## Rivers through geological time: the fluvial contribution to understanding of our planet

**David R. Bridgland[a]*, Jenny A. Bennett[b], Sarita E. McVicar-Wright[c], Richard C. Scrivener[d]**

[a] *Department of Geography, Durham University, Science Site, South Road, Durham DH1 3LE, UK*
[b] *4 Crockernwell Court, Crockernwell, Exeter, Devon EX6 6NA,UK*
[c] *University of Exeter, Penryn Campus, Penryn, Cornwall TR10 9FE, UK*
[d] *Demmitts Farm, Posbury, Crediton, Devon EX17 3QE, UK*

### 1. Introduction

This Special Issue of the Proceedings of the Geologists' Association has arisen from the Annual Conference of the Association, held at the Royal Albert Memorial Museum in Exeter in 2012, on the theme of 'Rivers through geological time' (the above title). It was convened jointly with the Devonshire Association, as part of the 150th anniversary of that organization, and was co-sponsored by the British Society for Geomorphology and the Quaternary Research Association, as well as being supported by the Fluvial Archives Group. The aim was to bring together interests related to fluvial geology spanning the whole of the history of Earth the planet, from the earliest records of rivers, pre-dating the influence of life, through the well-known 'red-bed' terrestrial geological systems, to the evolution of landscapes and drainage systems that survive today, determined by looking at Late Cenozoic–Quaternary sedimentary archives, geomorphological features and processes and culminating in the management that is increasingly required for modern societies to live alongside the Earth's rivers. It was also intended that the role of fluvial sediments as repositories for fossils that provide evidence for palaeo-enviornments and habitats, as well as the evolution of life on land, should be included. In the Quaternary this repository also houses important evidence for human ancestry: principally the artefact assemblages from early prehistory that have been recovered during quarrying of Pleistocene riverine sands and gravels, details of which have often been documented in the pages of the Proceedings.

To the Earth scientist those parts of the geological record that represent fluvial environments are not always the most immediately interesting or attractive, as they are generally not the ones that are bristling with fossils in the way, for example, of some shallow marine strata. They provide, however, perhaps the best connection with the terrestrial environment in which human-kind has evolved and operates at the present day. They are also a principal source of those relatively rare but ultimately most glamorous of fossils, the dinosaurs, and, indeed, of most other land-dwelling creatures, although the extension of the fluvial environment into deltas and low-lying coastal plains is particularly well represented. This is readily explained; the fluvial strata from deep time do not represent the riverine environments familiar in many parts of the world but rather the accumulations by rivers in large depocentres that existed in certain crustal provinces in the past, for which modern analogues can be recognized, and which are preferentially (although not exclusively) formed near the edges of continental land masses. Other patterns can be recognized, such as the representation of fluvial environments from the particular intervals of geological time across large tracts of continental crust, giving rise, for example, to the 'Old Red Sandstone' and 'New Red Sandstone' of the Devonian and Permo-Triassic respectively (represented in this issue by the contributions by Marriott and Hillier, by Warrington and by Hart). There has also been long-term persistence, on geological timescales, of large river valleys following deep-seated structural alignments. These provide a link between the overarching paradigm of 20th century geology, plate tectonics, and the study of rivers as they exist today and have evolved in the recent past: geomorphology and Quaternary geology.

The papers that follow were presented either verbally or as posters at the conference, with the exception of that by Hamblin: a review of the Palaeogene gravels of the Haldon Hills, close to the meeting venue at Exeter. This collection of papers charts the evolution, through Earth history, of rivers and, thereby, of an important part of the terrestrial environment, as well as exploring the value of fluvial archives to other, more specialist branches of the Earth sciences.

## 2. The earliest rivers

Fluvial sedimentary rocks are known from Earth's Archaean cratons, in which they can provide valuable indications of the hostile conditions during this early stage in the planet's evolution. For example, the rocks of the Pilbara Craton in Australia include fluvial sandstone–conglomerate representing braided river environments spanning ~3250–2750 Ma; these deposits contain detrital minerals that provide important evidence of the low-oxygen atmosphere of that time (Rasmussen and Buick, 1999). Fluvial sediments also form part of the ~2.650 Ma Shamvaian Group within the Bindura–Shamva greenstone belt of Zimbabwe (Hofmann et al., 2002), whereas alluvial fan and braided-river deposits of compatable or slightly greater age occur within the North Spirit Lake greenstone belt of the Superior Province of NW Ontario, Canadian Shield (Wood, 1980). Karpeta (1993) provided a detailed analysis of the sedimentology of Archaean braided-river deposits of the Witwatersrand Supergroup, within the Kaapvaal Craton of South Africa, much studied on account of their importance as a source of gold (Welkom Goldfield). In a remarkable link between these most ancient fluvial archives and Pleistocene–modern riverine environment, it is possible to differentiate topographical–morphological elements within these deposits: major channels, minor channels and interchannel terrace areas, representing different levels of the river system progressively occupied during flood cycles (Karpeta, 1993). Younger Precambrian fluviatile rocks in the Kaapvaal Province provide evidence of the transition to an oxygen-rich atmosphere; these are Lower Proterozoic strata spanning ~2500–1900 Ma that include the oldest known 'red beds' (Eriksson and Cheney, 1993).

It has long been realised that the rivers that flowed on the Precambrian Earth were somewhat different to those at the present day, largely because of the absence of the stabilizing effect of land plants and their other influences on the terrestrial domain (e.g., Tirsgaard and Øxnevad, 1998; Davies and Gibling, 2010a; Gibling and Davies, 2012, 2014/this issue). As Eriksson et al. (2006) noted, the binding, baffling and trapping of sediment by vegetation (particularly roots) would have been lacking from Precambrian river systems, as a result of which flashy surface runoff, lower bank stability, broader channels with abundant bedload, and faster rates of channel migration are likely to have characterized such rivers, in comparison with the more familiar vegetated systems that occurred later. The best evidence for such a pre-vegetation river system in Britain comes from the Torridonian succession of north-west Scotland, which comprises three groups of predominantly fluvial sediments, with a total thickness of >10 km (Prave, 2002; Stewart, 2002; Owen and Santos, 2014/this issue), although Prave (2002) noted evidence that single-cell organisms lived in the terrestrial environment represented by the Torridonian rocks, recognizing microbially induced sedimentary structures (e.g., wrinkle structures) and remnants of apparent microbial crusts. Indeed, he considered that there were indications of original cohesiveness and pliancy in sand-sized sediment within these late Mesoproterozoic to early Neoproterozoic rocks that implied an influence of life on terrestrial sedimentary envronments at that very early time (~1200–1000 Ma). Nonetheless, it has been suggested, based on their sheet-like sediment architecture, that pre-Devonian unconfined (unvegetated) braid- and floodplains were significantly wider than in later systems, with width-to-depth ratios from 200:1 to more than 1000:1 (Fuller, 1985; Els, 1990).

