Challenging orthodoxy: is the Present the Key to the Past?

Gary Nichols
School of Environment and Technology, University of Brighton, Lewes Road, Brighton BN2 4GJ, UK.
Also at RPS Nautilus, Goldvale House. Church Street West, Woking, GU21 6DH, UK
garyjnichols@live.co.uk

ABSTRACT

"If choosing a 'present' to be the 'key to the past' I wouldn't choose the present 'present'". The uniformitarian principle guides us to interpret sedimentary successions in the rock record through the prism of modern depositional environments: observing and measuring processes and products in, for example, a present-day delta environment should provide us with the information that we need to interpret ancient strata as deltaic. To a certain extent this is valid, but awareness of the limitations is important to successful analysis of sedimentary successions which can be difficult, if not impossible, to relate to anything seen around the world today.

This article is in two parts. In the first there is a somewhat speculative discussion of some of the issues that arise when using a uniformitarian approach to the analysis of the sedimentary record. This is followed by a case study of a Silurian succession that cannot easily be interpreted in terms of modern environments.

THE HISTORY

The origins of the concept of uniformitarianism lie back in the eighteenth century when early geologists, including James Hutton, recognised that processes occurring on the Earth's surface today could explain the formation of sedimentary rocks. At the time this was to provide a scientific alternative to catastrophist views and it was a concept that Charles Lyell (Fig. 1) further developed in 'The Principles of Geology' in the early part of the 19th century (Lyell 1832) to argue that, in general, the rates of surface geological processes have been constant through Earth history. Subsequently, the proposition that we can use observations and measurements of present day surface processes and their products as a fundamental tool to interpret the sedimentary record has become a tenet of sedimentology and stratigraphy. A note of caution was expressed by Derek Ager in the mid twentieth century (Ager 1973) by pointing out that occasional, large scale catastrophic events have been important in forming sedimentary successions, but in general the 'present is the key to the past' approach is widely used in geosciences.

THE PROBLEM

The limitations of the approach become apparent when the uniformitarian principle is extended from physical and chemical processes to whole environments of deposition, in particular, the assumption that modern environments can provide analogues for successions in the sedimentary record. It is quite a beguiling proposition that we can illustrate our interpretation of a subsurface succession by reference to somewhere on the planet today and is especially useful when attempting to create a geological model that a non-geoscientist can readily appreciate. The first problem with using modern analogues is that every depositional environment that has existed in Earth history has been unique and formed by combinations of processes that have never been replicated. The exact modern analogue for a past environment is of course a chimera generally appreciated by sedimentologists, but what seems to be less well appreciated is how wide of the mark modern settings can be as potential analogues. In this article some of the potential pitfalls in using the present as the key to the past in the interpretation of depositional environments are explored.

ICEHOUSE AND GREENHOUSE WORLDS

The Earth has gone through several cycles of overall cooler and warmer climate through the Phanerozoic: we have been in an icehouse world for the last few million years but most of the last 600 My have been times of warmer conditions in a greenhouse world (Fig. 2). A principal consequence of a long-term colder climate is the presence of large polar ice caps which hold enough water to change global sea level by tens of metres as the ice caps expand and contract. Evidence from the Holocene suggests that these changes in sea level occur relatively rapidly and high magnitude, high frequency sea level changes affect all depositional environments linked to marine base level and climate fluctuations affect deposition in continental settings. Consequently, modern environments are responding to sea level and climate changes that have occurred in the last few thousand years and at geological time scales are in transition between lowstand and highstand states.

Along coasts, recent episodes of sea level fall and subsequent rise have resulted in incision of coastlines and coastal plains at river mouths forming estuaries. Further upstream rivers have cut into their floodplains,

Figure 1: Charles Lyell, an early proponent of the uniformitarianism principle of the present being the key to the past: to what extent should this approach be applied with caution?

restricting lateral migration and confining channel belts. Out on continental shelves tidal sand bars formed during sea level lowstand may now be inactive as they are no longer subject to tidal currents on the shelf. Observations and measurements made in these modern settings do not reflect long-term stable conditions that would have existed under greenhouse climates. Confined estuaries are a specific coastal response to rapid fall and rise of sea level; over longer periods of time rivers reach an equilibrium with the basin plain depositing from distributive river systems that form broad expanses of channel and overbank deposits; longer-term sediment supply and reworking by tidal currents on the shelf can result in thick amalgamated packages of sands.

