Geology and geomorphology of alluvial and fluvial fans: current progress and research perspectives

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Abstract: Alluvial and fluvial fans are the most widespread depositional landforms bordering the margins of long-lived highland regions and actively subsiding continental basins, across a broad spectrum of tectonic and climatic settings. Their significance is relevant not only to the local morphodynamics of mountain regions and proximal basinal sectors, but also to the long-term evolution of sediment-routing systems, affecting the propagation of stratigraphic signals of environmental change and the preservation potential of stratal successions over much larger spatial scales than those they occupy. Subaerial fan systems archive information on the palaeoclimate, local tectonic history and landscape response to various allogenic factors, although our ability to decipher such information is still limited. Early recognition of alluvial fans dates from the late nineteenth century, but a coordinated research community on these systems has been active only over the last few decades and the full relevance of fluvial fan systems to the geomorphology of present day continental basins and to the interpretation of ancient stratigraphic successions has been convincingly demonstrated only over the last decade. This introductory chapter summarizes advances in our knowledge of alluvial and fluvial fans, identifies potential new lines of future inquiry, and presents the contributions to this volume in the context of the current state of research.

Alluvial and fluvial fans represent the dominant sedimentary systems developed along the margins of modern continental sedimentary basins and on tectonically stable highlands (except for pervasively glaciated regions). Both of these depositional landforms stem from the areal distribution of large volumes of clastic debris from point sources located where drainage catchment outlets encounter a topographic transition from elevated mountain ranges or plateaus to relatively subdued, open terrains (Bull 1977; Blair & McPherson 1994; Horton & DeCelles 2001; Weissmann *et al.* 2010). These alluvial systems currently occur worldwide in a variety of geomorphic settings, within or outside the boundaries of actively subsiding sedimentary basins, and over a complete range of climate settings, from hyper-arid (tropical or polar) to humid temperate to seasonal/monsoonal tropical. Stratigraphic records of subaerial fans have been identified in successions aggraded in essentially all climatic conditions and preserved in a broad variety of tectono-geomorphic settings. However, although tectonic subsidence is often cited as a precondition for the formation of alluvial and fluvial fans, this factor is actually only strictly relevant to the accumulation and long-term preservation of thick stratigraphic records; in fact, alluvial fans may also form at locations that are tectonically stable over timescales comparable with the time necessary for fan formation, as demonstrated by modern fans aggrading at the margins of recently deglaciated valleys (Ryder 1971; Church & Ryder 1972; Srivastava *et al.* 2009; Berger *et al.* 2011) or by tributary junction fans growing in correspondence with drainage network nodes in valley-confined, net-degradational settings (Wells & Harvey 1987; Harvey 2002; Wang *et al.* 2008; Stokes & Mather 2015).

A frequent misconception about the origin of subaerial fan systems is that they are primarily triggered by changes in substrate gradient from highlands to the immediately adjacent lowlands, the latter being the site of preferential aggradation as a result of the loss of competence in water flows or sediment gravity flows at the transition to a lower gradient topography. Whereas a reduction in bottom shear stress is associated with those particular systems in which there is an actual transition from a steep catchment drainage to a lower gradient basinal topography, the ultimate reason underlying the construction of fan-shaped alluvial landforms is the transition from laterally confined catchments/valleys in source areas to more open plains or broader

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valleys, where the radial spreading of sediment transport events through time is unobstructed. In fact, the dynamics of subaerial fan systems are inherently controlled by the progressive autogenic switching of sediment transport pathways and resulting depositional lobes. Following a process of topographic compensation, aggradational events raise the alluvial surface locally and induce successive events to take place at different, topographically lower positions or along different trajectories radiating from an apical zone. From this stems the characteristically fan-shaped, distributive plan view architecture shared by these systems.

There is long-standing controversy regarding the definition of alluvial and fluvial fans as either fundamentally distinct depositional landforms or as end-members along an idealized continuum of subaerial fan types, each identified by a characteristic set of sedimentary processes (Stanistreet & McCarthy 1993; Blair & McPherson 1994; McCarthy & Cadle 1995; Kim 1995; Nakayama 1999; Weissmann *et al.* 2010; Hartley *et al.* 2010). The terminological usage followed here considers alluvial fans to be landforms and sedimentary systems that are distinct from fluvial fans, while the term megafan, first adopted by Gohain & Parkash (1990), loosely applies to fluvial fans attaining radii in excess of *c.* 30 km and of large areal extent (up to 10^5 km^2) (e.g. Leier *et al.* 2005; Hartley *et al.* 2010; Fontana *et al.* 2014).

In spite of this controversial issue, the two end-member categories are clearly distinguishable when examining both presently active systems and Quaternary relict systems based on morphometric parameters and on the hydrological and sedimentological processes associated with primary depositional events in particular. Alluvial fans commonly aggrade directly adjacent to (and abutting) their source relief and are fed by areally restricted catchments, often with high internal relief (Melton 1965; Kostaschuk *et al.* 1986; Crosta & Frattini 2004), developing shorter radii (rarely up to several kilometres, typically from hundreds of metres to a few kilometres; De Scally & Owens 2004; Davies & McSaveney 2008) and higher gradients (especially over proximal domains, where they can attain slopes of up to several degrees). Their origin from relatively small, poorly integrated catchments implies that alluvial fans are mostly affected by hydrological events of short duration and markedly peaked hydrographs, irrespective of the climatic context in which they develop. In sedimentological terms this translates into a dominance of runoff events, unconfined or poorly confined within shallow channels of high aspect ratio, with highly concentrated bedloads and suspended loads (debris flows and hyperconcentrated flows), frequently (when not dominantly) within the spectrum of proper sediment gravity flows in which the water is actually a secondary phase by volume and sediment is mobilized in bulk by the direct action of gravity over sufficiently steep substrates (Hooke 1987; Whipple & Dunne 1992; Blair & McPherson 1994, 1998; Moscariello *et al.* 2002; Welsh & Davies 2011).

