Alluvial fans: geomorphology, sedimentology, dynamics – introduction. A review of alluvial-fan research

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This volume presents a series of papers on the geomorphology, sedimentology and dynamics of alluvial fans, selected from those presented at the ‘Alluvial Fans’ Conference held in Sorbas, SE Spain in June 2003. The conference was sponsored primarily by the British Geomorphological Research Group and the British Sedimentological Research Group, both organizations affiliated to the Geological Society of London.

It is some time since an international conference has been held that was exclusively devoted to the geomorphology and sedimentology of alluvial fans. The previous such conference was that organized by Terry Blair and John McPherson in 1995, and held in Death Valley, a classic setting for alluvial fans (Denny 1965; Blair & McPherson 1994a). Although many of the papers presented there have since been published, no dedicated volume on alluvial fans as a whole resulted from that meeting, so even longer has elapsed since there has been a specific publication devoted wholly to a series of papers on the geomorphology and sedimentology of alluvial fans (Rachocki & Church 1990).

South-east Spain was chosen as the venue for this conference, partly for logistic reasons and partly because it is a tectonically active dry region within which there is a wide range of Quaternary alluvial fans. These fans exhibit differing relationships between tectonic, climatic and base-level controls (Harvey 1990, 2002a, 2003; Mather & Stokes 2003; Mather et al. 2003), core themes in consideration of the dynamics of alluvial fans.

An emphasis within the previous alluvial fan literature has been on fans within the deserts of the American South-west (Bull 1977), with a focus especially on the alluvial fans of Death Valley (Denny 1965; Blair & McPherson 1994a). However, alluvial fans are not exclusive to drylands, nor to the particular combination of processes and morphology that characterize the Death Valley fans. Depositional processes may range from small debris cones (<50 m in length: e.g. Wells & Harvey 1987; Brazier et al. 1988; Harvey & Wells 2003) to fluvially dominated megafans (up to 60 km in length: Gohain & Parkash 1990). Alluvial fans, although common in desert mountain regions (Harvey 1997), may occur in any climatic environment, in arctic (e.g. Boothroyd & Nummendal 1978), alpine (e.g. Kostaschuk et al. 1986), humid temperate (e.g. Kochel 1990) and even humid tropical environments (e.g. Kesel & Spicer 1985).

In all climatic environments alluvial fans may play an important buffering role in mountain geomorphic or sediment systems (Harvey 1996, 1997, 2002b). They trap the bulk of the coarse sediment delivered from the mountain catchment, and therefore affect the sediment dynamics downstream, either in relation to distal fluvial systems or to sedimentary basin environments. In doing so, fans preserve a sensitive sedimentary record of environmental change within the mountain sediment-source area, rather than a broad regional record as would, for example, pluvial lake sediments (Harvey et al. 1999b).

One of the aims of the 2003 conference was to bring together current research on the geomorphology, sedimentology and dynamics of alluvial fans, ranging from studies of modern processes through to studies of Quaternary fans and to those of ancient fan sequences within the geological record. We sought papers relating to a range of scales and of climatic and tectonic contexts. Some of the papers presented at the conference were ‘in press’ in other publications at the time (e.g. Harvey & Wells 2003) or are being published elsewhere (Garcia & Stokes in press; Saito & Oguchi 2005; Stokes et al. in press). In this volume we present a selection of the papers presented at the Sorbas meeting that spans a wide range of alluvial fan research. We group them into three main themes: those dealing with processes on fans; those dealing with the dynamics and morphology of Quaternary alluvial fans; and those dealing with the interpretation of
Processes on alluvial fans

In recent years there has been growing recognition of the range of sedimentary signals of fan depositional processes. The importance of sheet-flood processes as opposed to channelized fluvial processes has been recognized on desert alluvial fans (Blair & McPherson 1994a), and there is growing recognition of the distinctions within mass-flow processes between true debris-flow processes and those associated with hyperconcentrated flows (Wells & Harvey 1987; Blair & McPherson 1994a, 1998), aided by advances in the understanding of the rheology of mass flows in the lahar literature (e.g. Cronin et al. 1997; Lavigne & Suwa 2004) and in hydraulic engineering (e.g. Engelund & Wan 1984; Julian & Lan 1991; Rickenmann 1991; Wang et al. 1994). In this volume we include two papers on fan sedimentation processes, in markedly contrasted environments, by Mather & Hartley and by Wilford et al. in hyper-arid and humid environments, respectively.

