). Repeated faulting gives rise to cyclic repetition of coarsening/thickening units or the asymmetric coarsening then fining units descirbed above. Heward (1978) suggested that simple fining-upward sequences may result when faulting causes retreat of the scarp front (Fig. 10c).

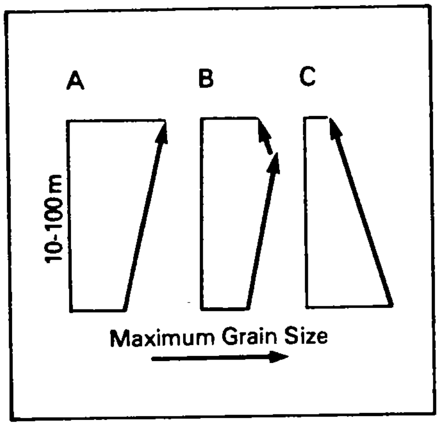

Figure 10
Allocyclic grain size/bed thickness trends in alluvial fan successions subject to periodic tectonic rejuvenation. a) Coarsening/thickening upward due to periodic fault uplift of source or subsidence of basin. b) Coarsening/thickening followed by fining/thinning in asymmetric cycles. Same mechanism as in a), but spacing between fault movements allows system to move toward equilibrium before renewed faulting. c) Fining/thining upward, ascribed to back-stepping of boundary fault (Heward, 1978).

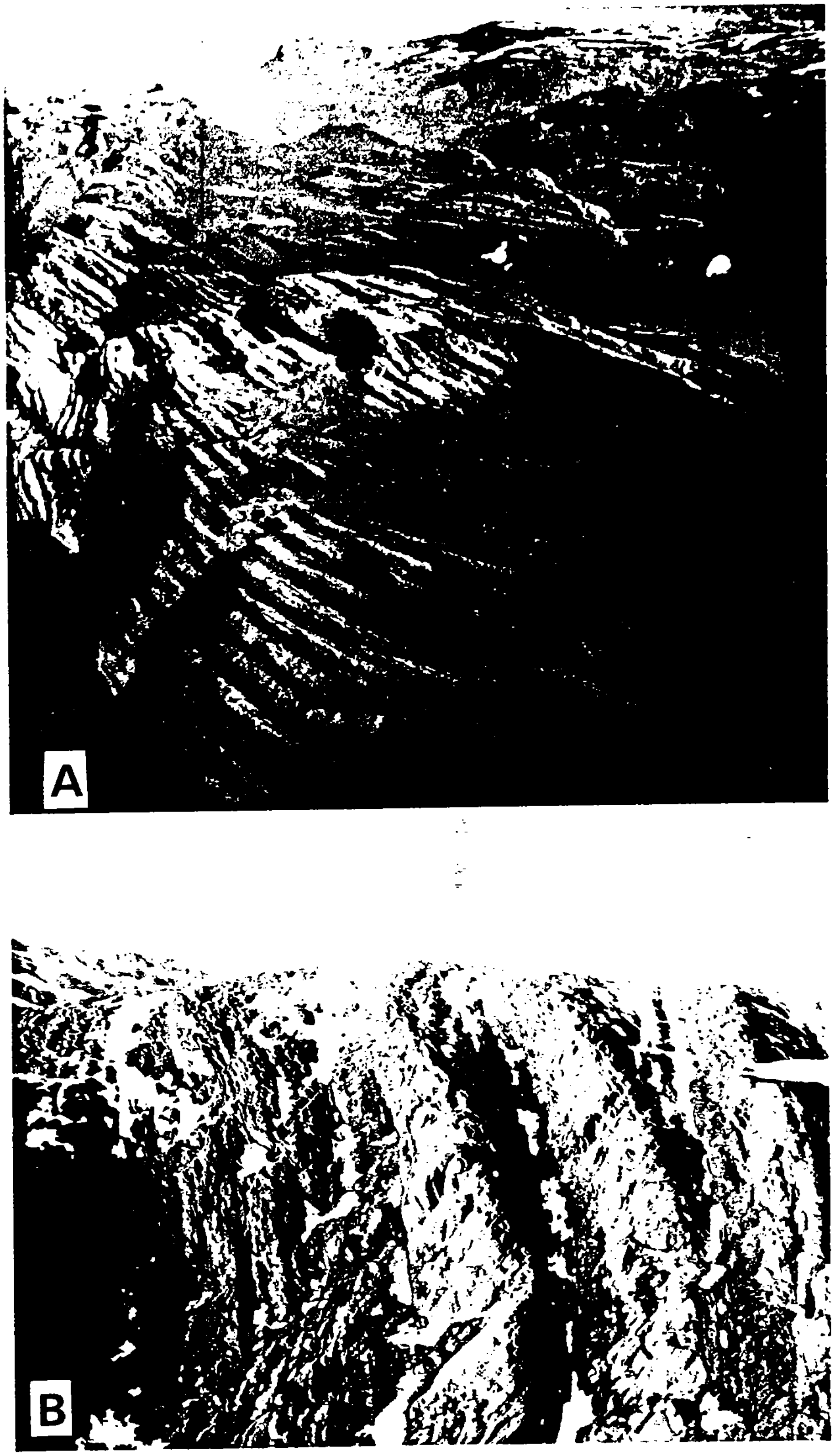

Figure 11
The Devonian Hornelen Basin, Norway, with its spectacular exposure of coarsening-upward cycles in alluvial fan deposits (Steel et al., 1977). A) Northern edge of the basin with successive scarps, ca. 100 m high, relating to each cycle. B) A steeply tilted, southern part of the basin showing three cycles which thin upwards (i.e., towards the basin centre) and interfinger with floodbasin/lake depostis. Photos kindly supplied by R.J. Steel who obtained 'A' from Fjellanger Wideroe A-5, Oslo.

