Controls upon Depositional Architecture and Cyclicity of Alluvial Fan Systems and Associated Environments: Implications for Hydrocarbon Potential*

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Abstract

Alluvial fans are key environments in continental basins. Their facies and architecture are influenced by interactions between 1) the varied environments of the fan, from debris-flow dominated, fluid-flow dominated to fan-surface lacustrine and overbank, 2) autocyclic processes of these environments, and 3) allocyclic controls of climate, base level and sediment supply. As some of these controls are cyclic at various scales, fans can include good, but stratigraphically complex, reservoirs associated with fan-related fluvial networks and debris flows, to admissible, localised or extensive seals and baffles provided by fan-surface deposits. Furthermore, fans can be long-lived throughout the history of the basin and thus interact with changing distal environments. Fan sediments may influence basin-scale migration, connect isolated distal reservoirs, or provide bypass to charge of those reservoirs. Thus, an understanding of fan architecture in response to changing controls is crucial to interpreting both fan reservoir potential and fan influence on the basin petroleum system.

We examine well-exposed fans from the Cutler Group of the Paradox Basin, U.S.A., deposited in a continental basin subject to arid-monsoonal climatic cycles, varied sediment supply and changing base level. The fan facies, architecture, relative dominance of fluid over debris deposits, and the connectivity of fluvial networks show spatial and temporal dependence on these competing controls, with cyclicity evident at a variety of scales. At a small scale, oscillating climate is a dominant control. Aridity is characterised by debris flow facies, with elevated permeability, whilst humidity is characterised by finer grained, less permeable facies. At a larger scale, the connectivity of fan-related fluvial networks is

influenced initially by changes in base level. The dominance of this control reduces with fill: climate and sediment supply are more dominant controls on younger deposits.

Generalised, spatial and temporal facies models characterising fan development in response to varied controls are developed from the outcomes of this work. These models provide input for both fan-scale reservoir modelling, and basin-scale petroleum systems modelling in continental settings.

The work is applied to the Permian basin of northwest England, to characterise facies, geometry and connectivity of fan-related fluvial networks and potential for hydrocarbon migration within this poorly exposed basin.

Introduction

Alluvial fans are key environments in continental basins. Their facies and architecture are influenced by interactions between 1) the varied environments of the fan, from debris-flow dominated, fluid-flow dominated, to fan-surface lacustrine and overbank, 2) autocyclic processes of these environments, and 3) allocyclic controls of climate, base level and sediment supply. As some of these controls are cyclic at various scales, fans can include good, but stratigraphically complex, reservoirs via fan- related fluvial networks and debris flows, to admissible, localised or extensive baffles from fan-surface deposits. Furthermore, fans can be long-lived throughout the history of the basin and thus interact with changing distal environments. Consequently, fan sediments may influence basin-scale migration, connect isolated distal reservoirs, or provide bypass to charge of those reservoirs. Thus, an understanding of fan architecture in response to changing controls is crucial to interpreting both fan reservoir potential and fan influence on the basin petroleum system.

Alluvial fans dominate proximal margin fill in continental basins forming plano-convex clastic wedges that interact with distal depositional environments, and with multiple secondary environments of deposition on the fan surface, which both rework and influence contemporaneous sedimentation. The complex interactions between deposits, and the geometric shape of the alluvial fan, leads to complex differences in the internal structure, which act as controls upon subsequent fluid flow through the deposits. Highly porous beds occur throughout the succession, defining fluid pathways, and occur contemporaneously with low porosity, low permeability beds. In addition to this, different transport mechanisms dominate the system in relation to allocyclic controls.

Alluvial Fan Transport Mechanisms

Alluvial fan transport processes can be linked to both sediment gravity flows and fluid gravity flows initiated through both bedrock and colluvial slope failure. Bedrock failure occurs due to extensive fracturing and faulting of drainage basin slopes leading to slope destabilisation and gravitational failure. All manner of bedrock will eventually fail in slope conditions. However, changing climate, uplift and the pre-existing geology will affect the rates of destabilisation (Blair and McPherson, 1994). Slope failure occurs due to a reduction in internal shear strength resulting from denudation of bedrock (Leeder, 1999). Slopes can be further destabilised through increased water content and seismic ground movement. The three main types of transport mechanisms through slope failure are rock falls, rock slides, and avalanches (Figure 1). Rock falls occur in conical accumulations of normally graded boulder- to cobble-grade deposits, interbedded with finer grained colluvium. Rock slides appear reversely graded from coarse- to very-coarse brecciated basal deposits to cobble- to boulder-grade overlying conglomerates (Grainger and Kalaugher, 1987). Avalanche deposits occur in both the proximal zone and on the fan surface. The facies consist of angular boulder-grade deposits which interact with cobble-grade, and finer, colluvial deposits.

Colluvial slope failure is predominately initiated in relation to increased moisture content within the slope, and therefore correlates directly to climate variability. Colluvially sourced sediment gravity flows are related to interacting moisture content and gravitational forces. Colluvial slides and debris flow deposition are common (Figure 1). Colluvial slides initiate in response to increased hydrological pore pressure which leads to shear failure in the deposits. The deposits can be distinguished from those of bedrock failure by their clay-rich matrix. Debris flow deposits exhibit similar features to colluvial slides; however there are indications of increased velocities and plastic flow due to entrained gas and water within the flow (Leeder, 1999). Proximal facies include reversely graded, boulder-grade, clast supported deposits with little internal structure. These flows commonly grade, with distance from the fan apex, into levee and snout facies, with larger clasts occurring at the front, sides and top of the flow. Distal facies show frequent intercalations of beds consisting of reversely graded, massive, cross- bedded, angular, pebble-grade deposits.