It has also been suggested that the greater roundness of grains in Precambrian and Lower Palaeozoic quartz arenites has a causal link with the absence of macroscopic land plants at those times, although this is probably related to the greater efficacy of aeolian processes in the absence of vegetation (Dott, 2003).

## 3. Palaeozoic to Mesozoic rivers

Gibling et al. (2014/this issue) note the rapid and profound change in the character of fluvial systems during the latter half of the Palaeozoic, as a result of the colonization of terrestrial environments by plants. Thus what they regard as the co-evolution of river systems and the plant kingdom had essentially transformed rivers between the beginning of Old Red Sandstone (ORS) deposition and the emplacement of the New Red Sandstone (NRS). Indeed, they suggest that meandering rivers became common for the first time in the Devonian, perhaps because of the rise of rooted plants, which, by strengthening river banks, would have encouraged meander formation (Tal and Paola, 2007), although the role of plant cover in promoting induration of floodplain surfaces would have had a comparable and perhaps equally important effect (Gibling et al., 1998, 2014/this issue; Nanson et al., 2005). The importance of the advent and expansion of terrestrial plants in the parallel evolution of river systems is an important paradigm that researchers have established and reinforced during the past half century (e.g. Schumm, 1968; Went, 2005; Corenblit and Steiger, 2009; Davies and Gibling, 2010a, b; Gibling and Davies, 2012). The most important influences of vegetation during this period of change were on rock weathering, landscape stability and sediment supply to valley-floors, sediment storage, and, acting less directly on river systems, on the composition of the ocean and atmosphere (Algeo and Scheckler, 1998; Davies and Gibling, 2010a).

Marriott and Hillier (2014/this issue) describe example tracts of ORS in south-west Wales, within which three formations of the Milford Haven Group are represented. From careful recording and various analyses they have been able to recognize the influence of tectonic activity and changes in climate, although the latter was predominantly hot, semi-arid and with seasonal rainfall, giving rise to ephemeral streams with flashy flow regimes. Detailed analyses of sediment facies, palaeosols and palaeogeography, together with comparisons with modern-day dryland river systems, have provided important bases for interpretation (see also Allen, 1974; Channel et al., 1992; Marriott and Wright, 1993; Edwards and Richardson, 2004).

The density of plant life during following Carboniferous Period is well known, from reconstruction of the environments from which the coal seams formed (e.g. Leveridge and Hartley, 2006; Waters and Davies, 2006). The envisaged environments, widespread in the Northern Hemisphere, are low-lying well vegetated swamps in the lower reaches of rivers. The result was prominently organic sediment but with interbedded sandstone units within the Coal measures cyclothems that represent fluvial activity. This was a period of glaciation in the Southern Hemisphere, with the cyclothems related to Milankovitch-type glacial–interglacial cycles. With striking similarities to the Quaternary, the warmest of the interglacials gave rise to the highest sea levels, producing marine incursions recorded in the 'marine bands' that provide valuable markers within Coal Measures stratigraphy.

New Red Sandstone Supergroup (NRS), as defined in the British Geological Survey Stratigraphical Lexicon (ref. http://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=NRS), includes, from oldest to youngest, the Exeter Group (? late Carboniferous to Permian), the Aylesbeare Group (early Triassic), the Sherwood Sandstone Group (mid-Triassic) and the Mercia Mudstone Group (late Triassic). The Exeter Group forms a considerable thickness (~2500m) of continental red beds at the western margin of the Wessex Basin, exposed within the UNESCO-designated Dorset and East Devon Coast World Heritage Site. In SW England the relatively undeformed strata of the NRS rest with marked unconformity on the Devonian and Carboniferous rocks of the Variscan Fold Belt (Leveridge and Hartley, 2006). The Permian in SW England is dominated by red conglomerates, sandstones, mudstones and marls. In the Mid- to Late Permian the sediment, in general, becomes finer as alluvial fans grade in to fluvial and eventually aeolian deposits, culminating in the Dawlish Sandstone Formation. The Exe Breccia Formation, seen at Lympstone on the Exeter Meeting field excursion, marks a considerable rejuvenation of the Permian topography and this is suggested by McVicar-Wright (2014) to form the base of the Aylesbeare Group, and possibly also to define the base of the Triassic in the area. These rocks represent an arid to semi-arid climate, which continued into the Triassic.

The Triassic was well represented in the Exeter field excursion, with a visit to exposures of the Budleigh Salterton Pebble Beds (BSPB) Formation (Sherwood Sandstone Group; Lower or possibly Middle Triassic) at its type locality: the cliffs to the west of Budleigh Salterton. Seen here are up to 26 m of red-brown horizontally bedded gravel with subordinate lenticular beds of through cross-bedded pebbly sandstone and sandstone beds. The gravel contains of well-rounded pebbles, cobbles and boulders, dominantly (90%) metaquartzite with minor porphyry, vein quartz, sandstone, chert, tourmalinite and feldspathic conglomerate clasts. It is attributed to a large braided river system, possibly of Scott type (Miall, 1978). The metaquartzite pebbles are thought to have been sourced from the south, probably from the Armorican massif, where similar rocks are present in the Grés Armoricaine and Grés de May of Brittany and Normandy. This provenance interpretation is corroborated by Ordovician fossil assemblages common to the gravel clasts and the Armorican rocks (Edwards and Scrivener, 1999). The BSPB rocks represent a somewhat wetter climate than those from the Permian. They are overlain by the Otter Sandstone Formation (Sherwood Sandstone Group, Middle Triassic), which includes up to 120 m thickness of red–brown, generally cross-bedded fluvial sandstone representing yet wetter climatic conditions. On a more global scale, the supercontinent of Pangea started to break up at this time, heralding the end of the prevailing continental conditions. The Otter Sandstone is an important aquifer in East Devon and is the main reservoir rock of the Wych Farm oilfield to the east. NRS basins are also recognized in other parts of Europe and the British Isles; indeed, that in Cheshire is the topic of a contribution to this special issue by Warrington (2014/this issue; see below).