Building on previous work (e.g. Bull 1977; Kostaschuk et al. 1986), it is realized that distinct fan surface gradients result from different depositional processes, but the concept of a specific ‘slope gap’ (Blair & McPherson 1994b) between alluvial fan and river gradients has since been demonstrated to have been flawed (Kim 1995; McCarthy & Candle 1995; Harvey 2002c; Saito & Oguchi 2005). To some extent Blair & McPherson’s (1994a) classification of alluvial-fan styles, based on process combinations, reinforces the traditional concept of ‘wet fans and dry fans’ (Schumm 1977); however, the application of that concept to a climatic association with humid and arid climates, respectively, is clearly oversimplified. On the contrary, arid environments tend to be more fluviually dominant than do humid regions (Baker 1977), and many studies have demonstrated an increase in fluviual activity on fans, resulting from climatic aridification (e.g. Harvey & Wells 1994), or an increase in hillslope sediment supply from debris-flow activity following a climatic change towards greater humidity (e.g. Gerson 1982; Bull 1991; Al-Farraj 1996).

There is increasing recognition that alluvial fans represent a continuum of depositional processes (Saito & Oguchi 2005) from small debris cones, characteristic of many mountain environments (e.g Brazier et al. 1988), especially in paraglacial zones (Ryder 1971), to large fluviually dominant fans, such as the Kosi megafan in India (Gohain & Parkash 1990). In this volume we include two papers on large fluviually dominated fans in contrasted environments (by Arzani in Iran, and by Gabris & Nagy in Hungary).

Dynamics of Quaternary alluvial fans

Research on Quaternary alluvial fans tends to focus on the relationships between fan sediments and morphology, but has moved beyond earlier descriptive morphological studies (e.g. Denny 1965; Hooke 1967, 1968; Bull 1977) and basic morphometric studies (Bull 1977; Harvey 1984, 1997). More attention has been paid to the morphological style of alluvial fans insofar as this reflects fan setting, including the conventional tectonically active mountain-front setting and backfilled fans on tectonically stable mountain fronts (Bull 1978), or tributary-junction settings (Harvey 1997). Fan setting, in turn, affects the degree of confinement (Sorriso-Valvo et al. 1998; Harvey et al. 1999a) and accommodation space (Viseras et al. 2003). In addition, fan style reflects the geomorphic regime of the fan, from aggrading through to prograding telescopic fans and to fans undergoing dissection (Harvey 2002a). This is controlled fundamentally by the relationships between sediment supply to the fan and by flood power, in other words by the threshold of critical stream power (Bull 1979).

Perhaps the main emphasis over recent years in research on Quaternary alluvial fans has been to consider how the gross factors controlling alluvial-fan environments (catchment controls, tectonics and long-term geomorphic evolution, climatic controls, base level) interact to create fan morphological and sedimentary styles, and how fans respond to changes in the controlling factors. Studies of fan morphology have developed to focus on these interactions (Silva et al. 1992; Calvache et al. 1997; Harvey et al. 1999a; Harvey 2002c; Viseras et al. 2003).

It has long been realized that of the controlling factors, catchment characteristics (including drainage basin area, relief and geology) control the supply of water and sediment to the fan, and therefore the process regime on the fan and the resulting fan morphology. Although emphasized in the geological literature (see below), tectonic controls may influence sediment production in the source area, and, together with gross topography, appear primarily to control fan location, fan setting and gross fan geometry (Harvey 2002a) rather than fan-sediment sequences. Tectonics appear to influence fan morphology and sedimentary sequences primarily through an influence on accommodation space (Silva et al. 1992; Viseras et al. 2003).