During long periods of a greenhouse world, such as the Cretaceous, any fluctuations in relative sea level due glacio-eustacy would have been minor. Coastal environments may therefore have looked very different to those of today, with low-relief coastal plains merging into paralic regions. In particular, the distributive fluvial systems that are important regions of sedimentation in many settings could have reached shorelines and fed coastal depositional systems, a relationship that is only seen in a few places today (Fig. 3).

THE APPROPRIATE MODERN ENVIRONMENTS

There is a long history of studies of rivers from across North America and Europe that have contributed to the body of literature on fluvial forms and processes. These studies are widely used to aid the interpretation of fluvial successions, for example by analysing the ways that various mid- and side-channel bars migrate and assuming that these are similar to the ways that bars have led to the formation of cross-stratified sandstones in channel deposits. However, the vast majority of rivers in Europe and North America are not in sedimentary basins and are therefore not sites of net sediment accumulation (Hartley et al 2010; Weissmann et al 2010). The same group of authors also contend that most modern depositional fluvial systems in other parts of the world are distributive in form (e.g. Fig 3), rather than tributary, the exceptions being where distributive channels join a trunk channel in large basins such as the example of the River Ganges in the Himalayan foreland basin. A distributive form of river system has been recognised in sedimentary basins at a wide range of scales, in various climatic zones and in all tectonic settings (Hartley et al 2010; Weissmann et al 2010).

The choice of analogue for a fluvial succession should therefore consider the possibility, if not probability, that the basin-scale river pattern would have a distributive form and that any modern, tributary river that is not in an aggradational setting cannot be an appropriate analogue. At the scale of individual channels and their associated floodplains, modern rivers that are non-depositional or

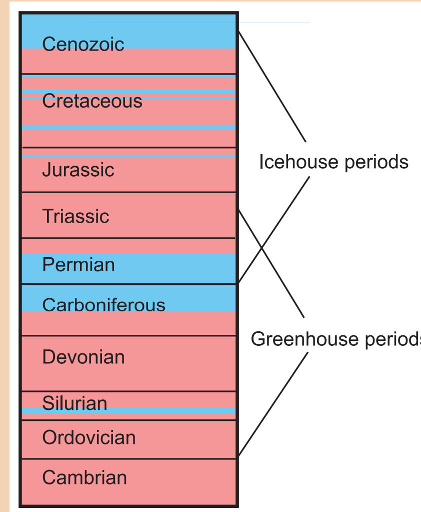

Figure 2: Icehouse and greenhouse worlds during Phanerozoic (Royer et al. 2004)

erosional cannot provide any insight into how a succession of channel sill and overbank is built. Similarly, sandy deserts that are undergoing deflation, beaches and shorelines that are currently regions of net loss of sediment are not going to provide analogues for sedimentary successions in the rock record.

HIGH MAGNITUDE DEPOSITIONAL EVENTS

On a human timescale there are occasional extreme weather events such as cyclonic storms and floods that are sometimes referred to as 'hundred-year' or 'thousand-year' occurrences, implying that the magnitudes are, on average, only experienced at these frequencies. However, if the longer timescales involved in the accumulation of sedimentary successions are considered, are there likely to be larger magnitude events that occur during periods of tens to hundreds of thousands of years?

Floods are most commonly associated with unusually high rainfall events which may on occasions be considered extreme (Browne 2002). They may also be the result of phenomena such as natural dam bursts and jokhulhaups triggered by tectonic or volcanic activity. The deposits of these truly catastrophic