By contrast, fluvial fans (also known as distributive fluvial systems; Hartley *et al.* 2010; Weissmann *et al.* 2010) develop over much larger surfaces, attaining radii of several tens of kilometres and up to a few hundred kilometres (with a notable present day maximum in the Pilcomayo River fan of central South America, which reaches *c.* 700 km in radius) but maintaining low gradients within restricted ranges of fractions of a degree from the proximal to distal sectors. These systems are commonly fed by extensive and well-integrated catchments, which develop over long time spans, occasionally exceeding the age of the source relief (e.g. large antecedent catchments in active orogenic belts; Parkash *et al.* 1980; Damanti 1993; Friend *et al.* 1999; Horton & DeCelles 2001), and giving rise to proper rivers along whose courses a distinction between channels (or channel belts) and overbank domains is unambiguous, unlike alluvial fans. The strongly avulsive dynamics of such rivers (Slingerland & Smith 2004; Reitz *et al.* 2010; Fuller 2012) are probably induced by excess sediment loads from highland catchments and are at the origin of the distributive planforms progressively attained by fluvial fans.

Alluvial and fluvial fans have long been the object of geomorphological and sedimentological research, but only a few books and article compilations have been dedicated specifically to these systems (Rachocki & Church 1990; Harvey *et al.* 2005; Schneuwly-Bollschweiler *et al.* 2013), compared with the many tens of publications devoted to the analysis of fluvial, glacial, lacustrine and aeolian environments. In part, this may result from the deceptively simple configuration and small areal extent of alluvial fans, covering limited distances over their source to sink axes, and to their traditional, if erroneous, identification as significant geomorphic elements only within dryland landscapes (hence the frequent occurrence of essays on alluvial fan morphodynamics and sediments in compendia dedicated to the geomorphology of arid regions; e.g. Parsons & Abrahams 2009; Thomas 2011).

Explicit recognition of the potentially great importance of fluvial fans to the geomorphic dynamics of modern sedimentary basins and to interpretations of ancient stratigraphic records dates only from the last decade. Major gaps still exist in our knowledge of these depositional systems in terms of basic research and of their societal and geo-economic applications. In addition, their recent recognition on the surfaces of other planetary bodies within the Solar System (Jerolmack *et al.* 2004; Moore &

Howard 2005; Williams *et al.* 2006; Kraal *et al.* 2008) raises their importance to the understanding of environments still inaccessible for direct study. Most books devoted to alluvial fans (and traditionally including work on fluvial fans) originate from research presented at conferences. However, topical meetings on the subject date only from slightly longer than 20 years ago (Death Valley, USA 1995; Sorbas, Spain 2003; Alberta, Canada 2007; Ras Al-Khaimah, United Arab Emirates 2012; Canterbury, New Zealand 2015), probably a sign that an initially sparse research community only recently succeeded in bringing together a critical volume of data and working hypotheses. This Special Publication of the Geological Society, London aims to add to the classic books and to follow in their multidisciplinary approach, compiling thematic papers on alluvial and fluvial fans that range in scope from geomorphic and hydrological analyses of present day systems to sedimentological studies of ancient stratigraphic successions.

Alluvial fans: research progress and perspectives

Alluvial fan systems have two modes of operation that influence the processes operating on the fan surface and its resultant morphology: aggradation, where sediment is deposited on the fan; and degradation, in which sediment is eroded from the fan surface and out of the fan system. An erosional–depositional threshold, termed the threshold of critical power by Bull (1991), separates these two modes. These relationships are controlled by variations in flood discharge and sediment supply (Bull & Schick 1979; Bull 1991). In the simplest sense, excess sediment supply leads to local sediment deposition and therefore fan aggradation, whereas excess power will lead to erosion and fan degradation. This has been quantified using a number of sediment models for alluvial fans that explore the impact of sediment quantity and grain size on fan growth (see Parker *et al.* 1998; Duller *et al.* 2010, 2012; Allen *et al.* 2013 for further details and for a quantitative approach). These relationships can vary over different timescales and even a minimal change can have a significant effect as the fan system approaches dynamic equilibrium following the disturbance.One of the long-standing challenges in alluvial fan research is to determine whether changes in fan processes have been caused by allogenic factors influencing the fan environment through sediment or water supply, or through some process-driven threshold intrinsic to the fan system (i.e. autogenic factors).

The fan morphology is often controlled by the characteristics of the contributing catchment. A number of early studies (Bull 1964, 1977; Denny 1965; Hooke 1968; Church & Mark 1980; Kostaschuk *et al.* 1986; Parker *et al.* 1998; Whipple & Trayler 1996) explored the relationship between the size of alluvial fans and the size of their contributing catchments to understand the mechanisms of fan construction. The larger the area of the catchment, the greater the potential to store sediment within it and therefore the more likely a decrease in the total amount of sediment delivered to the fan per transport event. By contrast, smaller catchments have less potential for sediment storage and so are more likely to effectively deliver sediment to the fan surface for any given transport event. However, the increased potential for discharge in larger catchments, given the larger surface area for precipitation to fall over, can lead to the high delivery of sediment in some instances (Allen *et al.* 2013). Investigations into the morphology of alluvial fans and their catchments (Sorriso-Valvo *et al.* 1998; Harvey 2001, 2007, 2012; Crosta & Frattini 2004) have found that catchment area is the primary control on fan area; however, other factors, such as the geological setting and bedrock lithology, have also been found to be important (e.g. Kostaschuk *et al.* 1986; Blair 1999*a*; Webb & Fielding 1999; Coe *et al.* 2003; Nichols & Thompson 2005; Welsh & Davies 2011), which will now be explored.

In tectonically active settings, where the source highlands are uplifting with respect to the adjacent basin, alluvial fans tend to aggrade as accommodation is continuously created, resulting in fans with a relatively small area with respect to their catchment area (e.g. Ferrill *et al.* 1996; Viseras *et al.* 2003). Therefore fan area–catchment area relationships must be considered in the context of the local tectonic setting (Whipple & Trayler 1996; Allen & Densmore 2000). Although there does appear to be a relationship between the size of alluvial fans and that of the contributing drainage basins, this is only evident in areas of limited tectonic activity. In complex environmental settings (i.e. those that have been affected by tectonics, base level changes and climate change), other factors can often have a more dominant control on alluvial fan development and fan size may bear little direct relationship to the physical characteristics of the drainage area (Allen & Densmore 2000).