Much of the Permo–Trias in Britain and Europe thus represents desert environments but by the end of NRS deposition the terrestrial environment was populated by a wide range of plants and animals, the latter including large vertebrates, for which the fluvial sediments represent a valuable fossil repository (e.g., Benton et al., 1993; Hone and Benton, 2008; Buffetaut and Smektala, 2014/this issue; Hart, 2014/this issue). The biosphere was, of course, profoundly affected by the largest of all mass extinctions, between the Permian and the Triassic, with ~90% of lifeforms estimated to have gone into extinction (see Benton, 2005); whatever caused this, it had relatively little influence on environments of deposition, such that NRS emplacement straddled this (Palaeozoic–Mesozoic) boundary. There were major tectonic changes between these systems: the N–S extension throughout much of the Permian was replaced by E–W extension from Mid-Triassic times (Scrivener et al., 1994), with a profound effect on the topography and the provenance of sediments, such as the BSPB.

By late in the Mesozoic some of the rivers that exist at the present day had come into existence, albeit sometimes in different environmental settings. For example, the high-level Nooitgedacht gravel of the Vaal, the oldest part of the diamond-bearing sedimentary sequence of that river, is attributed to the late Cretaceous or early Cenozoic (de Wit, 2004; see Bridgland and Westaway, 2014/this issue). A notable exception to the near-ubiquitous marine-dominated record of the later Cretaceous is provided by the terrestrial (including fluvial) rocks of North America, with their important dinosaur faunas (e.g., the Oldman Formation of Alberta; Eberth, 2005). Earlier in the Cretaceous rivers contributed to the British geological record by feeding to the alluvio-deltaic plain represented in the Wealden sequence in south-east England (Allen, 1959, 1981). With an Early Cretaceous glaciation in the Southern Hemispere (e.g., Stoll and Schrag, 1996; Alley and Frakes, 2003), the cyclicity apparent within the Wealden is perhaps an early analogue for the ubiquitous cyclic records from the Quaternary in mid–high latitudes; Allen (1981) attributed the alternation between subsidence and uplift to plate tectonic influences, although Britain was (as now) distant from plate boundaries and an influence, via erosional/sedimentation isostasy, from Milankovitch climatic fluctuation, as in the Pleistocene, seems possible (cf. Bridgland and Westaway, this issue).

## 4. Cenozoic rivers: closer to those that persist in the modern world

In the early Palaeogene conditions and continental patterns resembled those of the Mesozoic, although the transition from the warm, high-sea-level world of the later

Cretaceous, with its lack of ice caps (Rawson, 2006), to the colder world of the Pleistocene began during that first half of the Tertiary, to be completed (with reversals) in the Miocene and Pliocene. In southern England the sedimentary fills of the London and Hampshire basins include fluvial deposits amongst the dominantly marine formations, within which can sometimes be recognized the precursors of modern drainage. Thus the Reading Beds (now part of the Lambeth Group) of southern Buckinghamshire include gravel facies in which clasts derived from outside the London Basin have been attributed to drainage from Oxfordshire through an early breach in the Chalk of the northern synclinal limb (cf. White, 1906; Wooldridge and Gill, 1925). Whether this was coincident with the single modern breach at Goring, through which all Pleistocene Thames drainage has been routed (Bridgland, 1994; Westaway, 2011), is uncertain. The Hampshire Basin is the primary focus of the paper in the special issue by Newell (2014/this issue), who reviews its fluvial environments within the wider context of climatic and sea-level fluctuation during the Palaeogene (see also Plint, 1983; Edwards and Freshney, 1987; Gibbard and Lewin, 2003; Newell and Evans, 2011) and of the more widespread Palaeogene Anglo-Paris-Belgian depo-centre(s), these being parts of an extended early North Sea basin (King, 2006; Newell, 2014/this issue), probably formed as a 'failed arm' during Atlantic rifting (Evans, 1990; Cameron et al., 1992; Bridgland, 2002; King, 2006). Hamblin, meanwhile, provides an updated description and interpretation of a set of Palaeogene deposits from yet further west, now capping the Haldon Hills east of Dartmoor. These record fluvial drainage eastwards from Dartmoor towards the Hampshire Basin, including probable correlatives of the Reading and Poole formations as recognized in that basin (Hamblin, 2014/this volume).

Britain generally has a significant hiatus between its earlier Cenozoic fluvial records and the Pleistocene sequences that are much more readily comparable with modern river systems. This hiatus can be attributed to considerable erosion following the cessation of the basin infill that is almost invariably represented by the Palaeogene–Neogene sedimentary record and the concomitant initiation of incision into the basin sediments and other substrates that is a characteristic of the Quaternary on land. This inversion of the depocentres that were commonplace in the earlier Cenozoic is indeed a worldwide phenomenon and is well recorded by fluvial archives from the Late Cenozoic–Quaternary (see Bridgland and Westaway, 2014/this issue). In Mediterranean regions the basin-fill sequences extend to the Miocene and even, in places, the Pliocene, with basin inversion occurring during the Late Cenozoic, quite possibly as a response to global cooling and the uplift that might have resulted from this by way of erosional isostasy (Bridgland and Westaway, 2014/this issue).

## 5. Quaternary rivers and geomorphology

The impressive increase in data on Quaternary fluvial deposits, and on interpretation of drainage history there-from, arising during the first 50 years of the Quaternary Research Association (QRA), and documented extensively in the publications of that organization, became apparent to the first author when he undertook a review in celebration of the half-century anniversary (Bridgland and Allen, 2014). This recent contribution, dominantly but not exclusively about Britain, can inform the reader and need not be repeated in detail here. It points to various divisions in such archives, in particular between longer records from beyond the maximum extent of the Quaternary glaciations and the surprisingly rich and topographically elevated (terraced) sequences from within the last glacial limit (cf. Bridgland and Westaway, 2014/this issue). It also documents the role of the Fluvial Archives Group (FLAG), initiated in 1996 as a working group of the QRA and continuing as an international collaboration of fluvial specialists (e.g., Vandenberghe et al., 2010; Cordier et al., in press; both the QRA and FLAG were cosponsors of the Exeter meeting). Work carried out under the auspices of FLAG, particularly in the form of sequential International Geological Conservation (Geoscience) Programme (IGCP) projects, provided a wealth of new data from which comparisons have been possible between records in different parts of the world, as described in this issue by Westaway and Bridgland (2014). Another notable division of Quaternary fluvial research is that devoted to Holocene records, including those that can be classified as 'geoarchaeology'; much of the emphasis here, beyond documenting depositional records, has been on distinguishing natural influences on fluvial activity, and particularly Holocene climatic variation, from the impacts of human kind, through direct exploitation of and interference in river channels to indirect effects from land-use changes (e.g., Brown, 2002; Macklin et al., 2006). In particular, it has been realised that the Holocene alluvium that is so characteristic of the Holocene cover of valley floors is largely a product of increased fine-grained sediment supply, as a result of ploughing and other disturbance of valley sides and catchment surfaces (Brown, 1997, 2009; Hudson-Edwards et al., 1999). The deposition of alluvium, which began, along with farming, in the Neolithic, thus has no interglacial analogues. Much later came the disturbance of selected river valleys as a result of industrial uses, particularly metal mining, another rich source of research data (Beer and Scrivener, 1982; Macklin et al., 1997; Gerrard, 2000; Coulthard and Macklin, 2003).