Fluid gravity flows are initiated through large influxes of fluvial water into the feeder channel, indicating complex interactions with climate variability. Sediment laden, unconstrained sheetfloods occur across the fan surface (Figure 1). Multidirectional flows also occur due to the overall geometry of the alluvial fan. Sheetflood facies associations are distinctive in the alluvial fan system and consist of basal planar-bedded couplets overlain by normally graded beds of boulders, pebbles and cobbles, which can exhibit clast imbrication and crude cross-bedding, and fine with spatial migration from the source. Sheetfloods are commonly interbedded with laminated, course-grained sand, and are commonly overlain by sieve deposits, which are characterised by their fine grainsize (Blair and McPherson, 1994). Incised channel deposition occurs when a feeder channel has extended onto the fan surface creating a pathway for fluid gravity flows, allowing the flow to maintain its physical properties over a greater distance from the source (Figure 1). The main facies consists of thick beds of boulder-sized deposits within a finer grained matrix, exhibiting a significant lack of internal structure. It is associated with interbeds of fluvial, sheetflood and debris-flow deposits.

On the fan surface, colluvial facies associations commonly coincide with the facies of immature, braided fluvial systems which rework a proportion of the deposits with increasing distance from the apex. Braided stream facies are distinguishable by prominent channelisation and interlinking fluvial bars (Figure 1). The facies are characterised by a gravel-rich bedload which is deposited as longitudinal bars, after a period of flashy discharge, and contain little to no internal structure. During low-water conditions, medium- to fine-grained, parallel- to cross-bedded, traverse bars are deposited. Commonly overlying these deposits a parallel-laminated, medium- to fine-grained sandstone facies occurs, and exhibits occasional ripples.

Lacustrine systems can occur on the fan surface in wetter climates, and where the deposits occur they indicate climate variability (Blair, 1987). Common facies include reworked debris flow pulses that appear normally graded, conglomeritic deposits that fine into parallel-laminated sandstone and siltstone beds (Heward, 2006). The occasional occurrence of palaeosols in distal settings is again important in determining climate at the time of deposition; increased moisture content tends to increase the amount of weathering and results in elevated accumulations of palaeosols and the appearance of rhizoliths above the soil horizons indicates a degree of surface stabilisation representing a period of depositional quiescence (Blum, 2000).

Climate variability is most influential upon colluvial slope failure and its transport processes. Slopes become inherently unstable over geological time through processes of denudation or through structural over-steepening. The slope will remain stable until the forces acting on the slope overcome the materials shear and/or cohesive strength either through gravity (sediment driven flows) or through a change in the physical processes, mainly achieved through the injection of water into the system. It is important to note that physical weathering processes will be heightened in warm, humid environments. Humid environments also lead to the increase of moisture input into the system, which in turn lowers the internal shear strength facilitating gravity to overcome the cohesive and shear strength of the colluvium (Leeder, 1999). If the internal cohesive strength is unaffected it results in cohesive debris flow deposition.

In addition to the importance of water content in the initiation of depositional processes, storm influxes also heighten the probability of slope failure, and increase deposition of sheetflood deposits. Storm events lead to flashy run-off from upland fluvial systems and increase sediment transfer onto the alluvial fan surface. Storm events are important in understanding periods of increased deposition in more arid alluvial fan settings, for example, the input of Pangean mega-monsoons during the deposition of the Permian Cutler Group (Soreghan et al., 2009).

The most important parameter of climate variability is the relative wetting or drying of the overall systems. With increased water input into the system, the stream interaction with the fan surface on the upland drainage basin is affected, with the net effect of sourcing more sediment through the fan apex. This also increases water - sediment interaction on the slope surface, leading to an increased probability of slope failure. Prolonged wet climates also raise the water table, resulting in increased probability of slope failure. Interglacial periods see relatively higher rates of alluvial fan deposition due to increased meltwater run-off and increased rates of sediment sourcing from the upland basin, whereas global glacial periods see relatively higher deposition of sheetflood sedimentation (Blair and McPherson, 1994).

The study concentrates on the three-dimensional interpretation of the alluvial fan deposits of the Permian Cutler Group, Utah, U.S.A, using the interpretation of spatial facies variations to interlink them into a larger model (Figure 2). The three-dimensional model is then applied to the disparate outcrops of the Brockram Facies, northern England (Figure 2). The Brockram represents a potential aquifer in the Lake District region of northern England and further investigation will indicate the likelihood of ground water flow through the facies.

Permian Cutler Group

The Permian Cutler Group is present throughout the Paradox Basin in Utah and Colorado (Condon, 2000) and is late Pennsylvanian to early Permian in age (Carter, 1955). The Paradox Basin is a foreland basin (Kluth and Coney, 1981) that subsided rapidly throughout the Pennsylvanian Period, during the formation of the Uncompahgre Highlands (Hite, 1968). During the Permian Period, the Paradox Basin was situated around equatorial Pangea, in an arid- to semi-arid environment (Vaughn, 1973). Throughout the Permian, the Paradox Basin migrated northwards into sub-tropical latitudes (Soreghan et al., 2009). The relative sea level was considerably low during the Permian Period, leading to a dominance of continental deposition in an arid climate. The equatorial palaeogeographical position of the Permian Cutler led to an influx of megamonsoons at the time of deposition, and the deposits reflect this regular influx of meteoric water (Parrish and Peterson, 1988).

The Brockram Facies, of the Permian strata of northern England also exhibits an alluvial fan succession (Jones and Ambrose, 1994), which is interpreted to cover an area of 240 square miles (Kendall, 2009). Deposition occurred within the Penrith Basin, with provenance currently inferred as the Lake District Block.

Facies

The Cutler alluvial fan is well exposed at Castro Draw and Gateway in Colorado and at Fisher Towers, Onion Creek, Castle Valley, Moab and Potash in Utah, and data were collected from these localities. Within the Gateway and Castro Draw localities, boulder- to cobble-grade conglomerates dominate and interact with other coarse-grained sedimentation to comprise interacting rock falls, rock slides, avalanches, debris flows, and confined fluvial systems. Cyclicity can be determined in these deposits giving indications of both the internal architecture of the deposits and alternating specific flow processes. The interpretation of transport mechanisms can constrain overall depositional processes and climatic alterations in these localities. Despite the clear occurrence of cyclicity within the deposits, associations can be disrupted by erratic bedrock failure. Ten successions can be identified within the proximal Paradox Basin at the Gateway and Castro Draw localities. The basal deposits of each succession comprise rock fall associations (RF), rock slide associations (RS), avalanche deposits (AV) and bedload and sieve deposits (BS). Braided stream channel fill associations (BC) interact with deposits within the piedmont zone. The succession is commonly overlain by sieve deposits (SI) (Figure 3).