Well exposed successions of ancient alluvial fan deposits were described from the Devonian of Norway by Steel *et al.* (1977), Steel and Gloppen (1980) and others (Fig. 11). They contain coarsening-upward sequences about 100 m thick, with coarsening-upward subcyles in the 10 to 25 m range, all attributed to allocyclic (tectonic) causes. Cycles of internal (autocyclic) origin are also present in these and other fan deposits. They result from major floods, or from the switching of deposition from one fan lobe to another. Repetitive units of this type are thinner, commonly a few metres thick, and fine upwards or coarsen then fine symmetrically (Muir and Rust, 1982).

Another feature which has been recognised mainly from studies of ancient fan successions is the relationship between maximum particle size (MPS, mean of 10 largest clasts) and bed thickness (BTh). Bluck (1967) demonstrated for both water-laid and debris flow conglomerates that these parameters commonly correlate, both decreasing downslope. Gloppen and Steel (1981) showed for debris flow deposits that the MPS:BTh ratio also decreases downfan, indicating that competence decreases more rapidly than other attributes of the flow. Bluck (1969) suggested that MPS:BTh ratios are higher for subaerial than for subaqueous flows, which would permit identification of submerged parts of coastal alluvial fans. In most cases, however, fossils and other subaqueous facies provide better environmental indicators.

Ancient debris flow deposits have been recognised in the Quaternary of Tasmania (Wasson, 1977a) and Spain (Harvey, 1984), the Miocene of Switzerland (Burgisser, 1984), the Permo-Triassic of Scotland (Steel, 1974) and in numerous other successions. Surface features such as lobate terminations are rarely preserved because of subsequent erosion or lack of exposure. However, Daily *et al.* (1980) recognised an example in Cambrian coastal fan deposits, in which a lobate termination with upward coarsening was apparent (Fig. 12). Commonly preserved features include a lack of internal stratification and imbrication, and a sheet-like form, in contrast with the common channel forms of water-laid deposits (Wasson, 1977a; Wells, 1984).

Figure 12
30 cm scale rests on top of coarsening-upward debris flow deposit wih boulders emergent from its upper surface. The debris flow deposit forms a lobe, whose base is parallel to horizontal stratification in overlying shallow marine sandstones. Coastal alluvial fan deposits in the Lower Cambrian Boxing Bay Formation of Kangaroo Island, South Australia (see Daily et al., 1980).

Figure 13
Paleosol of nodular calcrete in finer upper part of fining-upward sequence formed by flood deposition on an alluvial fan. Lower Member, Carboniferous Cannes de Roche Formation, Barachois-de-Malbaie, Quebec. Tape open 20 cm.

Red colouration and evaporitic paleosols (facies P, Table 1) occur in several ancient alluial fan deposits, and point to a semi-arid paleoclimate (Williams, 1973). Canadian examples are the Carboniferous Cannes de Roche Formation of eastern Gaspé (Rust, in press, a) and the Bonaventure Formation of Gaspé and New Brunswick (Zaitlin and Rust, 1983). The paleosols are predominantly nodular limestones (calcretes) within finer lithologies (Fig. 13). Other types of paleosol can provide paleoclimatic evidence, although with less confidence (Retallack, 1983). According to Bown and Kraus (1981), paleosols are the rule rather than the exception in ancient alluvial deposits, and therefore have considerable potential for paleoclimatic interpretation.

Ancient successions containing coastal fan deposits were recognised in the Miocene of Turkey (Hayward, 1983), the Devonian of Norway (Steel and Gloppen, 1980) and Arctic Canada (Muir and Rust, 1982), and the Cambrian of South Australia by Daily *et al.* (1980). In the Devonian example discussed by Steel and Gloppen (1980), the basin sediments are lacustrine. Repetitive cycles in marginal alluvial fan deposits were also recognised in the lacustrine succession, indicating that the cause of cyclicity was basin-wide subsidence. Daily *et al.* (1980) described a Cambrian fan succession that prograded across shallow marine environments. The unidirectional alluvial paleocurrents provide a clear indication of the orientation of the ancient coastline and therefore help in understanding the multipolar nature of the marine paleocurrents. For example, longshore currents can be distinguished from those induced by onshore wave attack, and by offshore flows such as rip currents.

Depositional Models for Fans

Miall (1977, 1978b) used a study of the modern Trollheim fan, California (Hooke, 1967) as the principal basis for his alluvial fan model. The Trollheim is a small fan with abundant debris flow deposits. Sedimentation is strongly influenced by two factors: the semi-arid climate and the active tectonic setting. It has been suggested that fans in humid climatic settings produce relatively fewer debris flows, and are therefore dominated by water-laid deposits (Schumm, 1977). This is probably true, but the concept has not been demonstrated quantitatively, and some humid-region fans contain abundant debris flow deposits (Broscoe and Thomson, 1969; Winder, 1965).