## 6. Fluvial archives as repositories

Fluvial archives are of clear importance as records of conditions on land during geological history. Of course they can indicate much more about lowland (valley-floor) conditions than they can about other environments, some of which, given that they invariably coincide with erosion rather than deposition, will be poorly if at all represented in the geological record. Thus, as Smektala et al. (2014/this issue) report, from the emergence of life on land, rocks of fluvial origin are important sources terrestrial fauna and flora. Also in the present volume, Hart (2014/this issue) describes the context and taphonomy of a specimen of juvenile rhynchosaur from the Triassic Otter Sandstone of East Devon. Fluvial sediments are also important amongst the Cenozoic continental records from which are documented the rise of mammals following the demise of the dinosaurs at the end of the Mesozoic Era (e.g., Whitmore, 1962; Emry, 1975; Eberle and Lillegraven, 1998; Tedford et al., 2013). In the fluvio-lacustrine sequence of the Siwaliks, in the Himalayan foreland, an important vertebrate record includes fossils of hominin ancesters (Johnson et al., 1983). Fine-grained floodplain sediments can also preserve trace fossils (e.g., Pollard, 1985), a classification that in the Pleistocene includes the artefacts that record the presence of early humans (Wymer, 1999; Bridgland, 2000; Bridgland et al., 2006; Mishra et al., 2007). Numerically these artefacts are dominated by waste material from the manufacture of stone tools, although the tools themselves represent a conspicuous and highly informative body of data. In the Pleistocene, the cyclic nature of the fluvial record, largely in the form of river terraces, can be used as a framework for the chronology of the terrestrial record, bridging between the restricted windows of time within which geochronological (numerical) dating is possible (Bridgland et al., 2004). Fossils, and even archaeology, where present, can assist in establishing this framework.

## 7. Discussion and synthesis

The Geologists Association meeting in 2012 was a rare opportunity for workers specialising in different geological periods to come together and compare data, the common theme being the depositional environment rather than geological system. Having celebrated the aggregation of data on fluvial archives from different geological systems for the Exeter meeting, this editorial overview has thus far been organized using those same systems. It is perhaps worth emphasizing here some overarching principles that arise from reviewing the record of the fluvial environment throughout geological time: principles that underpin much of the research on the different elements but are rarely examined specifically.

First, not only can fluvial depositional environments never represent more than a fraction of the terrestrial domain, they can not indeed be expected to represent all aspects of the contemporaneous fluvial environment. Much of this is readily apparent. The higher reaches of most river systems are in upland areas where erosion holds sway and any deposits formed are highly ephemeral. Furthermore, only those fluvial sediments laid down in largely subsiding depocentres, where thick accumulations build up, are likely to be represented in the long-term geological record. Such environments are not wholly representative of fluvial environments at the present day, although they may have been more common during some parts of the geological past (cf. see above; Bridgland and Westaway, 2014/this issue); characterized by large flat plains, often drained by multiple river systems, as with the Pannonian Basin of Hungary (Gábris and Nádor, 2007), they can scarcely even be termed valleys.

The progressive subsidence of such basins ensures that some of them persist over lengthy intervals of geological time. Commonly initiated by tectonic controls, this persistence will be enhanced by the positive feedback of sedimentary isostasy. Nowhere is this exemplified more impressively than the foreland basins of the great mountain systems, most impressive of all being the Himalayan foredeep, which holds, in the Neogene Siwalik Group (see above) and its successors, a >4 km thick record of ~13 Ma of fluvial evolution (Keller et al., 1977; Sinha et al., 2007).

Also persistent over long periods of geological time are the great river systems that occupy the world's great rift systems, the aulacogans or failed arms of continental rifting and ocean formation (cf. Summerfield, 1991). These systems, which occur along passive continental margins, coincide with many of the Earth's largest rivers (cf. Burke and Dewey, 1973; Potter, 1978; Bridgland, 2002), including the Amazon (Potter, 1997), Rhine (Reugg, 1994) and Mississippi, the latter seemingly involving reactivation of rifting from an earlier oceanic (Iapetus) cycle (Braille et al., 1986). The modern Bristol Channel lowland can be seen to have its origin in a much older rift system (Kamerling, 1979; Nemčok et al., 1995; Belayneh and Cosgrove, 2010) that was utilized by the Triassic river system that deposited parts of the NRS (see above). This linkage between fluvial systems and plate tectonics is underlined by the relation between the great continental systems of the ORS and NRS and mountain building phases. The cycles of collisional mountain building and subsequent collapse gave rise to these Palaeozoic and Mesozoic fluvial systems, the ORS relating to the Caledonian Orogeny and the NRS to the Variscan.

**8. Contents of the special issue**

The contributions to the special issue provide a rich coverage of fluvial archives through the geological record. They are arranged in a broadly chronological order of geological system, even where there is a strong thematic component to the contribution. Thus the first paper, by Geraint Owen and Mauricio Santos, concerns fluvial rocks from the Precambrian, in this case the familiar Torridonian redbeds of NW Scotland. There is description of the characteristics, history of research and interpretation of these pre-vegetation fluvial deposits, before the paper moves on to a thematic review of the soft-sediment deformation features they display, arising from research by the authors that integrates the analysis of such phenomena with sedimentology, with the aim of improving understanding of pre-vegetation fluvial palaeoenvironments. The important changes brought about by the earliest vegetation are thoroughly explored in the following paper, by Martin Gibling et al., entitled '**Palaeozoic co-evolution of rivers and vegetation: a synthesis of current knowledge**'. This contribution, which reviews the changes in fluvial style and the geometry of resultant sediment bodies that came about with the development of early plants on the Earth's surface, emanates from Martin's keynote address at the Exeter conference, in which these themes were explored. The next paper is also on the Palaeozoic; it is by Susan Marriott and Robert Hillier, on '**Fluvial style in the Lower Old Red Sandstone: examples from southwest Wales, UK**'. Despite the name, the system in the research area is dominated by muds. The authors review the sediment geometry, of sands and conglomerates as well as the dominant muds, and are able to make inferences about aspects of Siluro-Devonian climate and palaeogeography.