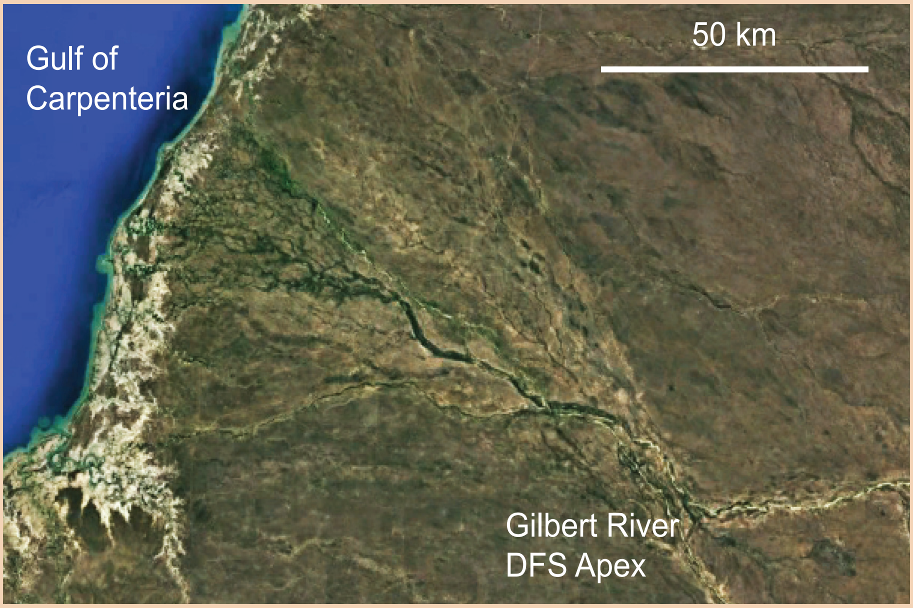

Figure 3: The Gilbert River in northern Queensland is one of few modern examples of a distributive fluvial system reaching the coast (Owen et al. 2015

floods indicate flooding events of an almost unimaginable scale: gravelly bars resulting from a flood event in the Altai Mountains, Siberia, are up to 120 m tall and 5 km in length (Carling et al. 2002). These particular deposits are in an area that is undergoing net degradation and along with most continental glacial deposits they do not have long-term preservation potential. Flood events such as this are the product of an unusual set of circumstances, but serve as a reminder that provided something is physically possible there is every chance that such an event could have occurred though geological time, even if it requires imagining something that is way outside the range of scales of processes experienced on human timescales.

Strong winds associated with storms also affect continental settings and in desert regions events when there is large-scale transport of sand within ergs is associated with storm events. Wind velocities are determined by distances between areas of different atmospheric pressure: the extent of the region of higher pressure associated with polar ice caps varies between glacial and interglacial (Fig. 4), with compressed global air circulation belts when polar ice is more extensive. This raises the possibility that during glacial periods in earth history winds may have been stronger than any experienced today, with the higher velocities capable of carrying coarser sediment. Assumptions that the maximum grain sizes seen in modern aeolian sands apply to wind-blown deposits in the stratigraphic record may therefore need to be questioned.

There are some depositional processes and their products that are so infrequent relative to human time scales that they are difficult to observe and measure, whatever their magnitude. The deep seas are challenging environments for analysing modern processes, and there are few documented examples of turbidity currents on record: the data from the Grand Banks earthquake (Heezen and Ewing 1952) is still one of the most commonly quoted examples of a modern turbidity current. On alluvial fans in arid environments debris flow processes are a primary mechanism for building up the sediment body, but again they are relatively infrequent events that are difficult to predict and measure whilst they are occurring. Studies of 'active' fans from SW USA (Beaty 1970) suggest that the recurrence interval for debris flow events on an alluvial fan is in the region of 300 years.

THE EVOLUTION OF LIFE

The large-scale changes fauna and flora on land and in the sea through time are the most obvious ways in which modern environments will look quite different from areas of deposition in geological history. The way that different assemblages of carbonate-forming organisms during the Phanerozoic have created distinct ecosystems and limestone facies is well documented (Tucker 1992). The impact of the development of vegetation on the land surface has also been well recognised: Schumm (1968) noted that the binding effects of root systems from different plant groups would have controlled the stability of floodplain surfaces and their susceptibility to surface scouring or the erosion by river channel margins. Grasses have dense, fibrous root networks that are extremely effective at binding soil and therefore have a big impact on river bank stability. However, modern grasses did not become widespread until the mid-Cenozoic and although other flowering plants will have acted to stabilise land surfaces they may not have been so effective. Before flowering angiosperms evolved and diversified in the mid-Cretaceous, plant communities were dominated by gymnosperms with much simpler root structures with a weaker soil-binding effect (Fig. 5).