For Quaternary alluvial fans in a wide variety of environments, climatic factors appear to have an overwhelming control on fan morphology and sedimentary styles. This is not to say that there are...
fundamental differences between fans in different climatic environments; there are differences, of course, but the primary processes differ remarkably little between humid and arid environments, or between arctic and subtropical environments. In each case the fan morphology appears to be adjusted to the prevailing sediment supply and flood regime. If a climatic change alters flood power and/or sediment supply, the fan responds by a change in erosional or depositional regime, resulting in a change in the sedimentary environment. There are numerous examples of studies demonstrating where climatic shifts have resulted in changes to fan systems (e.g. Wells et al. 1987; Bull 1991; Harvey et al. 1999; Harvey & Wells 2003). Studies that have evaluated the relative roles of tectonism and climate for changes in sedimentary and geomorphic sequences on Quaternary fans, demonstrate that climate is overwhelmingly the primary control (Frostick & Reid 1989; Ritter et al. 1995; Harvey 2004).

Most fans toe out at stable base levels, therefore base-level change is not a common cause of changes in fan behaviour on Quaternary fans. However, on fans that toe out to coasts or lakeshores and on fans subject to ‘toe trimming’ (Leeder & Mack 2001) by an axial river system, base-level change may be an effective mechanism for triggering incision into distal fan surfaces (Harvey 2004). However, base-level fall may not always trigger incision; this very much depends on the gradients involved. Indeed a base-level rise may trigger distal incision on coastal fans, if rising sea levels cause coastal erosion and fan profile foreshortening and steepening (Harvey et al. 1999a). Base-level change, such as a eustatic sea-level change or a change in the level of a pluvial lake, may be ultimately climatically controlled. The effectiveness of base-level change will depend on how it relates temporally to changes in sediment supply that are also climatically led. In cases where base-level change has been identified as an effective mechanism on Quaternary alluvial fans, the primary signal is a climatically led sediment signal, modified by the effects of base-level change (Bowman 1988; Harvey et al. 1999b; Harvey 2002d, 2004).

Within this volume we present several papers that deal with interacting controls on Quaternary alluvial fans in a range of mostly dry climate settings: in Andean mountain environments in Argentina (Columbo), and in deserts in the Middle East (Al-Farraj & Harvey), Chile (Hartley et al.) and the American West (Harvey).

In the past, a full appreciation of the response of alluvial fans to environmental change or of their wider role within fluvial systems has been hampered by the lack of suitable dating methods, applicable to alluvial-fan sediments. While it is true that radio-carbon dating has been effectively applied to late Pleistocene or Holocene sequences of alluvial-fan development in humid regions (Brazier et al. 1988; Chiverrell et al. in press), the precise dating of dry-region alluvial fans over longer timescales has always been a problem. Traditional methods have involved the mapping and correlation of fan surfaces on the basis of relative age, expressed through desert pavement or soil development especially of calcified surfaces (Lattman 1973; Harden 1982; Machette 1985; McFadden et al. 1989; Amit et al. 1993; Alonso-Zarza et al. 1998, Al-Farraj & Harvey 2000). In some cases fan sequences have been correlated with dated lake or coastal sediments (Harvey et al. 1999, b). Three new dating techniques have potential in alluvial fan research. Cosmogenic dating, applied to depositional surfaces (Anderson et al. 1996) or to questions of sediment flux (Nichols et al. 2002), U/Th dating of pedogenic carbonates (Kelly et al. 2000; Candy et al. 2003, 2004), and applications of optically stimulated luminescence (OSL) dating to fluvial-terrace and alluvial-fan sediments have opened up new opportunities for alluvial-fan research. Two papers in this volume focus on recent applications of luminescence dating to alluvial-fan sediments (Pope & Wilkinson; Robinson et al.).

Alluvial-fan sedimentary sequences

The challenge facing research on alluvial-fan sedimentary sequences is to develop interpretive models that are compatible with the findings of research on contemporary processes and on extant Quaternary alluvial fans. To some extent previous models may be seen as simplistic. The assumptions about overall coarsening-up sequences within alluvial-fan sediments (Steel 1974; Steel et al. 1977; Rust 1979) may be appropriate for distal-fan environments, when the proximal-fan sediments are being reworked by fanhead trenching, but are certainly not appropriate for proximal environments on aggrading fans (Harvey 1997). There we would expect an overall fining-up trend as the topography becomes progressively buried and each location effectively becomes more distal.