Moving directly from the Old to the New Red Sandstone, the somewhat quirky title of Geoff Warrington's paper '**Inside Mid-Triassic fluvial deposits in Cheshire**' arises from the fact that it documents evidence from underground mining in an area where Triassic fluvial and aeolian graben-fill sediments are host to ore bodies, and were mined primarily for copper. The availability of this underground evidence, partly as a result of SSSI designation, makes up for the poor surface exposure of these beds. As the paper elucidates, the comprehensive examination of exposures in underground galleries can provide a useful insight into sediment geometry. The NRS is also the context for the next contribution, by Malcolm Hart on '**The 'Otter Sandstone River' of the mid-Triassic and its vertebrate fauna**'. As well as providing descriptions and palaeo-geographical interpretations of the fluvial Triassic formations of East Devon, the location of the GA excursion in 2012, Hart describes the occurrence of important rhynchosaur fossils from these deposits: terrestrial animals that lived and died within the contemporaneous fluvial environment. That theme is continued, albeit from a later part of the Mesozoic and from a different geographical region, in the next paper, by Franck Smektala, Eric Buffetaut and Jean-François Deconinck, entitled '**Rivers as repositories for fossil vertebrates : a case study from the Upper Cretaceous of southern France**'. This is essentially a study of taphonomy and sedimentological context, as is fitting for the special issue; it has shown that deposition resulted from flood events in a braided-river environment and under a tropical climatic regime.

Next there are two papers, both from BGS officers, on the Palaeogene of southern England. In the first, by Andrew Newell and entitled '**Palaeogene rivers of southern Britain: climatic extremes, marine influence and compressional tectonics on the southern margin of the North Sea**', the author describes and discusses the fluvial systems initiated in this area by the sea-level decline as global climate cooled following the peak of the Late Cretaceous. The preserved record represents river systems in lowland coastal regions influenced by sea-level fluctuation and by Alpine tectonic activity. If the deposits and geological context described by Newell are rather typical of fluvial archives within the long-term geological record, that is less obviously the case for the Palaeogene Haldon Formation of South Devon, the topic of the next paper, by Richard Hamblin. This formation, interpreted as a sequence of residual, fluvial and periglacial gravels and clays, including a possible lacustrine component, capping the Haldon Hills, South Devon. The comparable disposition of these deposits to high-level gravel outliers representing the earliest drainage of southern Britain, such as the 'pebble gravels' of the London Basin (Wooldridge, 1927; Hey, 1965; Bridgland, 1994), is perhaps misleading, however; Hamblin suggests that the Haldon Hills were uplifted quite late within the Pleistocene, implying that the deposits now capping them were part of the fill of a once more extensive (Wessex) basin. The author also explores some of the difficulties in applying formal lithostratigraphical nomenclature to such deposits, which have been significantly modified and partly remobilized during the Pleistocene, as a result, in particular, of periglacial activity. These are issues that anticipate the thinner and more superficial sediments dating from the Late Cenozoic–Quaternary, with the transition being made between solid geology and what was formerly termed 'drift'. This transition is highly relevant to the content of the first of the final group of papers, that group being devoted to Quaternary fluvial archives.

The final group of papers starts with a review, by David Bridgland and Rob Westaway, of Pleistocene fluvial records and their implications for an understanding of landscape evolution. This paper, which is copiously illustrated with case-study examples, goes some way to bridging the gap between solid and more superficial geology, since it notes the contrast between accumulating fluvial sediment stacks in subsiding basins and the emphemeral terrace deposits that are widespread representatives of rivers in the Pleistocene, and are linked with geomorphological landforms. They also suggest that subsiding 'depo-centre' basins occurred my widely in other parts of the geological record, including the warmer Miocene and Pliocene, immediately before the Pleistocene glaciations commenced, with a potential connection between changing global climatic patterns and such large-scale landscape evolutionary changes. This paper combines separate presentations by the two authors as part of the Exeter meeting, by Bridgland on the fluvial records and their global patterns and varying styles of occurrence, and by Westaway, on the linkages between these fluvial archives and different crustal types and crustal activity, the latter being an important explanatory contribution that arises from his mathematical modelling of patterns of river terrace distribution in different systems worldwide. An important conclusion from this review is that, by way of coupling between crustal activity and surface processes (including climate), the Pleistocene glaciations have resulted in changes of more far-reaching effect than the immediate results of erosion and deposition by the ice sheets that formed during glacial maxima.  The following paper brings such comparisons to bear on a much shorter timescale, being a detailed account of the outcomes of the most recent of the Pleistocene glaciations in the Canadaian Arctic in respect of a particular fluvial system. It is by Peter Worsley and is entitled '**Pattern of paraglacial fluvial landscape change on continuous permafrost around the 'Twin Creeks' catchment post 15 ka BP, south-western Banks Island, western Canadian Arctic**'.  This describes the development of drainage in a small tundra catchment from deglaciation of the last ice sheet to the Late Holocene, with its early post-glacial evolution, in particular, being heavily affected by the aftermath of glaciation ('paraglacial' effects).  Finally, the contribution by Jenny Bennett and Tony Brown takes the coverage of the special issue forward to the most recent geological interval, the Holocene, taking as a case study the River Exe, which drains into the English Channel through Exeter.  This paper links a presentation at the conference with the final part of the field excursion, when the floodplain at Brampford Speke was visited, with Middle–Late Holocene palaeochannels (Bennett et al., 2011) visible from their preserved morphology (for which this is a Site of Special Scientific Interest), emphasized on the day of the visit by ponded floodwater.  The Bennett and Brown paper draws attention to the use of archaeological reports and historical archives as a means for reconstructing past fluvial  course and activity in urban areas.

**References**


Algeo, T.J., Scheckler, S.E., 1998. Terrestrial-marine teleconnections in the Devonian: links between the evolution of land plants, weathering processes, and marine anoxic events. Philosophical Transactions of the Royal Society of London B 353, 113–130.