The localities at Fisher Towers, Onion Creek, and Castle Valley display more mature facies than those at in Colorado. The deposits interact more intrinsically on the fan surface leading to less prominent beds, more erosional contacts, and more influence from secondary environments. The deposits are dominated by debris flow deposition, which fines from boulder-grade conglomerates to cobble-grade. Cross-bedded, parallel-laminated and trough-cross-bedded strata of varying grain-size represent channel-fill sedimentation. Sheetflood and overlying sieve deposition can also be determined from rhizolith rich, normally-graded sandstones than fine from medium- to coarse-grained to fine-grained deposits. Cyclic interactions are more prominent in these localities in comparison to those at Gateway. Erosional contacts of in-filled, more extensive, incised channel associations (IC) occur at the base of the facies successions in these areas. They are distinguishable from the braided stream association (BC) because they comprise thicker units within the sequence. The presence of sheetfloods (SF) indicates periods of elevated flow, and is commonly overlain by lowstand braided stream associations. As fluvial discharge increases, highstand deposits and traverse bars become more prominent. Thinner, laterally extensive, coarse-grained beds indicate periods of flashy discharge from the upland feeder basin (Figure 3).

Within the Moab and Potash localities, the grain-size is dominantly finer, and the beds thinner. The non-conglomeratic deposits comprise trough-cross-bedded to parallel-laminated to cross-bedded strata. The conglomerates are pebble- to- cobble grade and exhibit normal grading, poor sorting, and occasional cross-bedding. There is an abundance of calcareous sandstone, which appears parallel-laminated and nodular throughout the deposits. In addition to this, basal interbeds of limestone are present. Two general successions occur within the Moab and Potash localities. Occurrences of intermittent calcareous-rich sandstone beds suggest cyclic interactions with the underlying Honaker Trail Formation; however, these deposits dissipate out towards the top of the outcrop indicating an overall sea level regression, containing several cycles of marine incursions. The cessation of each marine incursion is symbolised by the reactivation of fluvial systems, overlain by thin overbank associations (OB). Thick injections of sheetflood deposits (SF) force alluvial fan lobe switching, and the cessation of fluvial systems. Younger successions have a higher dominance of fluvial deposits. Debris flow associations (DF) are less pronounced in these localities, and interact with contemporaneously deposited fluvial facies. Large, fining upwards incised channel deposits (IC) are overlain by sheetfloods and overbank (Figure 3). Increased meteoric water sourced from the monsoonal climate leads to the catastrophic fluid gravity flows including both incised channel and sheetflood deposition.

Facies Model

After the elements of each spatial locality have been identified and constrained, a facies model for the Permian Cutler Group can be determined. The Castro Draw and Gateway localities equate to a proximal alluvial fan setting and comprise bed rock failure derived sediment gravity flows, and represent the fan apex, (Castro Draw), and the fan piedmont zone, (Gateway). Inputs of immature debris flows are also common, indicating sourcing from colluvium. The succession generally coarsens upwards, which is commonly representative of proximal alluvial fan deposition (Steel, 1974). Fisher Towers, Onion Creek, and Castle Valley exhibit internal architectures that represent mid-fan deposition. The deposits are dominated by mature debris flows and braided fan-surface stream architecture. The presence of fluid gravity flows in the mid-fan indicates influxes of flashy-streams from the upland feeder basin. The palaeoclimate at the time may provide explanation for the presence of pronounced fluid gravity flows (Soreghan et al., 2002). The Moab and Potash localities signify a distal alluvial fan setting, demonstrating developed fluvial systems and subsequent channel fill facies. Inputs of sediment and fluid gravity flow deposition is significantly less frequent, however the deposits are still apparent. Other secondary depositional environments indicate a distal setting. The deposits contain an abundance of calcareous sandstone and limestone strata indicating the presence of water bodies at the time of deposition. The input of debris flows becomes less frequent, and surface stabilisation is evident.

Throughout the Permian Cutler alluvial fan it is apparent that the sediments are evolving both spatially and temporally. The palaeoenvironment at the time of deposition was arid- to semi-arid, however the northwards migration of Pangea throughout the Permian displaced the Paradox Basin to sub-tropical latitudes (Soreghan et al., 2009). The resulting semi-humid climate initiated an increased amount of fluid gravity flow deposition, leading to a prevalence of sheetflood and incised channel facies associations in the upper strata.

Brockram Facies

The Brockram Facies was deposited throughout the Permian and lower Triassic periods, during a time of increasing aridity (Burgess 1965). The outcrops, located in Eden Valley, northern England, are examined to constrain internal architectures to allow for an interpretation of the deposits' relative position within the Permian Cutler architectural models. The locations of Knock Bank, Rowley Wood, Burrells-Hoff, Lookingflatt, Thistley Hill, and Belah Bridge were studied (Figure 4).

The Knock Bank locality comprises a reddened sandstone matrix, with frequent occurrences of calcareous beds, and an abundance of limestone clasts. Relatively immature, poorly sorted and matrix-supported debris flow associations are apparent (DF). The fines in the matrix comprise immature fluvial associations, comprising both gravel-grade bed-load, and coarse-grained channel-fill deposits.

The Burrells-Hoff locality exhibits clast-rich conglomerates. The clasts consist mainly of chert, limestone and hematised sandstone. The general geometry fines upwards from clast supported conglomerates to finer grained, fluvially dominated lithologies. Thistley-Hill exhibits more defined internal architectures due to the lack of both carbonate clasts and subsequent secondary calcification of the beds. There is evidence of incised channel deposits which form large concave-up erosional forms which are back-filled with cobble- to boulder-grade, poorly-sorted facies. The deposits are also abundant in fragmented fossiliferous content. Belah Bridge is the most distal of the observed localities. The surrounding fluvial facies appear more mature than the relatively more proximal localities. Debris flow facies (DF) are common and are poorly sorted, with relatively well-rounded clasts that exhibit common a:b plane imbrication. Massive channel forms are also prominent indicating inclusions of incised channel facies associations (IC). Finer grained sediments overlie the porous alluvium, and represent sheetflood (SF) and sieve (SI) associations. These facies uniformly blanket the underlying strata. Due to the poor exposure of the Brockram facies, temporal variation is difficult to determine. However, where facies successions can be identified they exhibit a fining upwards sequence suggesting wetting upwards climatic changes.