Other indicators of paleoclimatic influence in the ancient record are paleosols (discussed earlier), associated facies and biota. The facies indicative of a dry paleoclimate are evaporites in lacustrine or tidal flat deposits associated with coastal alluvial fans. Eolian deposits are less diagnostic, because they could be formed in paraglacial as well as arid climatic conditions (Brookfield, "Eolian Facies", this volume). However, the association of paraglacial alluvium with ancient glacigenic deposits has strong interpretive value. These include deposits from glacier ice (tillites), as well as characteristic facies assemblages of glaciomarine or glaciolacustrine environments (Eyles and Miall, "Glacial Facies", this volume). Paraglacial alluvial successions show upward-coarsening during periods of glacial advance and fining during retreat. The situation is complicated by the fact that coarse detritus results not only from proximity to glaciers, but also from the isostatic uplift consequent on the retreat of continental ice sheets. In general, alluvial successions generated in response to episodic glacial advance should show approximately symmetric coarsening-up, fining-up cycles, but such a situation has not been documented.

The preservation potential of fossils is not high in coarse-grained alluvium. However, Gostin and Rust (1983) described vertebrate and insect burrows and large upright tree trunks buried in Holocene alluvial fan gravels in South Australia. The preservation of xerophytic plant stems and associated faunal traces is likely to leave a permanent stratigraphic record of the semi-arid climatic conditions.

As described previously, tectonic influence can be recognised in the form of repetitive cycles of grain size and bed thickness variation with alluvial fan successions. However, the absence of such cyclicity should not be taken as evidence that tectonic influence was lacking. Small, frequent movements on faults maintain transport energy within fluvial systems, without being individually large enough to induce repeated trends.

Coastal alluvial fans are distinguished from their purely terrestrial counterparts largely by the presence of marine or lacustrine fossils. The effects of reworking by waves and subaqueous slumping may also be recognized (Kleinspehn *et al.*, 1984), but if the water body is small and protected, the resultant subaqueous deposits may be hard to detect.

BRAIDED RIVERS AND BRAIDPLAINS

Modern Examples

Gravelly braided rivers are common features of modern paraglacial environments (Rust, 1982a, 1975; Church and Gilbert, 1975). Gravelly braidplains are less common to-day, but their lateral extent gives them a high preservation potential, and they are more abundant in the ancient record.

The most abundant facies of coarse-grained proximal braided rivers and braidplains is horizontally bedded, imbricate gravel, which may appear massive where bedding is thick and texture uniform (Figs. 7, 8 and 14). This

Figure 14
Middle Devonian Malbaie Formation at Petite Pte. St-Pierre, Quebec, showing horizontally stratified conglomerate (facies Gm), planar cross-stratified conglomerate (Gp) and horizontally stratified sandstone (Sh). Notebook (arrowed) is 19 cm long.

facies dominates proximal braided rivers of paraglacial environments (Boothroyd and Ashley, 1975; Church and Gilbert, 1975; Rust 1972a, 1975) as well as braided gravels not influenced by glacial melting (Ore, 1964, p. 9; Smith, 1970, p. 2999). The dominance of facies Gm reflects the low ratio of mean particle size to water depth, in turn a function of the relatively low relief of bars and channels in proximal reaches. The bars are mostly longitudinal, that is, elongate parallel to flow, with gentle slopes into surrounding low sinuosity channels. Diagonal bars are similar, but oblique to flow (Smith, 1974, p. 210). Leopold and Wolman (1957) proposed that longitudinal bars start as a nucleus of the coarsest bedload fractions deposited in mid-channel as flow diminishes, and grow by addition of finer sediment mainly downstream from the nucleus. Smith (1974) observed similar processes during diurnal stage fluctuations in the Kicking Horse River, British Columbia: lateral and downstream growth of 'unit bars' with predominantly depositional morpholoy. In the same river Hein and Walker (1977) observed an initial stage of bar formation as 'diffuse gravel sheets' a few pebble diameters thick. They postulated that the sheets evolve into longitudinal or diagonal bars with horizontal stratification, or transverse bars with cross-strata. The latter, however, are rare in gravel-bed braided streams (Smith, 1974, p. 218).

It is clear that falling-stage modifications of gravel bars occur by depositional and erosional processes, but observations during flood stage are hampered by turbid water and the impossibility of walking across bars, let alone channels. Remote sensing is also impracticable under these circumstances. Rust (1978b, p. 614-5) suggested that longitudinal bars are stable bedforms at flood stage, when all the bedload is in motion. An indication that this is so comes from the giant longitudinal bars (1.4 to 2.5 km long, 15 to 45 m high) of catastrophic Pleistocene floods in eastern Washinton (Bretz *et al.*, 1956; Malde, 1968). Giant cross-bed sets with boulders up to 3 m diameter formed in estimated water depths up to 100 m (Malde, 1968), and longitudinal bar forms were preserved. Preservation of such large bars implies stability under the conditions prevailing. A possible analogy may be with the apparent bar forms in channels on Mars (Baker, 1978; Komar, 1983).