The lithology and mechanical properties of the bedrock underlying the catchment also influence the volume and quality of sediment produced. Bull (1962) and Hooke (1968) reported that catchments underlain by rock types that are less resistant to erosion tend to produce alluvial fans that are larger in area than those produced by basins with more resistant rock types, the idea being that basins with less resistant rocks produce more sediment per unit area (i.e. sediment yield) and, because this material is finer, it can be transported further and therefore produce larger fans. By contrast, Lecce (1991) found that, in the White Mountains of California, the larger fans are supplied by basins underlain by more resistant rocks because these have feeder channels that flow in steep, narrow canyons with little sediment in storage, such that most of the sediment is ultimately delivered to the aggrading fan surface. Mills (2000) surmised that it is probable that these competing effects interact within most catchments: where the sediment production factor is dominant, catchments with relatively more erodible lithologies may produce more extensive fans; however, where the sediment storage factor is dominant, basins with less erodible lithologies may produce smaller fans. In addition, the bedrock lithology may have a direct influence on the sediment transport processes responsible for fan aggradation; for example, where catchments produce significant volumes of clay- and silt-sized debris, sediment–water mixtures will often reach the fan surface in the form of debris flows (e.g. Blair 1999*b*; Levson & Rutter 2000; Moscariello *et al.* 2002) rather than unconfined water flows, affecting not only the primary architecture of the fan deposits, but also the overall geometry of the system and its autogenic dynamics (e.g. Whipple & Dunne 1992; De Haas *et al.* 2016).

Despite the various controls exerted by catchment morphometry and geology, over long timescales these factors tend to be dominated by allogenic controls, such as tectonics and changes in base level and/or climate. Alluvial fans are often located in tectonically active areas and tectonics are often considered to be the primary control in dictating the location and morphology of fans, producing the setting, relief and accommodation space necessary for alluvial fan growth (Denny 1965; Bull 1977; Silva *et al.* 1992; Whipple & Trayler 1996; Allen & Hovius 1998). On an alluvial fan, periods of rising base level generally lead to increasing accommodation and deposition, whereas lowering of the base level may lead to a reduction in the available accommodation space, resulting in erosion and/or bypass at the fan surface (Harvey 2012, 2013). Conversely, climate change tends to act principally on geomorphic processes within catchments, controlling the spatial and temporal distribution of erosion, responsible for the primary sediment supply to the fan, as well as modulating the hydrological regime and therefore the discharge and stream power (increasing erosion). Climate also affects the vegetation cover in a catchment and on the fan surface, which, in turn, exerts a strong influence on the patterns of sediment yield and transport (Dorn 1996).

Numerous studies on Quaternary fan systems, which often have well-constrained chronological and palaeogeomorphic and palaeoclimatic information, have shown that the interplay between varying discharge and sediment supply is responsible for driving either fan aggradation or entrenchment (e.g. Ritter *et al.* 1995; Reheis *et al.* 1996; Pope & Millington 2000; Harvey & Wells 2003; Sohn *et al.* 2007; Scardia *et al.* 2010). This is typically observed in settings affected by glacial–interglacial cycles of geomorphic activity, where regional extremes in temperature and rainfall distribution favour fan sedimentation and growth at times of reduced vegetation cover (such as glacial times when temperatures cool) and/or enhanced sediment production, whereas fan dissection and lower aggradation rates predominate in phases of more widespread vegetation cover and/or increased discharge frequency and intensity (e.g. Ritter & Ten Brink 1986; Wells *et al.* 1987; Bull 1991; Harvey 1990, 2003; Harvey *et al.* 1999). Therefore in environments subject to active allogenic forcing, contextual factors such as catchment attributes may exert a minimal impact on alluvial fan morphology and development over the longer term (centuries to millennia). Disentangling the respective signals of autogenic processes and allogenic forcing requires an understanding of the system being investigated, with the frequency of autogenic behaviour related to the rate of change in allogenic forcing relative to the equilibrium time (Postma 2014). Therefore slow changes in aggradation rate do not significantly change autogenic behaviour, whereas fast change does.

Allogenic controls alone have often been unable to explain why, in some regions, landforms subjected to the same, or similar, environmental conditions during their evolution are not in the same stage of geomorphic development and cannot adequately explain certain details within landscapes (e.g. fanhead trenching; Hooke & Rohrer 1979; Schumm *et al.* 1987; Whipple *et al.* 1998). To account for such variability, it can be assumed that the development of landforms is influenced not only by external factors, but also by autogenic controls (Ventra & Nichols 2014). For example, both Ritter (1967) and Schumm & Parker (1973) concluded that terrace formation on alluvial fans was the result of dynamics internal to the fan system. Similarly, in a field study of 13 alluvial fans developed under constant climatic and tectonic conditions in the Howgill Fells, NW England (Wells & Harvey 1987), the dominant depositional processes were found to alternate between debris flows and stream flows according to geomorphic thresholds intrinsic to the fans. Complex interactions between forcing factors during fan evolution and the often chaotic and incomplete preservation of stratigraphic successions make it difficult to isolate the specific impact of autogenic dynamics in field studies (Clarke 2015). However, the use of experimental physical models that eliminate the interference of extrinsic factors under controlled boundary conditions has shown that autogenic processes during fan evolution can also induce alternating cycles of sheet flow and channelized flow related to critical slope thresholds on the aggrading surface (e.g. Schumm *et al.* 1987; Whipple *et al.* 1998; van Dijk *et al.* 2009, 2012; Clarke *et al.* 2010; Hamilton *et al.* 2013) on fans dominated by debris flow (De Haas *et al.* 2016).

As a consequence of their high-relief catchments, alluvial fans mostly tend to aggrade through catastrophic sedimentary processes associated with occasional flash flood events of relatively short duration and debris flows with higher sediment to water ratios. Many metropolitan areas throughout the world have experienced the uninhibited expansion of human settlements and infrastructure onto alluvial fans (Scheinert *et al.* 2012). Alluvial fans represent an ideal site for property owners because they often provide cooler conditions, cheaper or undesirable land in some regions, and/or a better view of the landscape. However, the occupation and urbanization of alluvial fan surfaces place humans at greater risk of flood and debris flow hazards (e.g. Wieczorek *et al.* 2001; Pelletier *et al.* 2005; Welsh & Davies 2011). Floods on alluvial fans, although characterized by relatively shallow depths, can strike with little warning, can travel at extremely high speeds and may carry tremendous amounts of coarse-grained sediment and debris, with potentially devastating consequences for any infrastructure developed along their path (Committee on Alluvial Fan Flooding 1996). There has been much research investigating the flood hazards posed by alluvial fans (e.g. Jackson *et al.* 1987; Kellerhals & Church 1990; French 1992; FEMA 2003; Hurlimann *et al.* 2003; Pelletier *et al.* 2005; Wolski & Murray-Hudson 2006). Thus far, the timing, location and occurrence of flooding on alluvial fans cannot be adequately predicted and broad margins of uncertainty are still associated with these predictions.