Discussion

The model for the architectural elements of the alluvial fans, based on the deposits of the Permian Cutler Group, can be used to understand the observed facies associations, geometries, and structure of the lesser-exposed Brockram Facies, in order to constrain an environmental interpretation of the deposits (Figure 5). The examined deposits of the Brockram Facies closely resemble a mid-fan setting. There is an abundance of conglomerates throughout the Brockram outcrops ranging from pebble to- granule grade, which suggests a correlation to the observed mid-fan deposition within the Cutler. The majority of conglomeritic clasts are sub-rounded suggesting a relatively mature debris flow. Coarse-grained, parallel-laminated, and cross-bedded strata are also prominent in outcrop in addition to medium-grained sandstone beds which lack internal structure. The coarse-grained beds comprise pebble-grade, sub-angular clasts, and are usually correlated with the presence of gravel bedload sediments; this suggests a relatively immature braided fluvial system. These interlink to represent both braided channel (BC) and debris flow facies associations (DF). For example, the facies at Knock Bank and Thistley Hill exhibit a general fining upwards trend, from the pebble- to granule- grade conglomerates to coarse-grained braided stream associations, and finally, overbank facies. Within the Brockram there is a prevalence of channels (BC), debris flows (DF), sheetfloods (SF), incised channels (IC), and sieve facies (SI), all of which are associated with alluvial mid-fan sedimentation (Blair and McPherson 1994). The observed facies are not dissimilar to the facies at the Fisher Towers locality, in terms of internal structure and variation, and therefore the Brockram observed within the Eden Valley area has been constrained to a mid-fan depositional system.

The development of an overall architectural model for an alluvial fan from well-exposed deposits, such as the Permian Cutler Group, allows for the easier interpretation of sparsely exposed alluvial fan deposits. The facies determined for the Permian Cutler alluvial fans have been generalised to make them applicable to other alluvial fan deposits. Because of this, the interpretation is based on both internal architectures and dominant flow processes that relate to spatial variations within alluvial fans. It is important to consider the overall facies analysis provided in both the scheme and models, to give a justified interpretation. In addition to internal differences, the environment of deposition can affect the appearance of the sediments; this can be affected by differences in fault-bounded uplift, basin size, climate variation, and interaction with secondary environments. As the Permian Cutler deposits are well exposed, the majority of these problematic factors can be determined. An example of this is the transgression of the palaeoclimate in the Paradox Basin from semi-arid to semi-humid which superimposes a wetting-upwards succession throughout the deposits, which in turn influences transport mechanism dominance. This interlinks with the palaeoenvironment in the Penrith Basin during the Permian Period, therefore correlates effectively with the Brockram. However, different transport mechanisms dominate deposition in different climates, and therefore the model should be constrained to describe arid- to semi-humid alluvial fan deposition.

Conclusions

The study of the well-exposed alluvial fan system of the Permian Cutler Group alluvial fans can be used to construct an overall valid model of deposition. This model incorporates facies schemes, associations, successions, and architectural elements for each of the geomorphological spatial positions within an alluvial fan. This can then be applied to disparate deposits such as the Brockram Facies, as presented in this study. To further understand the cyclicity within arid alluvial fan systems, correlation across the basin will be assessed in order to provide sufficient data to determine the both the effects of cyclicity and the resultant connectivity of the deposits. In order to achieve this, the deposits of the distal Paradox Basin will be examined to allow for the interpretation of the effects of the interactions between the alluvial fan system, and the contemporaneous distal environments, and how this, in turn, has implications on facies connectivity. The results derived from this further study will then be compared to borehole data derived from the Brockram Facies, UK.

References

Ackhurst, M.C., R.A. Chadwick, R.W. Holliday, M. McCormac, A.A. McMillan, D. Milward, and B. Young, 1997, Geology of the West Cumbria District: British Geological Survey Memoir, Sheets 28, 37, and 47.

Blair, T.C., 1987, Tectonic and hydrologic controls on cyclic alluvial fan, fluvial, and lacustrine rift-basin sedimentation, Jurassic to lowermost Cretaceous, Todos Santos Formation, Chiapas, Mexico: Journal of Sedimentary Research, v. 55/5, p. 845-862.

Blair, T.C., and J.G. McPherson, 1994, Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages: Journal of Sedimentary Research, v. 64, p. 450-489.

Blum, M.D., 2000, Fluvial responses to climate and Sea-level change: A review and look forward: Sedimentology, v. 47, p. 2-48.

Burgess, I.C., 1965, The Permo-Triassic rocks around Kirby Stephen, Westmorland: Journal of Sedimentary Petrology, v. 42, p. 245-251.

Carter, F.W., 1955, Geology of the Gateway Quadrangle Colorado: U.S. Geological Survey, Map GQ-55.

Condon, S.L., 2000, Geology of the Pennsylvanian and Permian Cutler Group and Permian Kaibab Limestone in the Paradox Basin, Southeastern Utah and Southwestern Colorado: U.S Geological Survey Bulletin, v. 46.

Grainger, P., and P.G. Kalauger, 1987, Intermittent surging movements of a coastal landslide: Earth Processes and Landforms, v. 12, p. 587-603.

Hite, R. J., 1968, Salt deposits of the Paradox Basin, southeast Utah and southwest Colorado: Geological Society of America, Special Paper 88, p. 319-330.

Heward, A.P., 2006, Alluvial fan and lacustrine sediments from the Stephanian A and B (LaMagdalena, Ciñera-Matallana and Sabero) coalfields, northern Spain: Sedimentology, v. 25, p. 451-488.

Hughes, R.A, 2003, Permian and Triassic Rocks of the Appleby District: Memoirs of the British Geological Survey, v. 30, (England and Wales).

Jones, N.S., and A. Ambrose, 1994, Triassic sandy braidplain and aeolian sedimentation in the Sherwood sandstone group of the Sellafield area, West Cumbria: Proceedings of the Yorkshire Geological Society, v. 50.