Sand facies are uncommon in proximal braided gravels, but where present include planar cross-stratified sand (facies Sp) and horizontally stratified sand (facies Sh, Fig 14.) Mud facies are rarely preserved. All these facies increase in abundance downstream, but unlike alluvial fan deposits the change is very gradual (Fig. 4). For example, clast-supported gravel is the principal lithotype of the Donjek River 50 km from its glacial source (Area 2, Rust 1972a).

Like alluvial fans, braidplains may also accumulate gravel in coastal environments (Leckie and Walker, 1982). Examples are the paraglacial coastal outwash plains of Alaska and Iceland (Boothroyd and Ashley, 1975; Boothroyd and Nummedal, 1978).

Ancient Braidplain Deposits

Like their modern counterparts, ancient successions formed in braided rivers and braidplains are characterised by gradual facies change and decreasing grain size in the downstream direction (Fig. 4). Examples of both confined and unconfined braided river deposits are known (Kraus, 1984), as well as close genetic relationships with neighbouring alluvial fan successions (Middleton and Trujillo, 1984; Rust, 1981). Although coarse-grained braidplain successions are generally thinner than those of alluvial fans, their extent parallel to paleslope may approach 500 km. Vonhof (1965) has documented cobble-grade Oligocene gravels at the Alberta-Saskatchewan border derived from the Montana area across a relatively steep foreland slope. Similarly, the Lower Cretaceous Cadomin Formation of the Cordilleran Foothills in Alberta and Montana (McLean, 1977; Schultheis and Mountjoy, 1978) is sheet-like, extending up to 300 km downslope from its source (McLean, 1977, Fig. 4). Maximum clast size decreases in the transport direction (northeastward) very gradually (McLean, 1977, Fig. 4). Plotted on Figure 4, these data are comparable with maximum clast size trends in modern braided rivers, but differ markedly from size trends on modern alluvail fans. In proximal reaches these deposits are characterised by an abundance of facies Gm (Fig. 7).

Other examples of proximal braidplain conglomerates in the ancient record include Triassic conglomerates in England (Steel and Thompson, 1983), conglomerate units within the Lower Paleozoic Piekenier Formation of South Africa (Vos and Tankard, 1980) and the Middle Devonian Malbaie Formation of Eastern Gaspé, Canada (Rust, 1978b, in press, b). Essentially continuous coastal sections of the Malbaie Formation expose braidplain conglomerates for about 4 km in the downslope direction and about 5.5 km across the slope of the plain. Within this area grain size does not vary appreciably, and paleocurrents determined from clast imbrication (Fig. 8) are essentially uniform (Rust, in press, b). This suggests that the rate of grain size reduction down the Malbaie braidplain was similar to that in the Cadomin conglomerate, and in modern equivalents. As with the other examples, Gm is the predominant facies of Malbaie conglomerate units. Planar cross-stratified conglomerate (facies Gp) makes up about 20% of the conglomerate, a much higher proportion than in the modern equivalents described above (Figs. 1 and 14).

Proximal braidplain deposits form in response to major glacial or tectonic events. However, they are not organised into smaller scale cycles that might represent individual tectonic episodes, as is the case with alluvial fans. It appears that the influence of individual tectonic episodes is lost when the resulting detritus has been transported away from the fans adjacent to the mountain front. Hence stratification and grain size changes are a response to major floods rather than tectonic events.

Distal gravelly braided fluvial deposits are not well represented in the ancient record. An example is the Upper Member of the Carboniferous Cannes de Roche Formation of Eastern Quebec (Rust, 1981; in press, a). Trough cross-stratified clast-supported conglomerate occurs in multiple sets above a sharp erosional base (Fig. 15). This facies (Gt) fines upwards to trough cross-stratified sandstone (St), commonly through intermediate units of horizontally bedded conglomerate (Gm) (Figs. 14 and 15). This succession is interpreted as a response to shallowing of water over bars and active gravelly channels as they accrete, accompanied by, or in response to migration of the active tract. The sequence ends with mudstone and organic material deposited as the tract

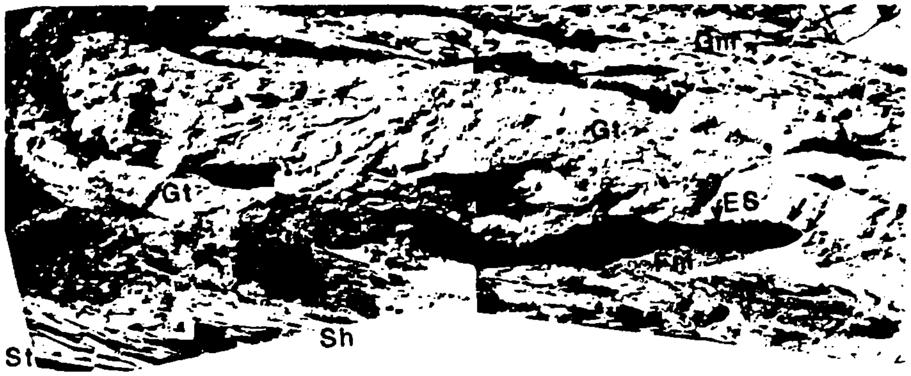

Figure 15
Repetitive stratification sequence in Upper Member of Carboniferous Cannes de Roche Formation, Coin-du-Banc, Quebec. Base of sequence is an irregular erosion surface (ES), overlain by trough cross-bedded conglomerate (Gt), comprising a coset in which some of the trough sets are sandstone-filled. These in turn are overlain by horizontally stratified conglomerate (Gm) and sandstone (Sh). Sandstone sets (Sh and shallow trough: St) are best seen at top of underlying sequence; in turn they pass upward into mudstone (Fm), cut into by erosional surface. Scale (arrowed) 1 m long.