Continental deposits are widespread in Devonian strata, for example in north western Europe, and were formed at a time when land plants were very simple and probably relatively sparse. The absence of stabilising vegetation would have enabled river channels to laterally migrate across floodplains with ease, resulting in broad sheets of fluvial channel sandstones. Consequently, channel margins are rarely seen, and

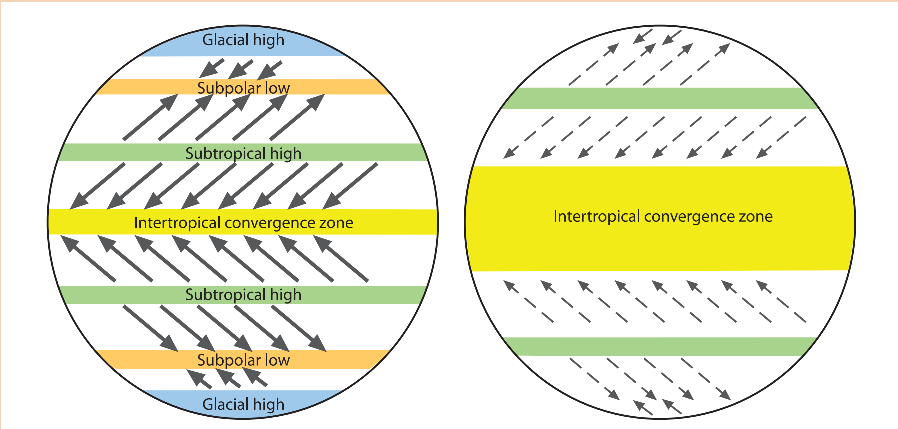

Figure 4: During glacial intervals the global wind belts are more compressed resulting in potentially stronger winds compared to interglacial intervals (Glennie 1987)

in the Devonian strata on Anglesey, north west Wales, the lateral accretion surfaces (epsilon cross stratification) first recognised by Allen (1965) are not associated with erosion surfaces representing channel margins. In the present-day vegetation on floodplains is only absent in very hot and dry or very cold settings: river channels in these places may show the same tendency to lateral migration and sweep across the alluvial plain. These settings do not provide appropriate analogues for the Devonian deposits of NW Europe. The Devonian is perhaps an extreme example of differences in vegetation, but any fluvial environments from pre-Mid Cenozoic times are unlikely to have reliably similar processes of channel formation and migration to the present day because of the importance of grasses on floodplain stability.

A CASE STUDY OF DIFFICULT INTERPRETATION

So having considered some of the general problems of using the present is the key to the past approach, there follows a case study that provides an example of how difficult it can be to find a modern analogue for a succession.

On the southern side of Killary Harbour in County Galway, Western Ireland, there is a hillside outcrop of rocks mapped as being part of the Upper Silurian Salrock Formation (Graham et al. 1989) (Fig 6, 7a). The succession was described by Laird (1969) as being 814 m thickness of sandstones and mudrocks that are generally red in colour. They are stratigraphically above the Lough Muck Formation and the basin setting is considered to be back-arc. Beds are typically tens of centimetres thick and the following depositional features are present

(a) The succession is heterolithic at different scales
(b) There appears to be a complete absence of any erosional surfaces but conversely there are upward-convex surfaces indicating preservation of dune and bar forms
(c) Cross-bedding apparently indicates bimodal flow directions
(d) Low angle inclined heterolithic cross stratification is present in some beds
(e) Both ripple-scale cross-lamination and dune-scale cross-bedding show evidence of stoss-side preservation of laminae, e.g. as climbing ripple cross lamination (Figs 7 b and c).
(f) The wavy ripple forms present are interpreted as preserved current ripples

This facies assemblage is consistent with deposition in a strongly tidally-influenced environment (Dalrymple 1992). Deposition from bidirectional currents is difficult to establish with confidence because of the smoothly-eroded rock surfaces preclude measurements of true dips of cross-beds, but the inclined heterolithic stratification, flaser and wavy lamination and heterogenous character are all consistent with tidal conditions.