Allen, J.R.L., 1974. Studies in fluviatile sedimentation: implications of pedogenic carbonate units, Lower Old Red Sandstone, Anglo-Welsh outcrop. Geological Journal 9, 181–207.

Allen, P., 1959. The Wealden Environment: Anglo-Paris Basin. Philosophical Transactions of the Royal Society of London B 242, 283–346.

Allen, P., 1981. Pursuit of Wealden models. Journal of the Geological Society, London 138, 375–405.

Alley, N.F., Frakes, L.A., 2003. First known Cretaceous glaciation: Livingston Tillite Member of the Cadna-owie Formation, South Australia. Australian Journal of Earth Sciences 50, 139–144.

Belayneh, M., Cosgrove, J.W., 2010. Hybrid veins from the southern margin of the Bristol Channel Basin, UK. Journal of Structural Geology 32, 192–201.

Beer, K.E., Scrivener, R.C., 1982. Metalliferous mineralisation. In: The Geology of Devon (E.M. Durance, D.J.C. Laming, Eds.). University of Exeter, pp.117–147.

Bennett, J.A., Brown, A.G., Schwenninger, J.-L., Rhodes, E.J., 2011. Holocene channel changes and geoarchaeology of the Exe River, Devon, UK, and the floodplain paradox. In:

Geoarchaeology, Climate Change, and Sustainability: Geological Society of America Special (Brown, A.G., Basell, L.S., Butzer, K.W., Eds.), pp. 135–152.

Benton, M.J., 2005. When life nearly died: the greatest mass extinction of all time. Thames & Hudson, London.

Benton, M.J., Hart, M.B., Clarey, T., 1993. A new rhynchosaur from the Middle Triassic of Devon. Proceedings of the Ussher Society 8, 167–171.

Braille, L.W., Hinze, W.J., Keller, G.R., Lidiak, E.G., Sexton, J.L., 1986. Tectonic development of the New Madrid Rift Complex, Mississippi Embayment, North America. Tectonophysics 131, 1–21.

Bridgland, D.R., 1994. Quaternary of the Thames. Geological Conservation Review Series 7, Chapman & Hall, London.

Bridgland, D.R., 2000. River terrace systems in north-west Europe: an archive of environmental change, uplift and early human occupation. Quaternary Science Reviews 19, 1293–1303.

Bridgland, D.R., 2002. Fluvial deposition on periodically emergent shelves in the Quaternary: example records from the shelf around Britain. Quaternary International 92, 25–34.

Bridgland, D.R., Allen, P., 2014. Quaternary fluvial systems and river terraces. In: The History of the Quaternary Research Association (J.A. Catt & I. Candy, Eds), Quaternary Research Association, London, pp. 249–300.

Bridgland, D.R., Maddy, D., Bates, M., 2004. River terrace sequences: templates for Quaternary geochronology and marine-terrestrial correlation. Journal of Quaternary Science 19, 203–218.

Bridgland, D.R., Antoine, P., Limondin-Lozouet, N., Santisteban, J.I., Westaway, R., White, M.J., 2006. The Palaeolithic occupation of Europe as revealed by evidence from the rivers: data from IGCP 449. Journal of Quaternary Science 21, 437–455.

Brown, A.G., 1997. Alluvial Geoarchaeology: Floodplain Archaeology andEnvironmental Change. Cambridge University Press.

Brown, A.G., 2002. Floodplain landscapes and archaeology: fluvial events and human agency. Journal of Wetland Archaeology 2, 89–104.

Brown, A.G., 2009. Colluvial and alluvial response to land use change in Midland England: an integrated geoarchaeological approach. Geomorphology 108, 92–106.

Burke, K., Dewey, J.F., 1973. Plume-generated triple junctions: key indicators in applying plate tectonics to old rocks. Journal of Geology 81, 406–433.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffery, D.H., Lott, G.K., Bulat, J., Harrison, D.J., 1992. The geology of the western English Channel and its western approaches. British Geological Survey, United Kingdom Offshore Regional Report. HMSO, London, 93pp.

Channel, J.E.T., McCabe, C., Woodcock, N.H., 1992. An Early Devonian (pre-Acadian) magnetization component recorded in the Lower Old Red Sandstone of South Wales (UK). Geophysical Journal International 108, 883–894.

Cordier, S., Bridgland, D., Vandenberghe, J., Harmand, D., in press. Fluvial archives from past to present. Boreas.

Corenblit, D., Steiger, J., 2009. Vegetation as a major conductor of geomorphic changes on the Earth surface: toward evolutionary geomorphology. Earth Surface Processes and Landforms 34, 891–896.

Coulthard, T.J., Macklin, M.G., 2003. Modelling long-term contamination in river systems from historical metal mining. Geology 31, 451–454.

Davies, N.S., Gibling, M.R., 2010a. Cambrian to Devonian evolution of alluvial systems: The sedimentological impact of the earliest land plants. Earth-Science Reviews 98, 171–200.

Davies, N.S., Gibling, M.R., 2010b. Paleozoic vegetation and the Siluro-Devonian rise of fluvial lateral accretion sets. Geology 38, 51–54.

De Wit, M.C.J., 2004. The diamondiferous sediments on the farm Nooitgedacht (66), Kimberley South Africa. South African Journal of Geology 107, 477–488.

Dott, R.H., 2003. The importance of eolian abrasion in supermature quartz sandstones and the paradox of weathering on vegetation-free landscapes. Journal of Geology 111, 387–405.

Eberle, J.J., Lillegraven, J.A., 1998. A new important record of earliest Cenozoic mammalian history: Eutheria and paleogeographic/biostratigraphic summaries. Rocky Mountain Geology 33, 49–117.

Eberth, D.A., 2005. The geology. In: Dinosaur Provincial Park: A Spectacular Ancient Ecosystem Revealed (Currie, P.J., Koppelhus, E.B., Eds.), Indiana University Press, Bloomington and Indianapolis, pp. 54–82.

Edwards, D., Richardson, J.B., 2004. Silurian and Lower Devonian plant assemblages from the Anglo-Welsh Basin: a palaeobotanical and palynological synthesis. Geological Journal 39, 375–402.

Edwards, R.A., Freshney, E.C., 1987. Lithostratigraphical classification of the Hampshire Basin Palaeogene Deposits (Reading Formation to Headon Formation). Tertiary Research 8, 43–73.