became inactive and started to support vegetation (Figs. 16 and 17).

Models for Braided River and Braidplain Deposition

Two models, proximal and distal, are required to describe the sedimentary characteristics of braided rivers and braidplains.

Miall (1977, 1978b) based his proximal model on proximal reaches of the Scott outwash. The model is essentially the same as facies assemblage G_{II} of Rust (1978b). Imbricate, horizontally-stratified gravel is dominant (facies Gm), with minor amounts of planar cross-stratified gravel (Gp) and sand facies (Sp and Sh). This assemblage (Fig. 18a) characterises their proximal outwash gravels, such as the Donjek

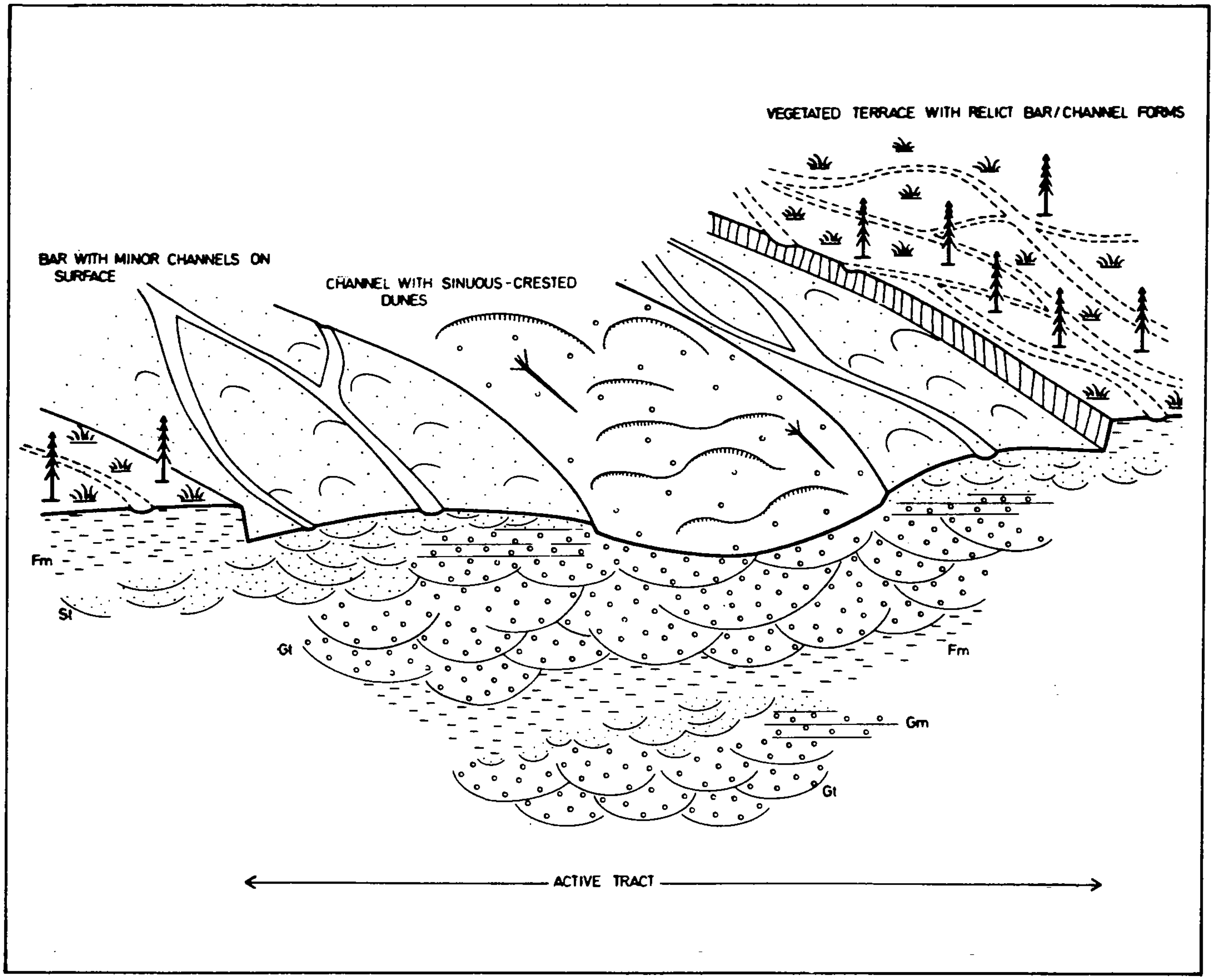

Figure 16
Repetitive stratification sequence in Upper Member of Cannes de Roche Formation, as related to facies assemblage G_{III} of Rust (1978b) and the Donjek model of Miall (1978b).