Kendall, P.F., 2009, On the Brockram of the Vale of Eden and the evidence they afford of an Inter- Permian uplift of the Pennine Faults: Geological Magazine, v. 9, p. 510-513.

Kluth, C.F., and P.J. Coney, 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10-15.

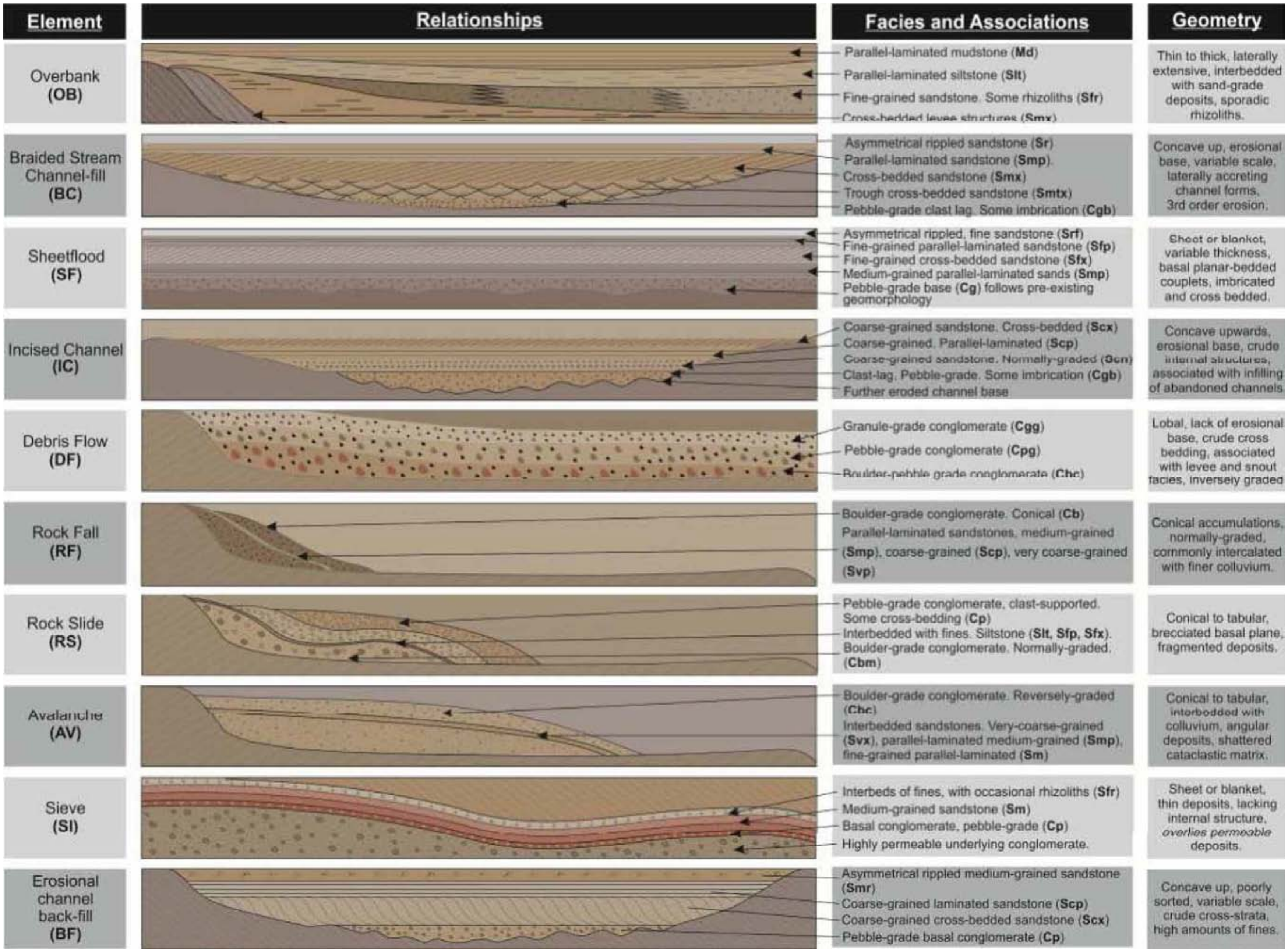
Leeder, M.R., 1999, Sedimentology and sedimentary basins: from turbulence to tectonics: Blackwell Science Publishing, Malden, MA, 592 p.

Parrish, J.M., and F. Peterson, 1988, Wind directions predicted from global circulation models and wind directions determined from eolian sandstones of the western United States: Sedimentary Geology, v. 56, p. 261-282.

Soreghan, G.S, D.R. Elmore, and M.T. Lowch, 2002, Sedimentologic-magnetic record of western Pangean climate in upper Palaeozoic loessite (Lower Cutler Beds, Utah): Geological Society of America Bulletin, v. 114, p. 1019-1035.

Steel, R.R., 1974, New Red Sandstone floodplain and piedmont sedimentation in the Hebridian Province, Scotland: Journal of Sedimentary Petrology, v. 44, p. 336-357.

Vaughn, P.P., 1973, Vertebrates from the Cutler group of Monument Valley and vicinity: New Mexico Geological Society, Guidebook 24, p. 99–105.