Debris flows are one of the most important formative processes for alluvial fans, capable of transporting large amounts of water and debris in very short time periods, posing great hazards for people and structures (D'Agostino *et al.* 2010). They can result in significant modifications to alluvial fan topography, both during and after an event (Scheinert *et al.* 2012). Topographic changes, in turn, affect the magnitude, trajectory, inundation and runout length of subsequent sediment transport events (Pelletier *et al.* 2005; Volker *et al.* 2007; De Haas *et al.* 2016). These interactions are further complicated when urbanized areas and built environments are constructed on fan surfaces.

Given the reduced temporal frequency of the primary events responsible for the transportation of sediment to the fan, secondary processes of weathering, reworking and erosion assume a certain relevance, directly affecting fan surfaces for most of the time through the mobilization and modification of surface sediments. Possible processes of fan surface modification include reworking by water, aeolian activity, bioturbation, groundwater activity, weathering and pedogenesis (e.g. Blair & McPherson 1994; De Haas *et al.* 2014; Regmi *et al.* 2014) and can differ in importance depending on the environmental context, with climate being possibly the most important factor. For example, Mills (2000) found that fans dominated by debris flows in the humid climate of the Appalachians (eastern USA) are affected by chemical weathering and bioturbation as a result of the natural presence of dense hardwood forest combined with low sediment deposition rates. By contrast, Blair & McPherson (1998) noted that wind, rains plash, overland flow and bioturbation are prevalent on the Dolomite Fan in the much drier climate of Owens Valley (SE California).

Research into alluvial fans has a long history, yet there are still unknown factors for future work to focus on. First, the link between geomorphological and sedimentological research needs to be strengthened through more interdisciplinary discussions to ensure that insights into processes observed and quantified over contemporary timescales are applied to inform the interpretation of stratigraphic successions, and vice versa. In particular, there is a need for the language and tools from studies on modern geomorphological investigations of alluvial fans to be transferrable to sedimentological research undertaken on much longer timescales. Second, experimental physical modelling on alluvial fans has shown the contribution of autogenic factors to fan evolution; however, the range of scenarios and boundary conditions applied in analogue modelling needs to be expanded so that these represent the range of environmental settings over which alluvial fans occur and are scaled to be applicable to real-world examples. In addition, new techniques need to be devised to derive insights useful to field researchers to better discriminate between the effects of autogenic dynamics and allogenic forcing through ancient successions. As Harvey *et al.* (2005) surmised, there is no doubt that autogenic change and fan 'ageing' occur in the absence of external forcing, but there is also no doubt that major externally induced changes in sediment production have a dramatic effect on fan processes. The challenge in unravelling field evidence still lies in determining the extent to which past changes in alluvial fan processes (i.e. facies associations) and morphology (i.e. stratigraphic architecture) reflect the concomitant influence of intrinsic feedbacks (autogenic factors) or environmental change (allogenic controls). Third, we are probably undergoing a phase of changing climate which will affect alluvial fan processes and potentially increase the probability of flood and debris flow hazards on urbanized fan systems. Major urban centres worldwide are located on alluvial fans, such as Los Angeles, Denver and Phoenix in the USA (Dorn 1994, 2009), and across regions such as India (Chakraborty & Ghosh 2010; Chakraborty *et al.* 2010) and Italy (Santangelo *et al.* 2011; Scorpio *et al.* 2015). Further understanding of the risk associated with climate change and an ability to predict future hazards are necessary to mitigate the potential threats.

Fluvial fans: current research and open questions

Fluvial fans are repeatedly presented as atypically large, river-dominated depositional end-members of an ideal continuum of alluvial fan processes and forms (e.g. Galloway & Hobday 1996; Reading 1996; Bridge & Demicco 2008), with common reference to the Kosi Fan of northern India as the most representative example (and probably the most photogenically fan-shaped when imaged from an aerial perspective). However, marked differences in hydrology, general morphology, sediment transport mechanisms and stratal architectures warrant a distinction from piedmont fans (Blair & McPherson 1994).

Fluvial systems affected by frequent avulsions and with a tendency to spread alluvium over large areas by continuous channel belt repositioning and/or distal bifurcation have long been reported from cratonic regions and from active sedimentary basins (e.g. Gole & Chitale 1966; Twidale 1972; Mukherji 1975; Jacobberger 1987). For many of these systems, an excess of sediment load supplied from hinterland catchments lies at the origin of the avulsive instability of channel belts at decadal to centennial timescales, and of the strong aggradational trends that, over longer timescales, build fluvial landforms markedly convex over transverse cross-sections tens to hundreds of kilometres wide, wedging out longitudinally downstream (i.e. basinwards) with a progressive loss of surface gradient. This morphological configuration stands in great contrast to the largely flat and locally even negative topography of alluvium (Syvitski *et al.* 2012; Lewin & Ashworth 2014; Lewin *et al.* 2017) in continental domains affected by long-term net degradation (with an exception for alluvial terraces, which may present a complex topography with locally high relief, but still relate to system-scale degradation, rather than net aggradation; Archer *et al.* 2011; Mather *et al.* 2017). Superposed on these general morphological trends are other trends common to most fluvial fans:

(1) active hydrographic networks and relict channel ridges that radiate down-fan from an apex (for single-channel systems this trait is developed over time, as successive channel belts avulse over the up-building fan surface);
(2) frequent superposition over the main fan surface of second-order alluvial lobes with gently convex, positive relief, kilometres to a few tens of kilometres wide, representing net aggradation in correspondence with individual channel belts during their time span of activity over specific fan sectors;
(3) frequent down-fan transitions in channel planform type, mostly from braided or wandering patterns in the proximal domain to higher sinuosity, single or anabranching channels over the lower gradient distal sector;
(4) a common (although not ubiquitous) down-fan reduction in channel depth and width, especially in arid or semi-arid climates where transmission losses and evapotranspiration strongly deplete discharge over significant distances (so-called terminal fans);
(5) a down-fan reduction in the texture of channel deposits and, less pronounced, of overbank deposits;
(6) a down-fan increase in the relative surface area of the overbank domain and its associated morphosedimentary sub-environments (e.g. swamps, ephemeral to semi-permanent ponds, forested areas, peat mires, local aeolian dune fields and sand sheets);
(7) down-fan shallowing (i.e. a reduction in depth below the active depositional surface) of the permanent or seasonal water table.