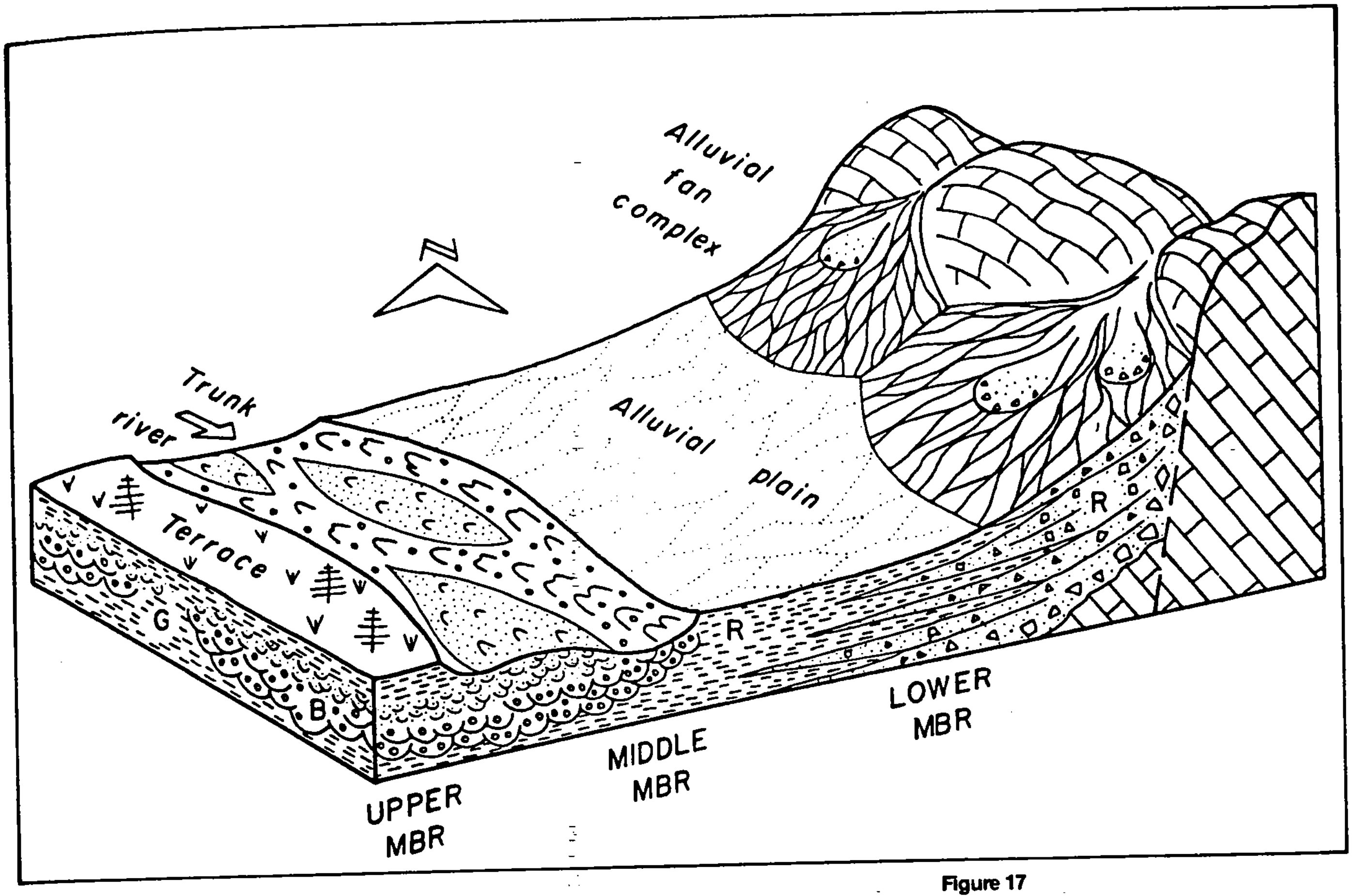

Figure 17
Depositional model for Cannes de Roche Formation, showing distal braided river deposits (Upper Member) in trunk valley confined by tributary alluvial fan deposits (Lower and Middle Members). R) red, B) buff, G) grey-green. See Rust (in press, a).