There are however, a number of aspects of the Salrock Formation that make it difficult to find a direct modern analogue. Firstly, the succession is largely devoid of body fossils, the only shelly material reported being sparse occurrences of Lingula (Laird 1969), and there is no sign of any trace fossils. Tidally-influenced environments are normally well-oxygenated and benign for shallow marine organisms. Secondly, the formation has a substantial thickness of over 800 m (Laird 1969) and shows remarkably little variation from bottom to top: there are changes in the proportions of different facies at different intervals, but no overall trends to suggest changes in the environment through time. Thirdly, the wholly aggradational pattern of the succession and absence of any evidence for erosive surfaces indicates

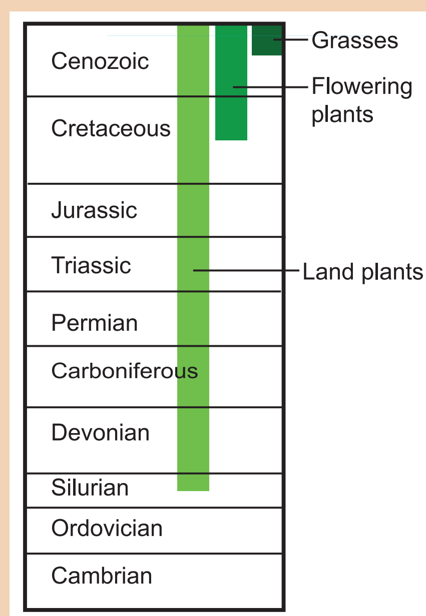

Figure 5: Stages in the evolution of land plants (Schumm 1968)

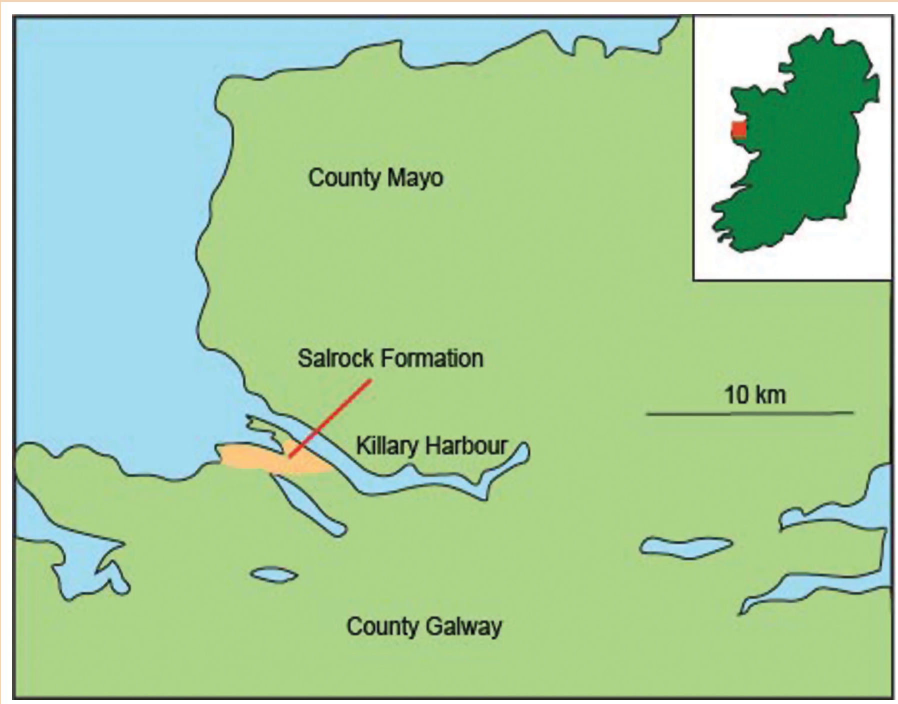

Figure 6: Location map for the Silurian Salrock Formation, Western Ireland

a balance between subsidence and sediment supply during the history of accumulation in the basin.

The setting for the deposition of the Salrock was relatively shallow with strong tidal influence and apparently anoxic conditions with high rates of fine sediment supply and increasing accommodation to keep pace with sedimentation in a back-arc setting. No analogous setting exists today and it does not slot easily into any established facies model pigeonholes. It is one of probably many instances where an innovative solution is required to solve the problem of interpretation of the environment of deposition.