Element	Relationships	Facies and Associations	Geometry
Overbank **(OB)**		Parallel-laminated mudstone (**Md**) Parallel-laminated siltstone (**Slt**) Fine-grained sandstone. Some rhizoliths (**Sfr**) Cross-bedded levee structures (**Smx**)	Thin to thick, laterally extensive, interbedded with sand-grade deposits, sporadic rhizoliths.
Braided Stream Channel-fill **(BC)**		Asymmetrical rippled sandstone (**Sr**) Parallel-laminated sandstone (**Smp**). Cross-bedded sandstone (**Smx**) Trough cross-bedded sandstone (**Smtx**) Pebble-grade clast lag. Some imbrication (**Cgb**)	Concave up, erosional base, variable scale, laterally accreting channel forms, 3rd order erosion.
Sheetflood **(SF)**		Asymmetrical rippled, fine sandstone (**Srf**) Fine-grained parallel-laminated sandstone (**Sfp**) Fine-grained cross-bedded sandstone (**Sfx**) Medium-grained parallel-laminated sands (**Smp**) Pebble-grade base (**Cg**) follows pre-existing geomorphology	Sheet or blanket, variable thickness, basal planar-bedded couplets, imbricated and cross bedded.
Incised Channel **(IC)**		Coarse-grained sandstone. Cross-bedded (**Scx**) Coarse-grained. Parallel-laminated (**Scp**) Coarse-grained sandstone. Normally-graded (**Scn**) Clast-lag. Pebble-grade. Some imbrication (**Cgb**) Further eroded channel base	Concave upwards, erosional base, crude internal structures, associated with infilling of abandoned channels.
Debris Flow **(DF)**		Granule-grade conglomerate (**Cgg**) Pebble-grade conglomerate (**Cpg**) Boulder-pebble grade conglomerate (**Cbc**)	Lobal, lack of erosional base, crude cross bedding, associated with levee and snout facies, inversely graded
Rock Fall **(RF)**		Boulder-grade conglomerate. Conical (**Cb**) Parallel-laminated sandstones, medium-grained (**Smp**), coarse-grained (**Scp**), very coarse-grained (**Svp**)	Conical accumulations, normally-graded, commonly intercalated with finer colluvium.
Rock Slide **(RS)**		Pebble-grade conglomerate, clast-supported. Some cross-bedding (**Cp**) Interbedded with fines. Siltstone (**Slt, Sfp, Sfx**). Boulder-grade conglomerate. Normally-graded. (**Cbm**)	Conical to tabular, brecciated basal plane, fragmented deposits.
Avalanche **(AV)**		Boulder-grade conglomerate. Reversely-graded (**Cbc**) Interbedded sandstones. Very-coarse-grained (**Svx**), parallel-laminated medium-grained (**Smp**), fine-grained parallel-laminated (**Sm**)	Conical to tabular, interbedded with colluvium, angular deposits, shattered cataclastic matrix.
Sieve **(SI)**		Interbeds of fines, with occasional rhizoliths (**Sfr**) Medium-grained sandstone (**Sm**) Basal conglomerate, pebble-grade (**Cp**) Highly permeable underlying conglomerate.	Sheet or blanket, thin deposits, lacking internal structure, *overlies permeable* deposits.
Erosional channel back-fill **(BF)**		Asymmetrical rippled medium-grained sandstone (**Smr**) Coarse-grained laminated sandstone (**Scp**) Coarse-grained cross-bedded sandstone (**Scx**) Pebble-grade basal conglomerate (**Cp**)	Concave up, poorly sorted, variable scale, crude cross-strata, high amounts of fines.

Figure 1. Facies, facies associations and architectural elements of common environments found within the alluvial fan system, based on field observations of the Permian Cutler Group, Undivided in the Paradox Basin, Utah, U.S.A.

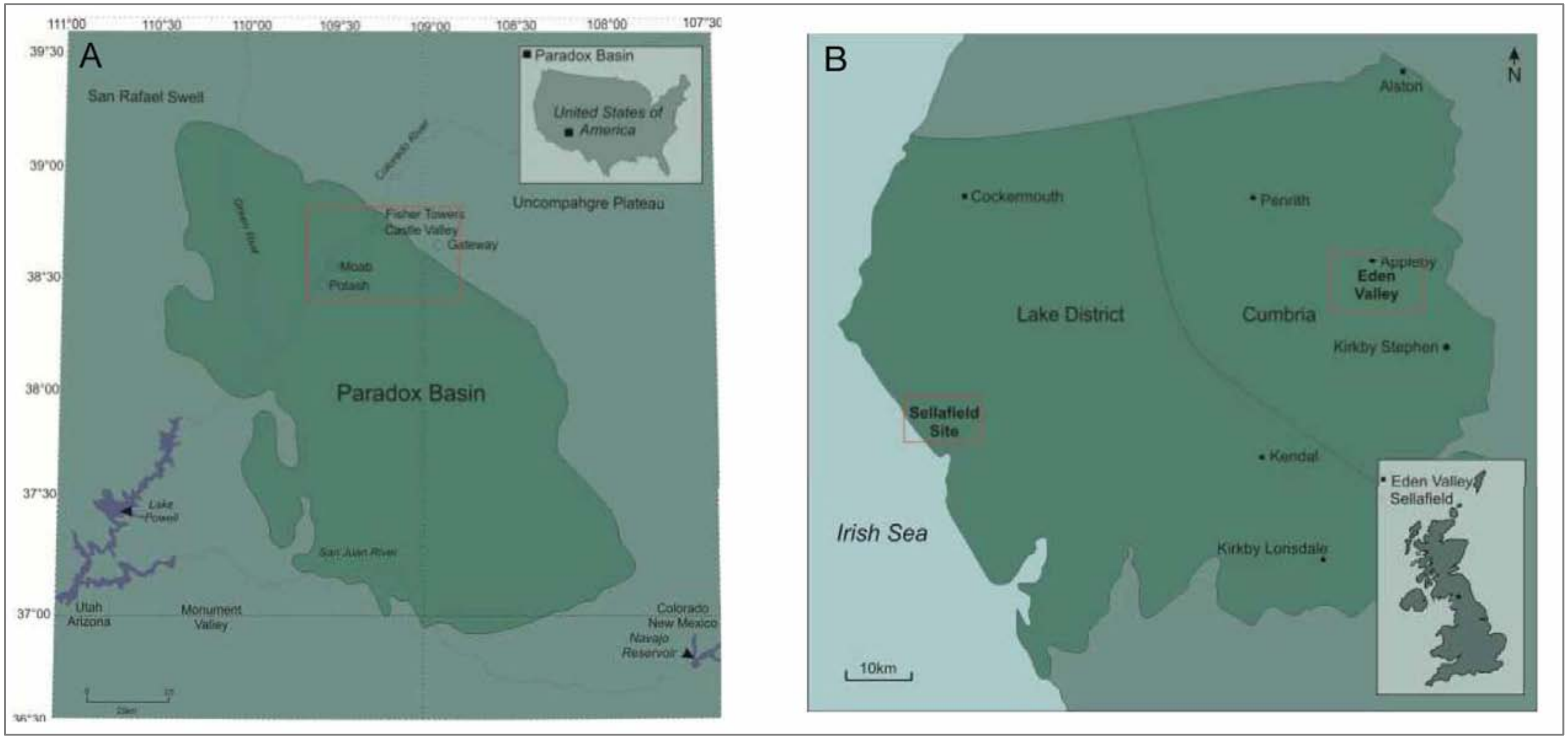


Figure 2. (A) The Location of the Paradox Basin, western U.S.A, and the position of field localities within it (after Condon, 2000). (B) The location of the field site (Eden Valley) and the area in which the examined boreholes occur (Sellafield) of the Brockram Facies, UK (after Akhurst et al., 1997).