With an exception for points (4) and (7), in part controlled by the regional climate and by the differential hydrology of catchment and basin regions, this set of characteristics is generally encountered on most distributive fluvial systems (Hartley *et al.* 2010; Davidson *et al.* 2013) irrespective of tectonic context, climatic zone, fan radius or surface extent, supporting the notion that these landforms are produced by drainage systems with dynamics fundamentally distinct from those of tributive fluvial networks and associated valleys, which have been the principal focus of attention in fluvial geomorphology and sedimentology for the longest part of their multi-decadal history.

Considering modern systems, most fluvial fans seem to originate from large catchments within tectonically active regions or extensive highland regions (isostatically uplifted or residual, inactive intracratonic plateaus), where a conspicuous overload of clastic debris is produced and conveyed towards the margins of adjacent lowlands. Contrary to widespread opinion, the formation of fluvial fans (and, by analogy, alluvial fans) does not require protracted accumulation in areas subject to long-term subsidence because the latter factor is a strict prerequisite only to the preservation of stratigraphic records for such landforms. A simple topographic transition over tectonically stable substrates still allows for the formation of distributive alluvial landforms over geologically short time spans, whether or not amenable to preservation in the rock record, provided an input (apex) point or zone for runoff and sediment remains fixed for long enough time.

Retro-arc foreland basins thus provide an ideal tectono-geomorphic setting for generating large fluvial fans at the transition between tectonically active relief, which provides abundant terrigenous supply, and adjacent lowlands subject to long-term subsidence (thus also allowing the stacking of thick fan successions). At present, this is shown by the numerous fluvial fans and megafans that occupy the vast alluvial plains sloping down from the Andes (Damanti 1993; Latrubesse *et al.* 2012; Rossetti *et al.* 2014; Assine *et al.* 2015), Himalaya (Wells & Dorr 1987; Sinha & Friend 1994; Chakraborty & Ghosh 2010), Alps–Pyrenees (Fontana *et al.* 2008, 2014; Mouchené *et al.* 2017), Zagros (Walstra *et al.* 2010; Heyvaert & Walstra 2016) and other active orogens (Weissmann *et al.* 2011, 2015).

Modern fluvial fans have also been recognized within rift, strike-slip and back-arc basins (McCarthy *et al.* 1988, 2002; Mack *et al.* 1997; Gábris & Nagy 2005; Fordham *et al.* 2010; Hartley *et al.* 2010; Weissmann *et al.* 2015; Galve *et al.* 2016), where they often attain a reduced extent due to the greater topographic restriction of such basin types. In addition, fluvial fans also originate within tectonically inactive, intracratonic settings as a result of the downstream loss of confinement for rivers that traverse plateaus or carve extensive valleys within Neogene–Quaternary deposits (Aslan *et al.* 2003; Rao *et al.* 2015; Sahu *et al.* 2015) or when rivers fed from residual, long inactive highlands spread over endorheic basins or terminate into shallow epicontinental seaways (McIntosh 1983; Jones *et al.* 1993; McCarthy 1993; Lang *et al.* 2004; Brooks *et al.* 2009; Cohen *et al.* 2010).

In other instances, short-range (a few kilometres in radius) fluvial fans may originate in particular geomorphic settings, such as ephemeral streams issued by the Atlantic margin of the African Plateau. These streams cross the Namibian dune fields through narrow corridors and then avulse and aggrade over the coastal plain (e.g. Krapf *et al.* 2005; Stollhofen *et al.* 2014), with drainage receiving excess sediment load from the volcanically active relief (Galve *et al.* 2016) or point-sourced sectors of proglacial outwash drainage (Boothroyd & Nummedal 1978; Zielinski & Van Loon 2002). Most such systems (erroneously identified as alluvial fans by some researchers) are tied to geologically transient combinations of geomorphic elements and/or climate extremes that only trigger particularly high sediment supplies on a local scale and thus are scarcely representative analogues of thick alluvial successions in the depositional record.

In this regard, major research interest on fluvial fans has been inspired from a stratigraphic perspective following the work of G. Weissmann, A. Hartley, G. Nichols and their co-workers, who proposed the now widely adopted term distributive fluvial systems (Nichols & Fisher 2007; Hartley *et al.* 2010; Weissmann *et al.* 2010, 2011, 2013, 2015; Nichols *et al.* 2011). Central among their results stands the observation that most geomorphic surfaces and elements in the aggradational sectors of present day continental basins belong to distributive fluvial systems of variable extent (but see Fielding *et al.* 2012 for a different perspective), almost always supplied from the basin margin with a strong radial component transverse to the basin axis or, more generally, to the marginal highlands. Considering that these drainage systems and the resulting landforms are produced by dominant aggradation, and applying this observation to interpretations of alluvial architecture in ancient basin fills, it is likely that large fractions of the continental stratigraphic record were deposited by distributive fluvial systems (Weissmann *et al.* 2010). This fundamental concept had been considered by previous researchers (e.g. Campbell 1976; Friend 1978; Rust & Gibling 1990; Bentham *et al.* 1993; DeCelles & Cavazza 1999), often just in passing, but not fully backed by worldwide geomorphic and stratigraphic evidence.

Most modern, large- and medium-scale river systems providing the base for classical fluvial facies and architectural models (especially of channel and channel belt deposits; e.g. Cant 1978; Crowley 1983; Bristow 1987; Bridge & Gabel 1992; Ashworth *et al.* 2000) belong almost invariably to tributary drainage systems, for which downstream-convergent runoff networks are associated with long-term erosional and bypass dynamics from a sediment-routing perspective and are thus less prone to accumulate long-term sedimentary records in most upstream (continental) segments of the system. The most protracted depositional activity of tributary networks is staged towards the downstream limits of their extent, where they meet base level (usually marine shorelines), losing transport efficiency, feeding major deltaic, estuarine or progradational coast–shelf systems and, in the limit, supplying clastic debris for the construction of large submarine fans (e.g. Shepard & Lankford 1959; Kolla & Coumes 1987; Blum & Hattier-Womack 2009; Covault & Graham 2010; Walsh *et al.* 2013).