Edwards, R.A., Scrivener, R.C., 1999. The geology of the country around Exeter. Memoir of the British Geological Survey, Sheet 325 (England and Wales).

Els, B.G., 1990.Determination of some palaeohydraulic parameters for a fluvial Witwatersrand succession. South African Journal of Geology 93, 531–537.

Emry, R.J., 1975. Revised Tertiary Stratigraphy and Paleontology of the Western Beaver Divide, Fremont County, Wyoming. Smithsonian Contributions to Paleobiology 25, Smithsonian Institution Press, Washington.

Eriksson, P.G., Cheney, E.S., 1992. Evidence for the transition to an oxygen-rich atmosphere during the evolution of red beds in the Lower Proterozoic sequences of southern Africa. Precambrian Research 54, 257–269.

Eriksson, P.G., Bumby, A.J., Brümer, J.J., van der Neut, M., 2006. Precambrian fluvial deposits: enigmatic palaeohydrological data from the c. 2–1.9 Ga Waterberg Group, South Africa. Sedimentary Geology 190, 25–46.

Evans, C.D.R., 1990. The geology of the western English Channel and its western approaches. British Geological Survey, United Kingdom Offshore Regional Report. HMSO, London, 93pp.

Fuller, A.O., 1985. A contribution to the conceptual modelling of pre-Devonian fluvial systems. Transactions of the Geological society of South Africa 88, 189–194.

Gábris, G., Nádor, A., 2007. Long-term fluvial archives in Hungary: response of the Danube and Tisza rivers to tectonic movements and climatic changes during the Quaternary: a review and new synthesis. Quaternary Science Reviews 26, 2758–2782.

Gerrard, S., 2000. The early British tin industry. Tempus, Stroud, 160pp.

Gibbard, P.L., Lewin, J., 2003. The history of the major rivers of southern Britain during the Tertiary. Journal of the Geological Society, London 160, 829–845.

Gibling, M.R., Davies, N.S., 2012. Palaeozoic landscapes shaped by plant evolution. Nature Geoscience, DOI:10.1083/NGEO1376.

Gibling, M.R., Nanson, G.G., Maroulis, J.C., 1998. Anastomosing river sedimentation in the Channel Country of central Australia. Sedimentology, 45, 595–619.

Hey, R.W., 1965. Highly quartzose pebble gravels in the London Basin. Proceedings of the Geologists' Association 76, 403–420.

Hofmann, A. Dirks, P.H.G.M., Jelsma, H.A., 2002. Late Archaean clastic sedimentary rocks (Shamvaian Group) of the Zimbabwe craton: first observations from the Bindura–Shamva greenstone belt. Canadian Journal of Earth Sciences 39, 1689–1708.

Hone, D.W.E., Benton, M.J., 2008. A new genus of rhynchosaur from the Middle Triassic of South-West England. Palaeontology 51, 95–115.

Hudson-Edwards, K., Macklin, M.G.F., R., Passmore, D.G., 1999. Medieval lead pollution in the River Ouse at York, England. Journal of Archaeological Science 26, 809–819.

Johnson, G.D., Opdyke, N.D., Tandon, S.K., Nanda, A.C., 1983. The magnetic polarity stratigraphy of the Siwalik Group at Haritalyangar (India) and a new last appearance datum for Ramapithecus and Sivapithecus. Palaeogeography, Palaeoclimatology, Palaeoecology 72, 223–249.

Kamerling, P., 1979. The geology and hydrocarbon habitat of the Bristol Channel Basin. Journal of Petroleum Geology 2, 75–93.

Karpeta, W.P., 1993. Sedimentology and gravel bar morphology in an Archaean braided river sequence: the Witpan Conglomerate Member (Witwatersrand Supergroup) in the Welkom Goldfield, South Africa. In: Braided Rivers (Best, J.L., Bristow, C.S., Eds.), Geological Society Special Publication No. 75, pp. 369–388.

Keller, H.M., Tahirkheli, R.A.K., Mirza, M.A., Johnson, G.D., Johnson, N.M., Opdyke, N.D., 1977. Magnetic polarity stratigraphy of Upper Siwalik deposits, Pabbi Hills, Pakistan. Earth and Planetary Science Letters 36, 187–201.

Leveridge, B.E., Hartley, A.J. 2006. The Variscan Orogeny: the development and deformation of Devonian/Carboniferous basins in SW England and South Wales. In: Brenchley, P.J., Rawson, P.F. (Eds.), The geology of England and Wales 2nd edition. The Geological Society, London, pp. 225–255.

King, C., 2006. Palaeogene and Neogene: uplift and a cooling climate. In: Brenchley, P.J., Rawson, P.F. (Eds.), The geology of England and Wales 2nd edition. The Geological Society, London, pp. 395–428.

Macklin, M.G., Hudson-Edwards, K., Dawson, E.J., 1997. The signifi cance of pollution from historic mining in the Pennine orefields on river sediment contaminant fluxes to the North Sea. Science of the Total Environment 194–195, 391–397.

Macklin, M.G., Benito, G., Gregory, K.J., Johnstone, E., Lewin, J., Michczynska, D.J., Soja, R., Starkel, L., Thorndycraft, V.R., 2006. Past hydrological events in the Holocene fluvial record of Europe. Catena 66, 145–154.

McVicar-Wright, S.E., 2014. The application of automated mineralogy to the provenance study of red bed successions: a case study from the Permo-Triassic of SW England. Submitted PhD thesis. University of Exeter.

Marriott, S.B., Wright, V.P., 1993. Palaeosols as indicators of geomorphic stability in two Old Red Sandstone alluvial suites, South Wales. Journal of the Geological Society, London 150, 1109–1120.

Miall, A.D., 1978. Lithofacies types and vertical profile models in braided river deposits: a summary. In: fluvial Sedimentology  (Miall, A.D., Ed.). Canadian Society of Petrolium Geologists Memoir 5, 597–604.

Mishra, S., White, M.J., Beaumont, P., Antoine, P., Bridgland, D.R., Howard, A.J., Limondin-Lozouet, N., Santisteban, J.I., Schreve, D.C., Shaw, A.D., Wenban-Smith, F.F., Westaway, R.W.C., White, T., 2007. Fluvial deposits as an archive of early human activity. Quaternary Science Reviews 26, 2996–3016.

Nanson, G.C., Jones, B.G., Price, D.M., Pietsch, T.J., 2005. Rivers turned to rock: Late Quaternary alluvial induration influencing the behaviour and morphology of an anabranching river in Australia's monsoon tropics. Geomorphology, 70, 398–420.