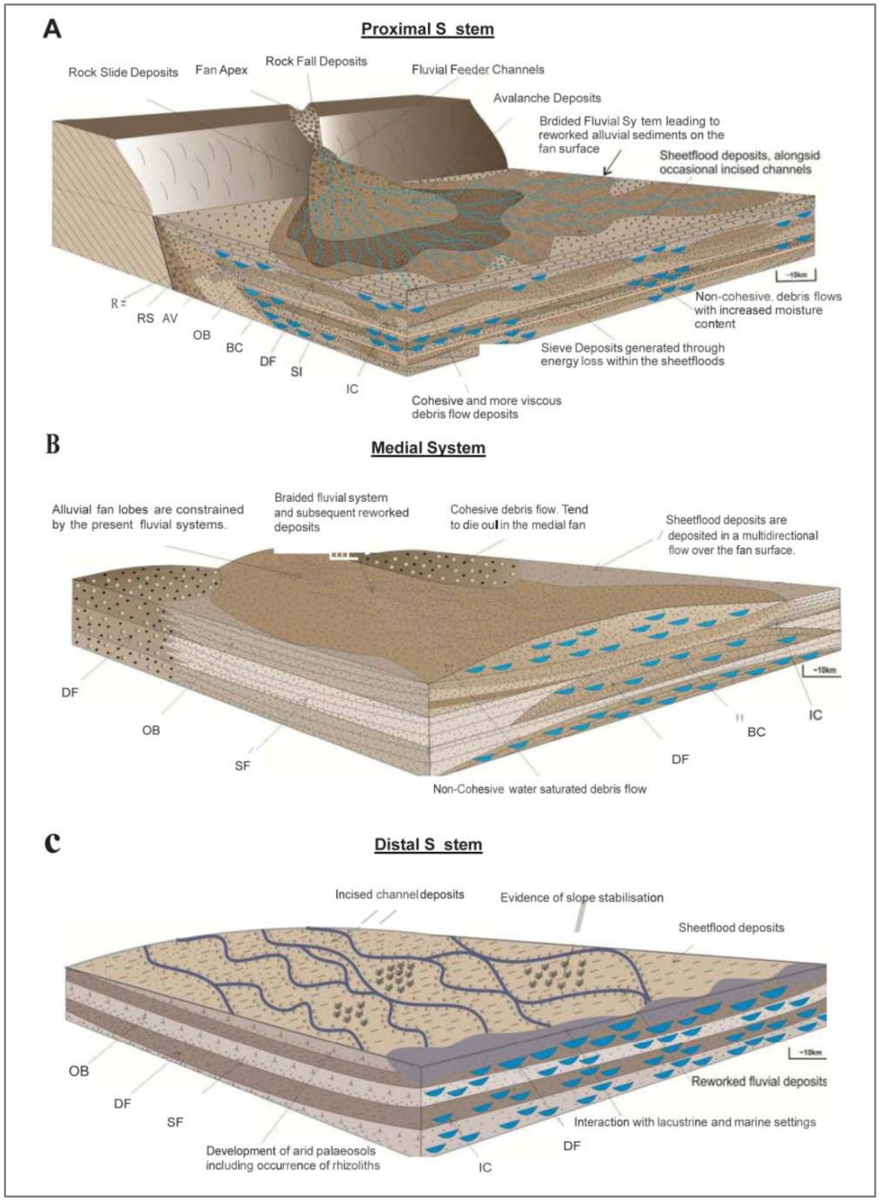


Figure 3. (A) Proximal alluvial fan system. The diagrams show that the predominant proximal depositional processes occur through sediment gravity flows, mainly sourced from bedrock failure. Fluid gravity flows, fluvial systems and overlying sheetfloods become more dominant with distance from the apex. (B) Medial alluvial fan system. Colluvially sourced sediment gravity flows dominate the medial system, with frequent influxes of fluvial systems, incised channels and intermittent sheetfloods. (C) Distal alluvial fan system. Fluid gravity flows dominate the distal system. Secondary environments also become more prominent, including fan-surface fluvial and lacustrine deposition.