In passing, it is worth noting that deltas and submarine fans, the ultimate repositories for fluvial sediment at and below base level, respectively, are characterized by distributive current and sediment–diffusion patterns, both in space and through time (e.g. Damuth *et al.* 1983, 1988; Twichell *et al.* 1991; Posamentier & Kolla 2003; Olariu & Bhattacharya 2006; Hori & Saito 2007), essentially analogous to those on aggrading fluvial fans. Over the last few decades, incised valley fills have been the most intensely studied stratigraphic systems associated with tributary drainage networks (e.g. Martinsen 1994; Willis 1997; Plint & Wadsworth 2003; Garrison & Van Den Bergh 2006; Joeckel & Korus 2012), not least owing to their economic interest. These consist almost invariably of alluvial deposits, commonly accompanied by substantial volumes of paralic and shallow marine strata, the accumulation and preservation of which have been sustained by a rising base level curve (Zaitlin *et al.* 1994). This stands in contrast with observations of modern distributive systems, which aggrade enormous volumes of alluvial deposits at all positions along the continental source to marine sink trajectory, from isolated interior basins unaffected by base level controls (McCarthy 1993; North & Warwick 2007; Ralph & Hesse 2010) to basinal domains regularly or at least intermittently connected to sediment-routing networks downstream (e.g. Sinha & Friend 1994; Wilkinson *et al.* 2010; Assine *et al.* 2015), to coastal areas fully subject to base level control (Aslan *et al.* 2003; Browne & Naish 2003; Fontana *et al.* 2014). This observational and conceptual framework to the relevance of fluvial fans for modern continental geomorphology and ancient stratigraphy has been subject to vigorous debate (e.g. Sambrook Smith *et al.* 2010; Ashworth & Lewin 2012; Fielding *et al.* 2012), but the exponential increase over the last few years in the number of publications dealing with these systems, their depositional records and their socio-economic impact seems to confirm the significance of the basic observations synthesized here (e.g. Mikesell *et al.* 2010; Ralph & Hesse 2010; Bernal *et al.* 2011; May 2011; Pati *et al.* 2012; Rossetti *et al.* 2012; Kukulski *et al.* 2013; Assine *et al.* 2014; Lawton *et al.* 2014; Goswami & Deopa 2015; Quartero *et al.* 2015; Galve *et al.* 2016; Shellberg *et al.* 2016; Van Dijk *et al.* 2016; Gulliford *et al.* 2017; Mouchené *et al.* 2017).

Research progress over the next few years will be crucial to a better understanding of the dynamics of fluvial fans and megafans and to an assessment of their importance in the stratigraphic record. The geomorphology, hydrology and active sedimentology of these systems are as yet only sparsely known compared with those of tributary drainage networks. Analyses of avulsion timing and mechanisms (Edmonds *et al.* 2016) should constrain the boundary conditions responsible for triggering the aggradation of fluvial fans, whereas detailed studies are needed to unravel how such systems acquire their radial zonation in terms of geomorphic attributes (e.g. surface gradient and mesotopography; channel morphometry, patterns and density) and sedimentological features (e.g. down-system textural and facies trends). Major flood events on fluvial fans have catastrophic consequences for these densely populated environments, especially in the tropics (e.g. Arzani 2005; Sinha *et al.* 2008; Chakraborty *et al.* 2010; Heyvaert & Walstra 2016), and studies of centennial to millennial avulsion and flood histories may inform guidelines for the prevention and mitigation of the related hazards. At the larger scale of alluvial basins, the mutual influence of modern fluvial fans and adjacent environments (from aeolian to wetland over different climatic zones) should be the object of integrated studies of present day processes and Late Quaternary sedimentary and palaeogeomorphic archives, providing information on how distributive fluvial systems are affected by environmental change and how, in turn, they weigh on the evolution of nearby areas. Perhaps more pressing in times of impending climate change, studies of geo-resource availability on/within distributive fluvial landforms should increasingly support socio-economic decisions on such issues as aquifer exploitation, land development and restoration, and infrastructure planning (Weissmann & Fogg 1999; Weissmann *et al.* 2004; Assine & Silva 2009; Chakraborty *et al.* 2010; Walstra *et al.* 2010; Sahu *et al.* 2015; Heyvaert & Walstra 2016; Shellberg *et al.* 2016; Van Dijk *et al.* 2016).

Research progress on the geology of fluvial fan successions has benefited from the recognition of an inherent pattern of architectural heterogeneity vertically through their deposits, resulting from long-term aggradation and progradation, in which dominantly fine-grained overbank deposits consisting of minor volumes of isolated, coarser channel fills are progressively followed upwards in the stratigraphy by coarser, possibly larger, and increasingly amalgamated channel bodies, with lesser volumes of preserved mud-prone overbank strata (Weissmann *et al.* 2013). This trend has been confirmed by several studies, especially on thick infills of continental foreland basins (e.g. Willis 1993; Nakayama & Ulak 1999; Shukla *et al.* 2001; Uba *et al.* 2005; Nichols & Fisher 2007; Wilson *et al.* 2014; Owen *et al.* 2017*a*, *b*) and, where not interrupted by angular or progressive unconformities, it can be explained by the basinwards progradation of fans. Over time, proximal sectors dominated by higher energy elements of the system come to aggrade over areas previously occupied by distal, lower gradient sectors, characterized by a lesser areal density of active channels and the higher preservation of finer floodplain deposits. In view of their origin, such stratigraphic patterns should also be recognizable as proximal–distal trends in the spatial distribution of alluvial architecture across continental basins, which would form another robust criterion for identifying ancient fluvial fan successions (Singh *et al.* 1993; DeCelles & Cavazza 1999; Nakayama & Ulak 1999; Martinius 2000; Klausen *et al.* 2015; Owen *et al.* 2015).

The collection and analysis of field datasets have been made more efficient by portable remote sensing technologies, such as LiDAR (Light Imaging Detection and Ranging), laser scanning and unmanned aerial vehicles (Flener *et al.* 2013; Rarity *et al.* 2014; Rittersbacher *et al.* 2014; Nieminski & Graham 2017), increasing the ability to document the geometries and distributions of facies associations over vast exposures, assessing large-scale trends in fluvial depositional architecture. A major priority for future research should be the establishment of a suite of diagnostic criteria for the recognition of fluvial fan successions, as the supposed dominance of these systems in continental strata might have a significant influence on stratigraphic prediction and palaeoenvironmental reconstruction at the basin scale (Moscariello 2005; Owen *et al.* 2017*a*, *b*).