SOME QUESTIONS

Do modern estuaries provide appropriate analogues for anything other than icehouse periods when there was rapid, high magnitude sea level variation? Are new depositional models required for river mouths at coasts that are undergoing transgression where an 'estuary' may not be laterally-confined in an 'incised valley' (aren't all valleys incised?).

Are the processes in modern rivers that are in a degradational or non-depositional setting relevant to understanding fluvial successions in sedimentary basins if these processes are not leading to net accumulation? Do the same limitations also apply to modern coastlines where sediment may be being redistributed but not actually being preserved?

To what extent is the sedimentary record made up of the deposits of events that are of a higher magnitude than anything observed today? If, as Ager suggested, mega-events are disproportionately preserved in strata then studies of the smaller-scale processes are only providing an insight into the way that a fraction of the strata were formed.

How much modification of our models for pre-Cenozoic environments is required to take account of the effects of evolving organisms and ecosystems on surface and submarine processes? Pre-Phanerozoic environments on land and in the sea are well known to be very different from those of today, but the effects of changes in flora and fauna through time have continued right through to the recent times.

CONCLUSIONS

The fundamental tenet of Lyell's approach of using the evidence of modern physical and chemical processes to interpret the sedimentary

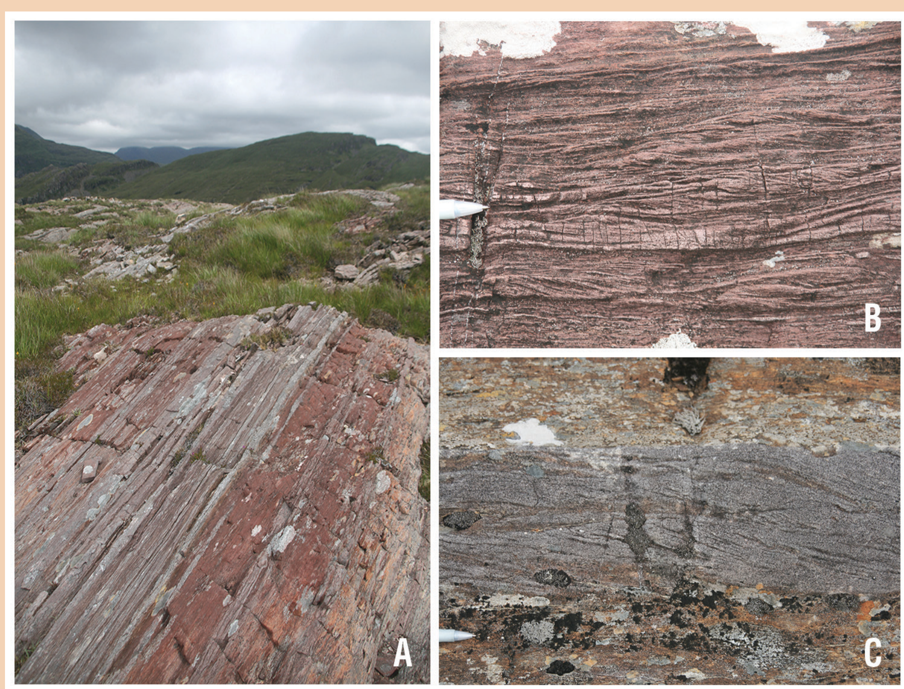

Figure 7: (a) outcrop of the Salrock Formation. Killary Harbour, Western Ireland; (a) climbing ripple lamination; (b) stoss-side preservation of subaqueous dune cross-bedding

record is sound: the problems arise in how it is applied. Modern environments do not provide an adequate range of analogues for the Phanerozoic and it is reasonable to interpret a succession as the product of a combination of processes in a setting not seen today. Choosing the right type of modern environment is critical, and any modern processes and products analysed from a non-depositional setting must be applied to strata which were self-evidently in a depositional setting with scepticism. Furthermore, the relationship between sea level changes, climate fluctuations and environments seen in recent history mean that conditions seen today are not representative of most of the Phanerozoic. The details and extent of these caveats to the uniformitarian principle require more discussion than is presented here as this article is intended to simply raise a few points for consideration.