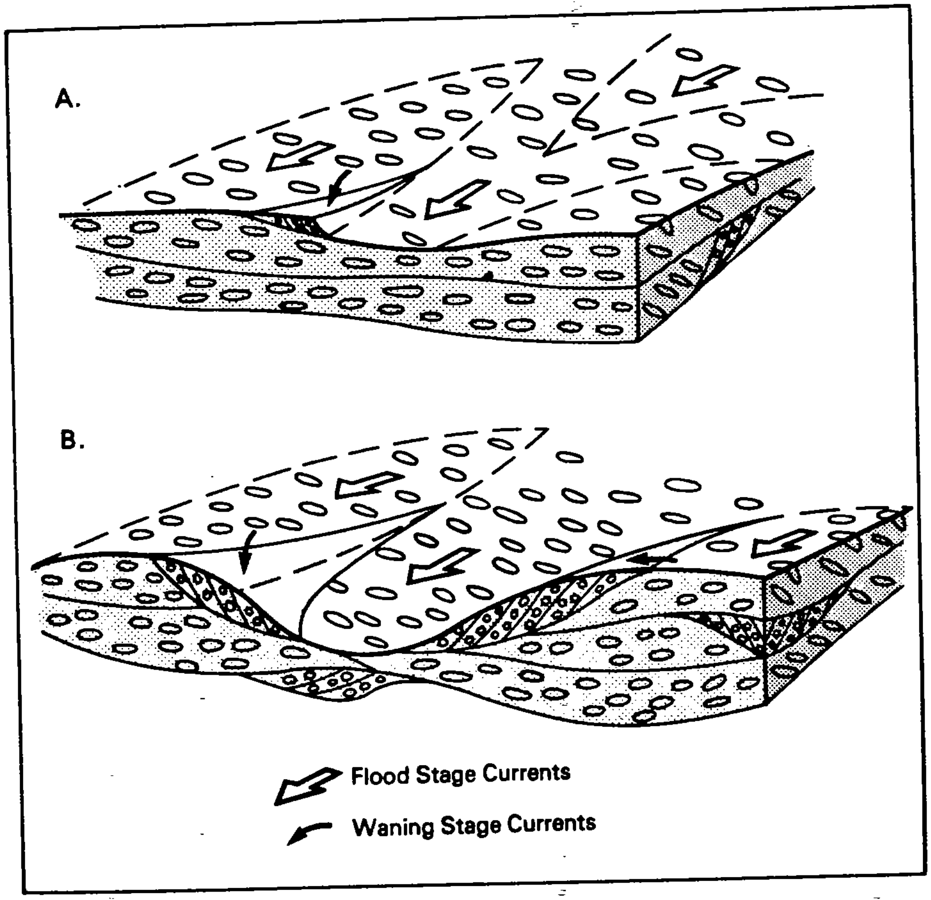

Figure 18
Depositional models for proximal gravelly braidplain/braided river deposits. A) Modern deposition, in which facies Gm is strongly dominant because of shallow flow in semi-arid or paraglacial settings. B) Ancient (Paleozoic) deposition, in which Gm is still the dominant facies, but Gp is more prominent, because the bar/channel relief is greater. This results from commonly recurring deep flood flows, due to formation under humid climatic environments.

(Rust, 1975) and gravelly braided rivers of non-glacial settings (Ore, 1964; Smith, 1970).

In the modern setting, deposits of this type are characteristic of climatic extremes (semi-arid or paraglacial), in which large amounts of coarse detritus are produced, and plant cover is sparse. In the Paleozoic, however, vegetation was confined to well-watered low-lying valleys or coastal plains. Hillslopes were unprotected, so upland gravels were generated abundantly in humid climates, forming extensive braidplains. Unlike modern counterparts, these floods were deeper and more frequent, so large-scale units of planar cross-stratified gravel (facies Gp) formed, together with falling-stage sequences of sand facies. In this sense the input into the model from modern and ancient deposits differs, but the difference is relatively minor (Fig. 18b).

The facies model for distal braided gravels discussed here (G_{III} of Rust, 1978b) is not as well established as that for proximal equivalents: it is offered as a guide for further investigation (Fig. 16). Miall (1977, 1978) chose the middle reaches of the Donjek River (Area 2 of Rust, 1972a, about 50km from its glacial source) as the type example of his facies assemblage for distal gravelly braided rivers. Clast-supported gravel is the dominant lithotype in this reach of the river, and is abundant in the active channel tract. In a similar setting in the Knik River, Alaska, Fahnestock and Bradley (1973, p. 241) identified dunes of fine gravel by echo sounding. They probably resemble the crescentic gravel bedforms observed in the North Saskatchewan River by Galay and Neill (1967), and would generate sets of trough cross-strata (facies Gt) by migration in flood. An alternative possibility in shallower rivers is the formation of transverse gravel bars (Hein and Walker, 1977, Fig. 3) which would generate principally planar cross-strata (facies Gp) on migration.

The mid reaches of the Donjek are also characterised by inactive tracts on levels or terraces above the active tract (Williams and Rust, 1969). The inactive tract is primarily subject to vertical accretion of fine sediment, and supports abundant vegetation. In flood, however, minor channels transport sand and fine gravel across the inactive tract. In time, migration of the active and inactive tracts can be expected to deposit a sequence which fines upward from trough cross-stratified clast-supported gravel through sand to mixtures containing mud and plant material, both transported and *in situ* (Fig. 16 and 17).

The depositional model described above is also representative of facies assemblage G_{III} of Rust (1978b). It has not been recognised in modern braidplain deposits, perhaps because confinement by valley walls is a necessary requirement for development of this facies sequence. The Upper Member of the Carboniferous Cannes de Roche Formation serves as an ancient example of facies assemblage G_{III} (Rust, 1981; in press, a). Paleogeographic reconstruction based on paleocurrents in alluvial fan deposits in the Lower and Middle Members suggests that the braided river deposits were confined to a paleovalley (Fig. 17) with tributary fans on either side. In this sense the Cannes de Roche Formation closely resembles the Donjek River, although the paleoclimatic setting is quite different. Abundant calcretes and red colouration in the Cannes de Roche fan deposits indicate a relatively dry paleoclimate.