A further priority for research on ancient successions should include unravelling fluvial fan responses to allogenic forcing and to tectonic activity at basin margins in particular (e.g. temporal and spatial changes in accommodation, signatures of catchment reorganization, recognition of retrogradational fan successions) and climate change (e.g. responses to variable sediment supply and axial incision and changing distal environments due to basin hydrology). Perhaps most pressing, there remains a need to identify the stratigraphic signatures of the distributive fluvial systems that prograded along epicontinental or open oceanic coastlines, building thick clastic wedges that are usually named fluvio-deltaic, but in which the actual deltaic component is subordinate in terms of preserved sediment volume. The avulsive and aggradational dynamics of large portions of such systems were linked to the same upstream controls that regulate fluvial fan aggradation in continental interiors, such as topographic unconfinement of drainage pathways, excess sediment supply and elevated rates of repositioning for proximal channel belts. By contrast, backwater effects and shallow marine processes (waves, tides, inshore and longshore currents) would have affected sediment distribution and aggradation along the most distal sectors. In this sense, Quaternary and present day examples of sea-facing distributive systems (e.g. Fontana *et al.* 2014; Shellberg *et al.* 2016; Hartley *et al.* 2017) are readily comparable with well-known ancient successions worldwide, such as the Devonian Catskill Group of the northeastern USA (Gordon & Bridge 1987; Willis & Bridge 1988), the Late Carboniferous Breathitt Group and Sydney Mines Formation in the eastern USA and Canada (Gibling & Bird 1994; Aitken & Flint 1995) and coeval fluvial successions of the northern Variscan foreland in the Dutch–German subsurface (Jones & Glover 2005), the Triassic Snadd Formation from the Norwegian Barents Sea (Klausen *et al.* 2014, 2015), and Cretaceous formations from the Western Interior and Alberta foreland basins in North America (Fanti & Catuneanu 2010; Corbett *et al.* 2011; Hampson *et al.* 2012; Kukulski *et al.* 2013).

A potential direction for future developments consists in deriving information from presently active, directly accessible fans, collating information from different tectonic and climatic settings, and integrating such evidence with stratigraphic data from Quaternary successions, which are relatively easily analysed within high-resolution chronological and palaeoenvironmental frameworks. Inferences on process and system-scale responses to changing environmental conditions are crucial in fine-tuning interpretations of ancient stratigraphic successions. Although observations from past records have inspired a renewed focus on present fluvial fan systems, studies of present day systems may represent the proverbial key to understanding past basin-fill histories, which remain our sole window to constrain the dynamics of these widespread alluvial systems over longer timescales and under the influence of variously interacting allogenic drives.

Volume overview

Alluvial fans

Novel and innovative techniques are increasingly being used to monitor and investigate the processes operating on alluvial fans and two papers in this Special Publication cover such advances. Satellite imagery from Google Earth was used by **Giles *et al.* (2016)** to extract morphometric attributes from fans interacting with axial river systems in Yukon and Alaska. Measurements comparing the length of profiles along the up-valley and down-valley sides of the studied fans were used to calculate the values of a fan morphology index. Fan asymmetry and the direction of axial river flow were found to be related, probably due to fan-toe trimming by the river on the up-valley side and to flow deflection enabling the down-valley sides to extend further due to sheltered flow conditions. This finding may stimulate new insights into the analysis of ancient alluvial fan successions and has implications for the discrimination of fan sectors subject to possibly different modes of evolution under changing environmental conditions, as well as for the interpretation of fan asymmetry in broad valley settings.

The paper by **Karymbalis *et al.* (2016)** applies a computational method to the clustering of 41 alluvial fans along the southern coast of the Gulf of Corinth, Greece, providing geomorphic constraints to models of the distribution of depositional systems along the active margins of sedimentary basins (e.g. Leeder *et al.* 1996; Gawthorpe & Leeder 2000). Fan and catchment morphologies were expressed quantitatively through 12 morphometric parameters and self-organizing maps were derived to investigate the clustering tendency of fans according to these parameters. Accommodation space, partially controlled by relative rates of tectonic uplift, determined the spatial distribution of alluvial fans, with smaller fans located where the uplift rates were higher and larger fan deltas distributed where uplift rates were lower.

Another basin-scale analysis of alluvial fan (and fan delta) distribution is provided by **Harvey *et al.* (2016)**, who discuss the late Neogene to Quaternary phases of alluvial fan activation in different subbasins of the Almería region of SE Spain, which are affected by a complex history of compression and transpression that caused continuous local variability in the physiography, accommodation and base level over timescales of millions of years. The basins are also affected by high-frequency climate change, which triggered stages of fan incision, terracing and aggradation, most evident in fans that were active in the Quaternary. The study provides a well-constrained example of how the regional tectonic context drives the positioning of alluvial fans and their long-term evolution, whereas superposed interference by climatic change may modify fan evolution over shorter timescales. The information that such studies provide on relatively recent, well-constrained relationships between fan development and landscape history is reflected in the frequent reliance on alluvial fan successions as indicators of active tectonics and/or high-relief topography (e.g. Frostick *et al.* 1992; López-Gamundi & Astini 2004; Charreau *et al.* 2009).

Leleu & Hartley (2016) provide one such example from Triassic deposits of the extensional Fundy Basin of Nova Scotia (SE Canada), associated with the early opening of the northern Atlantic Ocean. The onset of intrabasinal tectonics and associated topographic highs, responsible for the compartmentalization of sediment transport patterns during the successive basin history, can be determined by the occurrence of alluvial fan successions, recognizable by their facies signatures. The presence of an intrabasinal horst is further inferred by the spatial distribution of facies associations indicative of alluvial–aeolian interactions, where the accumulation of aeolian sediments is partly controlled by topographic obstacle effects.

In addition to active tectonics, the specific position of fan catchments along basin margins determines their geology and morphology, which affect fan development. This aspect is examined in the paper by **Mather & Stokes (2017)**, who examine bedrock structural controls on catchment-scale connectivity and processes on four young (<100-year-old) alluvial fans in Morocco, showing a link between increasing catchment area, decreasing catchment gradient and decreasing sediment–water ratios of primary depositional processes, which ultimately result in variable facies associations in fan stratigraphy. In particular, the tectonic altitude of catchment bedrock reflects on the longitudinal and transverse drainage connectivities within the catchment, which, in turn, are reflected by the sediment–water ratios of fan-formative flows.