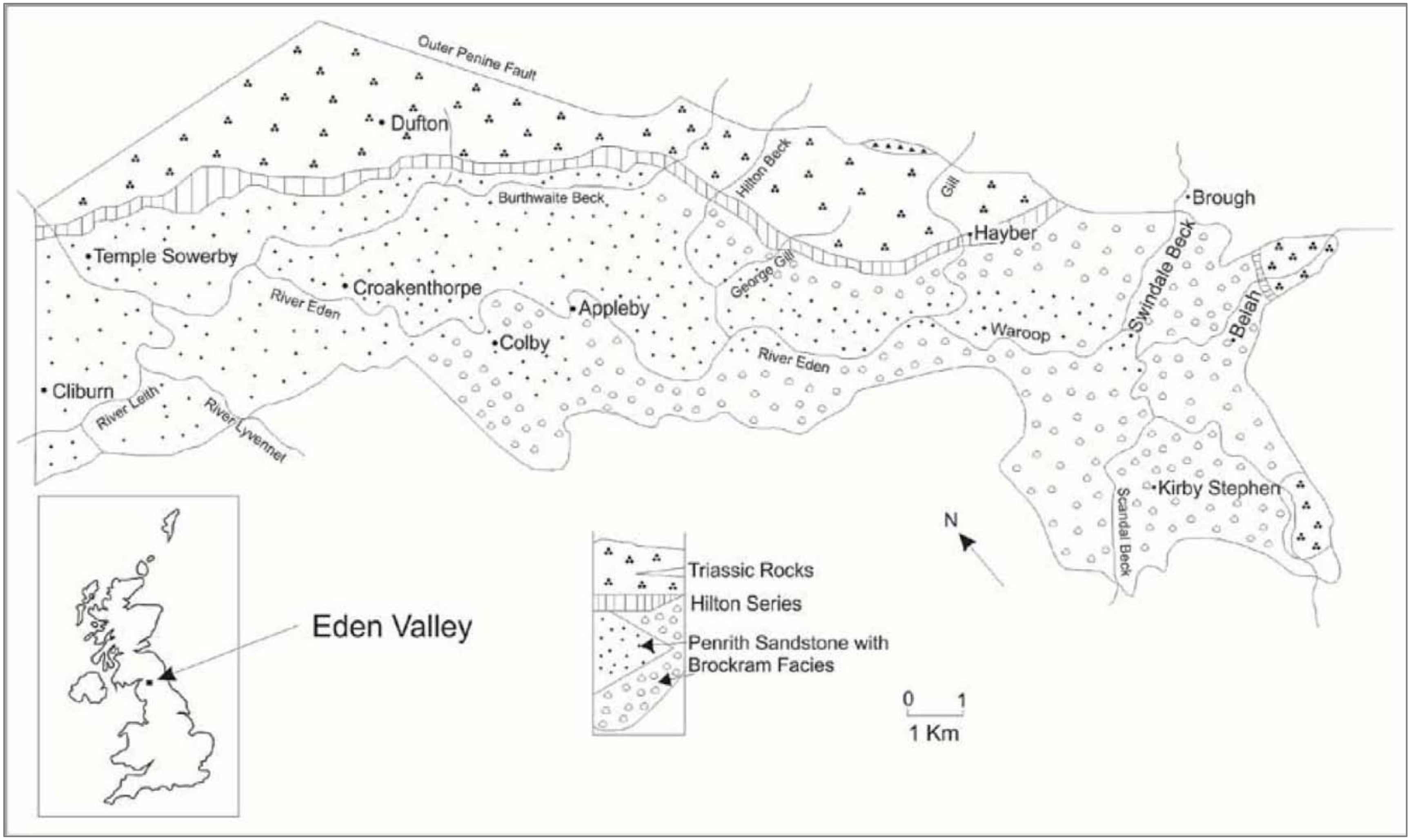


Figure 4. Map of the Vale of Eden showing the localities studied during the research. After Burgess 1965.

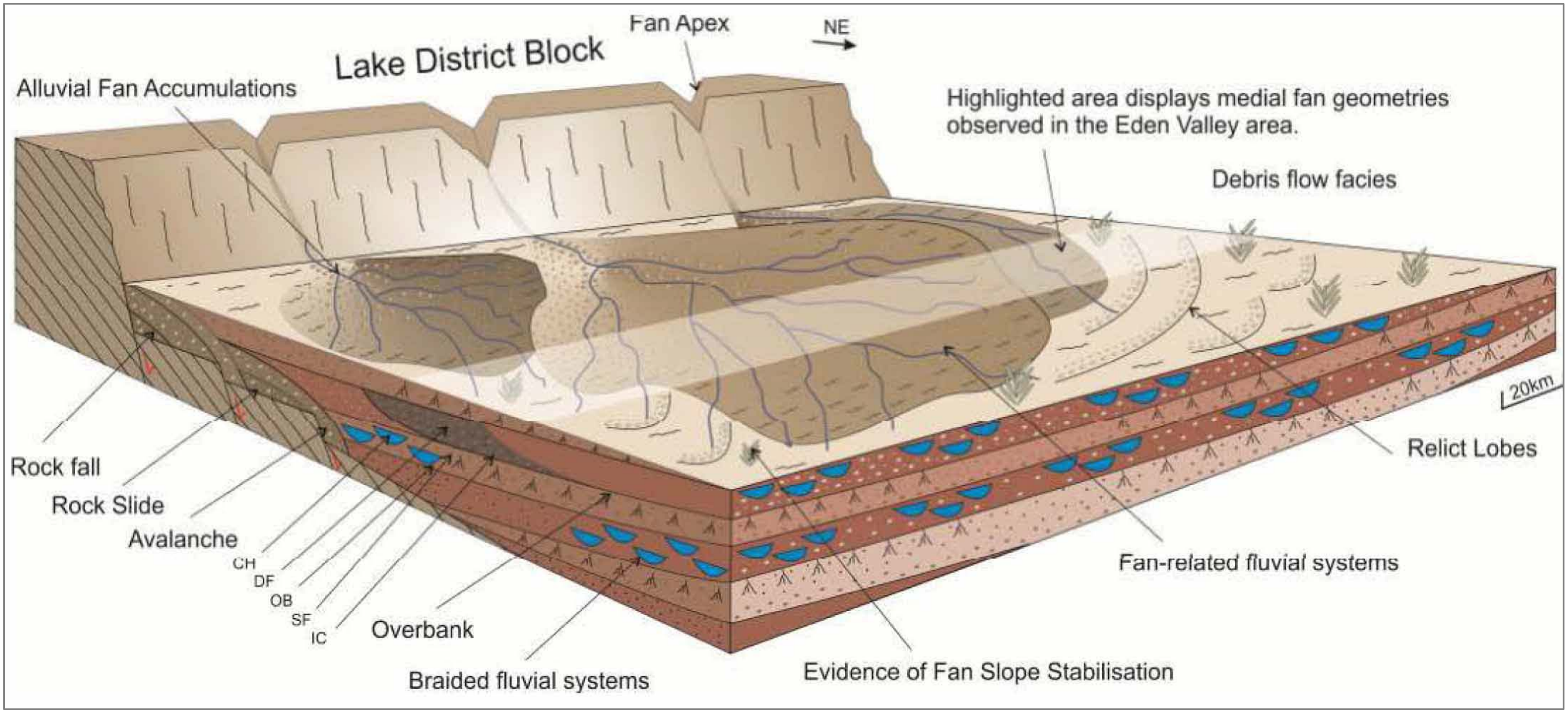


Figure 5. A 3D architectural model showing a schematic interpretation of the Brockram Facies system. With particular reference to the areas in which the outcrop in the Eden Valley occurs.