TECTONISM AND ALLUVIAL FACIES MODELS

Miall (1981) recognised twelve plate tectonic settings for alluvial basins, in which most conglomeratic sequences were deposited as fault-bounded fan accumulations in forearc or foreland basins, or in intermontane successor or pull-apart basins. Most ancient fan successions show distinct cyclicity, ascribed to periodic tectonism, and ancient braidplain deposits also owe their origin to tectonic causes. The question remains: is there any fundamental difference between the tectonic framework of alluvial fan and braidplain successions?

Ancient braidplain successions are widespread deposits that form in response to major tectonic uplifts. For example, the Cadomin Conglomerate formed in response to Cretaceous uplift of the Cordillera (McLean, 1977; Schultheis and Mountjoy, 1978). The Malbaie Formation and other time-equivalent molasse deposits of the Appalachian and Caledonian belts accumulated in response to the mid-Paleozoic Acadian and late Caledonian Orogenies (Rust, 1981; Allen and Friend, 1968; Allen, Dineley and Friend, 1967). Such major episodes of deformation call for extensive compression, such as that caused by collision of an outboard terrane with a continental margin (Keppie, in press).

In contrast, alluvial fan deposits are more localised accumulations formed adjacent to active fault scarps. Fans may develop in relation to several tectonic situations. In extensional rifting the alluvial successions are relatively thin, because once the continental plates separated or the rift failed, the fault scarps were worn down and became inactive. An example of this scenario was described by Hobday and Von Brunn (1979). An alternative setting for alluvial fan conglomerates is a strike-slip plate margin. In this case, fan accumulations continue to form along the fault complex as it continues to slip, and may reach considerable thicknesses. For example, about 12,000 m of Cenozoic fan deposits accumulated in the Ridge Basin, California, in response to largely strike-slip movement on faults of the San Andreas System (Crowell, 1974). Crowell (1974, p. 300) cited the post-Acadian (Carboniferous) rift basins of Maritime Canada as a similar example in which thick alluvial fan deposits accumulated adjacent to a predomonantly strike-slip fault complex. The Devonian deposits in Western Norway described by Steel and Gloppen (1980) represent a similar depositional situation. In terms of plate tetonics, these phenomena can be explained by the activity of a transform fault, causing strike-slip displacement of parts of two adjacent continental plates.

The coarse alluvial deposits of eastern Canada can be divided into pre-Upper Devonian rocks, dominated by braidplain deposits, and Upper Devonian and Carboniferous alluvial fan successions. Rust (1981) suggested that this change in alluvial style was a response to oblique continental collision during the Acadian (mid-Devonian) Orogeny, followed and partly overlapped by transcurrent shearing along the former continental margin during the Carboniferous. There is nothing unusual about such a deformation sequence, because continental collision, or docking of outboard terranes commonly takes place at an olique angle to the original continental margin. Hence initial compression is followed by transcurrent shearing, and the change in alluvial style described above is to be expected.

SUMMARY

Alluvial Fans

The basic model for alluvial fan deposition (the "norm" of the "General Introduction", this volume) is characterised by rapid fining in the downslope direction and by the presence of debris flow deposits (Fig. 3). An additional feature, which may not always be recognisable in the ancient record, is a radiating pattern of paleocurrents. This model can be used as a guide and predictor for understanding reasons for variations from the norm. These variations include:

i) Features associated with a semi-arid paleoclimate: arid-zone paleosols and biota, and association with evaporitic facies such as playa lake sediments.
ii) Features associated with a paraglacial setting: association with glacigenic sediments: tillites, glaciomarine and glaciolacustrine assemblages
iii) Coastal fan features: evidence of reworking by subaqueous processes; lacustrine or shallow marine biota.
iv) Sedimentary responses to tectonism: repetitive sequences of grain size and bed thickness trends on scales of around 10 to 100 m. Commonly they coarsen and thicken upwards, but asymmetric coarsening then fining, and thinning upward sequences are also encountered. A lack of such cyclicity does not necessarily indicate a lack of tectonic influence.

Braided Rivers and Braidplains

Deposits of these environments are essentially identical, and can be characterised by two models, which consititute norms for proximal and distal deposition, respectively (Fig. 17 and 18). The proximal model is simple, and is reasonably well established on several modern and ancient examples. The distal model is based on few case histories, and must be regarded as tentative.

1) *Proximal* deposits of gravel-dominated braided rivers and braidplains are characterised by an abundance of horizontally-stratified gravel deposited by vertical accretion on longitudinal bars. Planar cross-stratified gravel is the next most abundant facies, particularly in Paleozoic and older deposits. Debris flow deposits and tectonically-induced cyclicity are lacking, and the downstream transition to distal deposits typically occurs over a distance of several tens of kilometres.

2) *Distal* assemblages are characterised by autocyclic fining-upward sequences from gravel, chiefly trough cross-stratified, through sandstone to mudstone. The latter facies may include remains of *in situ* vegetation.

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