Catchment response to climate change is discussed for a Miocene case study from central Spain by **Ventra *et al.* (2017)**, relying on repeated patterns of stratigraphic contact between coarse-grained, distal fan strata and a fine-grained basinal section for which palaeoclimatic and chronological information have been independently constrained. The most extensive debris flow beds are regularly interbedded with basinal facies that represent climatic transitions from relatively arid to relatively humid times, suggesting that the largest volumes of clastic debris were mobilized at times when less vegetated, more unstable catchment slopes were increasingly subjected to an increase in sediment transport potential. The distinctly organized stratal architecture of sections through the medial fan body also reflects the possible influence of a cyclic allogenic factor, inferred here to be climate change occurring at orbital (10^4–10^5 year) timescales.

Also based on Miocene fan successions of northern Spain, **Nichols (2017)** proposes a stratigraphic method to estimate the recurrence rates of depositional events from pre-Quaternary basin margin deposits. Relying on the essential continuity of sedimentation in continental basins of internal drainage, the possibility to extract first-order chronological information from basinal successions (for example, by magnetostratigraphy or cyclostratigraphy) can be applied to translate sedimentological information from the stratigraphic depth domain to the time domain for coeval fan strata, based on the accurate correlation and determination of individual depositional events from bedding structure and architecture.

In an analysis of more recent Quaternary successions in northern Italy, **Ghinassi & Ielpi (2016)** reconstruct depositional processes and proximal to distal architectural trends on alluvial fans aggraded mostly by water flows rather than mass flows, developing textural and sedimentological attributes considerably different from those commonly observed in piedmont alluvial systems. The dominance of fine-grained sediments is related to the production of mostly sand-sized debris from the Cenozoic turbidites that constitute the catchment bedrock, whereas the distinctly fluvial character of facies associations hinders their attribution to an alluvial fan environment in the absence of context information.

The paper by **Deganutti *et al.* (2017)** closes the section on alluvial fans, providing a comparative analysis on the potential of numerical models to enhance the predictability of debris flow hazards. Applying topographic and hydrographic boundary conditions extracted from an active fan on the Italian Alps, these researchers compare event simulations obtained from two different models, verifying that one more accurately reproduces the extent of the flooded area, whereas the other performs better in predicting debris flow run-out distance and deposit thickness. The study confirms the utility of numerical models to predict the vulnerability of different areas to debris flow hazards on alluvial fans; however, it highlights discrepancies between the outputs from different models as well as the importance of taking into account local morphometric and geological variables for model set-up.

Fluvial fans

The distinction between alluvial and fluvial fans, still the object of occasional debate, is summarized in a review article by **Moscariello (2017)**, who starts from fundamental differences in catchment nature and sediment transport mechanisms between the two kinds of systems. This, in turn, reflects on major differences in facies associations, architectures and extent in stratigraphy. The implications of recognizing the correct depositional system from stratigraphic data are examined from the perspective of economic geology, where prediction and decision-making are based on commonly scarce subsurface data and the adoption of the fitting of sedimentological models has important repercussions for success in all phases from exploration to production.

As for alluvial fans, the geology of drainage basins may strongly affect the long-term evolution and the dominant processes of fluvial fans, an aspect explored by **Arzani & Jones (2016)** in their comparative analysis of three Quaternary fluvial fans in an intermontane basin of the Iranian interior. They report that fan development in their study area has mainly been influenced by the different bedrock lithologies and morphometric attributes of their respective catchments, which resulted in different potentials for longitudinal incision or protracted aggradation through Quaternary phases of climate change that altered the geomorphic equilibria in the hinterland and, consequently, also the sediment–water ratios of floods, which reached and effectively modified the fan surfaces.

Bilmes & Veiga (2016) further consider the possible role of catchment influence on the evolution of four Quaternary fluvial fans in the Gastre Basin of southern Argentina. Their analysis compares the actual fan areas with those that could theoretically be extrapolated from catchment areas and gradients, showing that the extent of the fans is also controlled by the horizontal accommodation space within the basinal domain. This, in turn, is determined by the occurrence and geomorphic state of adjacent depositional systems and geomorphic elements. The study has implications for estimating the relationships between the extent and position of ancient alluvial systems and the size of their catchments (e.g. Davidson & Hartley 2014), demonstrating that depositional basins are not passive collectors of debris shed from the surrounding highlands, but redistribute sediment internally depending on the morphology and dynamics of their landscape elements.

Similar catchment–basin relationships are inferred by **Radebaugh *et al.* (2016)** for the formation and distribution of alluvial and fluvial fans on Titan, Saturn's largest satellite. In spite of the remoteness of this world, based on images obtained by the Cassini spacecraft's Synthetic Aperture Radar, the morphologies, roughness, textural patterns and other properties of fan-shaped depositional landforms can be described and compared with Earth analogues. Evidence for a range of particle sizes and their differential distribution across some of the recognized landforms provides preliminary indications of possible sedimentary processes, enabling distinctions between alluvial and fluvial fans and supporting recent hypotheses on the complex, but substantially Earth-like, dynamics of Titan's surface environments (Lunine & Lorenz 2009; Savage *et al.* 2014). Fluvial fans aggrade by avulsive repositioning of the main channel belts over the alluvial surface on the occasion of major floods, but little information is yet available on the exact dynamics of such events and on the responses of the drainage network due to their low predictability and great hazard.

The paper by **Majumder & Ghosh (2017)** describes the runoff pathways and immediate geomorphic consequences of the most recent catastrophic flood affecting the Kosi Megafan (northern India). Inundation and depositional patterns on the affected fan sector are reconstructed by time series of satellite imagery, showing that most of the flood discharge was transferred down-fan through a pre-existing portion of the fan's distributary network. Despite the scale of the event, only limited modification to the fan's morphology and drainage network was evident in the aftermath. These researchers show that the antecedent history of the fan system is important in determining the morphological and hydraulic effects of successive events, even extreme events. Among the various applied perspectives of fluvial fan geomorphology and sedimentology, their importance in terms of groundwater resources is prominent.

Burbery *et al.* (2017) use smoke and water diffusion patterns as tracers to understand the spatial organization and connectivity of open framework gravels of the Rakaia Fan on the Canterbury coastal plains of New Zealand, where permeable, coarse-grained deposits constitute major aquifers and are important for the transmission of groundwater and possible contaminants. The findings will be part of the knowledge base to improve hydrogeological models for the Canterbury Plains and show that fluid transport through the coarsest fraction of deposits on these fans can be rapid, but non-uniform, with a manifest anisotropy related to the greater interconnectedness of gravelly facies along a longitudinal (down-fan) direction.

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