Nemčok, M., Gayer, R. 1996. Modelling palaeostress magnitude and age in extensional basins: a case study from the Mesozoic Bristol Channel Basin, UK. Journal of Structural Geology 18, 1301–1314.

Newell, A.J., Evans, D.J., 2011. Timing of basin inversion on the Isle of Wight: New evidence from geophysical log correlation, seismic sections and lateral facies change in the Palaeogene Headon Hill Formation. Proceedings of the Geologists' Association 122, 868–882.

Pazzaglia, F.J., Gardner, T.W., 1993. Fluvial terraces of the lower Susquehanna River. Geomorphology 8, 83–113.

Pazzaglia, F.J., Gardner, T., 1994. Late Cenozoic #exural deformation of the middle U.S. Atlantic passive margin. Journal of Geophysical Research 99, 12 143–12 157.

Plint, A.G., 1983. Sandy Fluvial Point-Bar Sediments from the Middle Eocene of Dorset, England, In: Collinson, J.D., Lewin, J. (Eds.), Modern and Ancient Fluvial Systems. Special Publication of the International Association of Sedimentologists, 6, pp. 355–368.

Pollard, J.E., 1985. *Isopodichnus*, related arthropod trace fossils and notostracans from Triassic fluvial sediments. Transactions of the Royal Society of Edinburgh: Earth Sciences 76, 273–285.

Potter, P.E., 1978. Significance and origin of big rivers. Journal of Geology 86, 13–33.

Potter, P.E., 1997. The Mesozoic and Cenozoic paleodrainage of South America: a natural history. Journal of South American Earth Sciences 10, 331–344.

Prave, A.R., 2002. Life on land in the Proterozoic: Evidence from the Torridonian rocks of northwest Scotland. Geology 30, 811–814.

Rasmussen, B., Buick, R., 1999. Redox state of the Archean atmosphere: Evidence from detrital heavy minerals in ca. 3250–2750 Ma sandstones from the Pilbara Craton, Australia. Geology 27, 115–118.

Rawson, P.F., 2006. Cretaceous sea levels peak as the North Atlantic opens. In: Brenchley, P.J., Rawson, P.F. (Eds.), The geology of England and Wales 2nd edition. The Geological Society, London, pp. 365–393.

Reugg, G.H.J., 1994. Alluvial architecture of the Quaternary Rhine–Meuse river system in the Netherlands. Geologie en Mijnbouw 72, 321–330.

Schumm, S.A., 1968. Speculations concerning paleohydrologic controls of terrestrial sedimentation. Geological Society of American Bulletin 79, 1573–1588.

Scrivener, R.C., Darbyshire, D.P.F., Shepherd, T.J., 1994. Timing and significance of crosscourse mineralization in SW England. Journal of the Geological Society, London 151, 587–590.

Sinha, R., Kumar, R., Tandon, S.K., Gibling, M.R., 2007. Late Cenozoic fluvial deposits of India: an overview. Quaternary Science Reviews 26, 2801–2822.

Stewart, A.D., 2002. The later Proterozoic Torridonian rocks of Scotland: their sedimentology, geochemistry and origin. Geological Society, London, Memoir 24.

Stoll, H.M., Schrag, D.P., 1996. Evidence for Glacial Control of Rapid Sea Level Changes in the Early. Cretaceous. Science, New Series 272, 1771–1774.

Summerfield, M.A., 1991. Global geomorphology. Longman, Harlow.

Tal, M., Paola, C., 2007. Dynamic single-thread channels maintained by the interaction of flow and vegetation. Geology, 35, 347–350.

Tedford, R.H., Zhan-Xiang Qiu, Flynn, L.J., 2013. Late Cenozoic Yushe Basin, Shanxi Province, China: Geology and Fossil Mammals: Volume I:History, Geology, and Magnetostratigraphy. Springer Science & Business Media, Dordrecht.

Tirsgaard, H., Øxnevad, I.E.I., 1998. Preservation of pre-vegetational mixed fluvio-aeolian deposits in a humid climatic setting: an example from the Middle Proterozoic Eriksfjord Formation, Southwest Greenland. Sedimentary Geology 120, 295–317.

Vandenberghe, J., Cordier, S., Bridgland, D.R., 2010. Extrinsic and intrinsic forcing on fluvial development: understanding natural and anthropogenic influences. Proceedings of the Geologists' Association 121, 107–112.

Waters, C.N., Davies, S.J., 2006. Carboniferous erosional basins, advancing deltas and coal swamps. In: Brenchley, P.J., Rawson, P.F. (Eds.), The geology of England and Wales 2nd edition. The Geological Society, London, pp. 395–428.

Went, D.J., 2005. Pre-vegetation alluvial fan facies and processes: an example from the Cambro-Ordovician Rozel Conglomerate Formation, Jersey, Channel Islands. Sedimentology 52, 693–713.

Westaway, R., 2011. The Pleistocene terrace staircase of the River Thame, central-southern England, and its significance for regional stratigraphic correlation, drainage development, and vertical crustal motions. Proceedings of the Geologists' Association 122, 92–112.
White, H.J.O. 1906. On the occurrence of quartzose gravel in the Reading Beds at Lane End, Bucks. Proceedings of the Geologists' Association 19, 371–377.

Whitmore, F.C., 1962. Review of Borisiak, A.A. and Beliaeva, E.I. Mestonak-hozhdeniya Tretichnykh nazemnykh mlekopita-yushchikh na Territorii SSSR (Tertiary terrestrial mammalian localities in the territory of the USSR): Akad. Nauk SSR, Trudy Paleontologicheskogo Instituta, vol. 15, no. 3, 115pp, 1948, in English translation by the American Geological Institute. International Geology Review 4, 863–864.

Wood, J., 1980. Epiclastic sedimentation and stratigraphy in the North Spirit Lake and Rainy Lake areas: a comparison. Precambrian Research 12, 227–255.

Wooldridge, S.W., 1927. The Pliocene history of the London Basin. Proceedings of the Geologists' Association 38, 49–132.

Wooldridge, S.W., Gill, D.M.C., 1925. The Reading Beds of Lane End, Bucks, and their bearing on some unsolved questions of London geology. Proceedings of the Geologists' Association 36, 146–173.

Wymer, J.J., 1999. The Lower Palaeolithic Occupation of Britain. Wessex Archaeology and English Heritage.