Another concept that clearly needs revision is the oversimplified association of the wet/dry fans dichotomy with wet/dry climates, respectively (see above). This in part relates to the debate on the relative roles of climate, tectonism and base-level change in ancient alluvial-fan sediment sequences. Studies of Quaternary fans (see above) recognize that tectonics may play a major role in controlling the location and setting of alluvial fans, but fan sequences respond primarily to climatic controls. Within most of the previous geological literature tectonics are seen as the primary control of change
in alluvial-fan sequences. We need to ask why there is this discrepancy. Are most of the geologists working on ancient sequences wrong? Is the climatic signal difficult to identify from the sediments alone, especially if some of the simplest climatic relationships are, in fact, oversimplifications? Perhaps this has something to do with scale. Most Quaternary fans are small in comparison with the scale of ancient systems described in the literature, therefore there is a question of preservation potential. Only the larger systems, especially those on the margins of sedimentary basins, and those developed over longer timescales are likely to be preserved in the geological record. It is known that responses to climatic change and to tectonic activity operate over different timescales (Harvey 2002b). Quaternary alluvial fans respond to climatic change over timescales of $10^2$–$10^4$ years, whereas tectonic change operates over timescales well in excess of $10^4$ years. Furthermore, during the global glacial–interglacial cycles of the Quaternary there were major changes in sediment input to fan environments in a wide range of climatic settings. Climatic changes during, say, the Triassic or the Cretaceous or the Neogene may have had less influence on geomorphic thresholds and therefore may have had a less overwhelming impact on sediment supply.

A second area of challenge in the understanding of ancient alluvial-fan sedimentary sequences lies in the development of an understanding of the three-dimensional (3D) geometry of alluvial-fan sedimentary bodies, and the interpretation of the 3D geometry in the context of models of sedimentary sequences in sedimentary basins. Of interest would be the application of sequence stratigraphy concepts to terrestrial environments, including alluvial fans, within which the salient events were not sea-level change, but climatic events. In such models (e.g. Weissmann et al. 2002) soil-covered fan surfaces could be seen as the sequence bounding surfaces. In this volume Weissmann et al. apply sequence stratigraphy concepts to the interpretation of the 3D geometry of Quaternary fans in the Central Valley of California. Although dealing with Quaternary fans, the methodology would be applicable to ancient fan sequences.

A final challenge for the application of concepts derived from modern fans to the interpretation of ancient sequences is to infer source-area characteristics from alluvial-fan sediments. A start has been made here by Mather et al. (2000) in applying morphometric relations derived from Quaternary fans to the assessment of drainage basin properties during the Pliocene in SE Spain. Pliocene fan geometry suggests that since emplacement of these sediments there have been major drainage reorganizations within the feeder catchments through river capture.

The influence of headwater river capture on downstream fluvial system development is itself an under-researched topic (Mather 2000).

Increasingly, there is more integration between studies of ancient fan sequences and studies of modern processes and of Quaternary fans. In each case the central theme of explanation lies in understanding the interactions between the tectonic, climatic and base-level controls. The final three papers in this volume illustrate this theme, addressing ancient fan sequences in different tectonic settings: Nichols on Tertiary fans of the Ebro Basin, Wagreich & Strauss on Tertiary fans in Austria and Leleu et al. on Cretaceous fans in Provence.

The future

Almost all the papers in this volume, whether dealing with ancient sequences, Quaternary fans or modern processes, address two fundamental questions. How do fans respond to the combinations of the controlling factors, and how is that response expressed in the morphology and the sediments? Challenges for the future lie partly in applied studies, for example hazards on alluvial fans, alluvial-fan sediments as reservoir rocks for water resources or in the ancient record, for oil. The major challenges, however, relate to the science itself. For Quaternary science: how far will more precise and more comprehensive dating allow integration of alluvial-fan research within wider basin-wide geomorphological and sedimentological models? For the study of ancient sequences: how far can the concepts derived from understanding modern fans be integrated more fully into basin sediment sequence models?

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References

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