An SEPM-sponsored conference session on this theme is planned for the annual meeting of the British Sedimentological Research Group to be held in Newcastle in December 2017 (www.bsrg.org).

ACKNOWLEDGEMENTS

My thanks to many colleagues for discussions over coffee, beer or more importantly in the field that have helped me frame my thoughts as expressed here.

REFERENCES

AGER, D.V. 1973. The Nature of the Stratigraphic Record, Wiley, 114p.

ALLEN, J.R.L. 1965. The sedimentation and palaeogeography of the Old red Sandstoner of Angelesey, north Wales. Proceedings of the Yorkshire Geological Society, 35, 139-158

BEATY, C.B. 1970. Age and estimated rate of accumulation of an alluvial fan, White Mountains, California, U.S.A. *American Journal of Science*, 268, 50-77.

BROWNE, G.H. 2002. A large scale flood event in 1994 from the mid-Canterbury Plains, New Zealan, and implications for ancient fluvial deposits. I.P Martini, V.R. Baker and G. Garzon (eds) Flood and Megaflood Processes and Deposits: Recent and Ancient Examples. International Association of Sedimentologists Special Publication 32, 99-112

CARLING, P.A., KIRKBRIDE, A.D., PARNACHOV, S., BORODAVKO, P.S. AND BERGER, G.W. 2002. Late Quaternary catastrophic flooding in the Altai Mountains of south-central Siberia: a synoptic overview and an introduction to flood deposit sedimentology. In: I.P Martini, V.R. Baker and G. Garzon (eds) Flood and Megaflood Processes and Deposits: Recent and Ancient Examples. International Association of Sedimentologists Special Publication 32, 17-36

DALRYMPLE, R.W., 1992. Tidal depositional systems. In: Walker, R.G., James, N.P. (Eds.), Facies Models—Response to Sea Level Change. Geological Association of Canada Publications, 195 – 218.

GLENNIE, K.W. 1987. Desert Sedimentary Environments, Present and Past - a Summary. Sedimentary Geology 50, 135-165

GRAHAM, J.R., LEAKE, B.E., AND RYAN, P.D., 1989. The geology of South Mayo, western Ireland: Department of Geology and Applied Geology, University of Glasgow, 75 p.

HARTLEY, A.J., WEISSMANN, G.S., NICHOLS, G.J. & WARWICK, G.L. 2010. Large Distributive Fluvial Systems: Characteristics, Distribution and Controls on Development. *Journal of Sedimentary Research*, 80, 167-183.

HEEZEN, B.C. AND EWING, M. 1952. Turbidity currents and submarine slumps, and the 1929 Grand Banks earthquake. American Journal of Science, 250, 849-873.

LAIRD, M.G. 1969. Sedimentation studies in the Silurian rocks of north-west Galway, Eire. PhD thesis, University of Oxford.

LYELL, C. 1832. Principles of Geology vol. II, John Murray, London.

OWEN, A., JUPP, P.E., NICHOLS, G.J., HARTLEY, A.J., WEISSMANN, G.S. & SADYKOVA, D. 2015. Statistical estimation of the position of an apex: Application to the geological record. *Journal of Sedimentary Research*, 85, 142–152.

ROYER, D.L., BERNER, R.A., MONTANEZ, I.P., TABOR, N.J. AND BEERLING, D.J. 2004. CO_2 as a primary driver of Phanerozoic climate. GSA Today, 14, 4-10.

SCHUMM, S.A. (1968). Speculations concerning palaeohydraulic controls of terrestrial sedimentation. Geological Society of America Bulletin, 79, 1573–1588.

TUCKER, M.E. (1992). Limestones through time. In: Understanding the Earth, a New Synthesis (Eds Brown, G.C., Hawkesworth, C.J. & Wilson, R.C.L.). Cambridge University Press, Cambridge; 347–363.

WEISSMANN, G.S., HARTLEY, A.J., NICHOLS, G.J., SCUDERI, L.A., OLSON, M., BUEHLER, H. & BANTEAH, R. 2010. Fluvial form in modern continental sedimentary basins: Distributive Fluvial Systems (DFS). *Geology*, 38, 39–42.

Accepted August 2017