The development of fluvial sedimentology in some Devonian and Tertiary basins

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RESUMEN

En los últimos cuarenta años, los geólogos han realizado investigaciones sobre el relleno sedimentario de cuencas fluviales con un nuevo nivel de detalle suficiente para incluir sus trabajos bajo la denominación de «sedimentología». Todo ello ha dado lugar a un importante avance en el conocimiento de la morfología fluvial, la paleoecología y los paleosuelos. Un mayor conocimiento de estos rasgos locales, ha permitido situar la litoestratigrafía sobre una base más firme. Junto a los avances en bioestratigrafía, los estudios a escala de cuenca han conducido a avances en el conocimiento de los efectos producidos por la tectónica, los cambios climáticos y las oscilaciones del nivel del mar. Para el futuro se abren atractivas posibilidades en la mejora de la precisión estratigrafica basadas en el reconocimiento de efectos cíclicos de origen astronómico (Milankovich). En general, los trabajos futuros tendrán que ser más pluridisciplinares, haciendo uso de métodos electrónicos de almacenaje, tratamiento y presentación de la gran cantidad de datos que tendrán que ser recogidos y analizados cada vez de forma más creciente.

Palabras clave: Sedimentación fluvial, Sedimentología comparada

ABSTRACT

Over the last forty years geologists have been investigating the sedimentary fills of fluvial basins with a new level of detail, sufficient for them to call

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their work «sedimentology». This has resulted in greatly improved understanding of river morphology, palaeoecology and palaeosols. Greater understanding of these local features has put the lithostratigraphy on a firmer basis. Along with advances in bio-stratigraphy, basin-scale studies have led to advances in knowledge of the effects of tectonism, along with climate and sea-level changes. In future, exciting possibilities appear to exist of improved stratigraphic precision based on the recognition of astronomical (Milankovich) cyclic effects. Future work generally must be increasingly multidisciplinary, and make full use of electronic methods of storing, handling and presenting the large amounts of data that will increasingly have to be collected and analysed.

Key words: Fluvial sedimentation. Comparative sedimentology

I) INTRODUCTION

When the name «sedimentology» was first used, about forty years ago, it represented a new desire to understand the detailed processes of sediment transport and deposition. Some of the geologists who first took up the challenge of working, in this new detailed way, concentrated on outcrops of river channel deposits. This was because knowledge of transport processes in river channels was more complete, at that time, than that of shallow- or deep-sea transporting processes.

My main object in this paper, is to consider the directions taken over the forty years of developing studies of fluvial basins. Detailed sedimentological work has undoubtedly succeeded in providing more complete interpretations of the hydraulics and morphology of ancient rivers, but what more has been achcived in terms of broader geological considerations? To what extent have our advances in river interpretation been accompanied by new understanding of the tectonic, climatic, sea-level and ecological settings of the basins? Can we recognise new directions for the future?

The first part of this paper provides a personal overview of the way that knowledge of certain fluvial deposits has developed over the last forty years. The deposits I have selected are those known best to me; they are from three basins of Devonian age, and from two basins of Tertiary age. This basin-by-basin survey (Figs. 1-3) will suggest that various approaches developed in the different cases did so partly because of the different outcrop situations.

2. TRENDS IN THE SEDIMENTOLOGICAL STUDY OF SELECTED BASINS

2a. Lower Old Red Sandstone (Late Silurian and Early Devonlan) of the Anglo-Weish basin

This area became a classic of the early days of fluvial sedimentology, largely because of the work of J.R.L.Allen, only a few of whose papers are quoted here. Allen used a rigorous review(Allen, 1965) of available literature on present-day river sedimentation, as a basis for the interpretation of the fluvial outcrops of the Old Red Sandstone of the Anglo-Welsh basin. These sediments had not previously been examined in detail as sediments, although their early vertebrate fossils were famous. Outcrops are largely restricted to small, discontinuous, stream sections, and much of Allen's earlier work consisted of the painstaking construction of sedimentological logs, with very little scope for lateral tracing.

Allen (1964) interpreted the sandstone-mudstone alternations (cyclothems, cycles) that were such a feature of his logs in terms of episodes of channel and overbank deposition, and speculated that the alternations might represent 1) simple wandering of rivers (autocyclicity), 2) varying base level of the contemporaneous sea, or 3) varying tectonic activity in the sediment source area. In later work, Allen (1983) helped to establish the dominant role of the wandering, autocyclic or avulsive behaviour of the rivers in generating this sort of cyclicity, and found no evidence of the influence of episodic sea-level or source-area tectonics on a cycle-by-cycle scale.

One generalisation that came from some of this earlier work concemed the morphology of the rivers that produced these cyclic successions. Because of the general, present-day, occurrence of muddy banks in meandering (high-sinuosity) rivers, it was proposed (Allen, 1965) that sandstone-mudstone alternations (or cycles) were likely to be typical of these types of rivers. Over the years, this was subsequently shown to be untrue (Allen, 1983; Moody-Stuart, 1966; Friend, 1983., Willis, 1993a). The identification of the deposits of meandering or of braided rivers requires good two-dimensional outcrops, and it was recognised early on (Allen, 1964) that suitable outcrops were particularly rare in the Anglo-Welsh basin.

One other feature of the morphology of the rivers that produced the cyclic sequences could be determined by using the thickness of the channel-fill, sandstone members, as a direct measure of the channel depth. In this way, Allen (1983) was able to suggest a discharge of 3000 m^3/s as a typical bank-full figure for the proximal Brownstones Formation. Inspection of other logs measured by Allen (Fig I a; Allen, 1964, 1974) suggests that most of the Lower Old Red Sandstone rivers of this basin had smaller discharges than this.

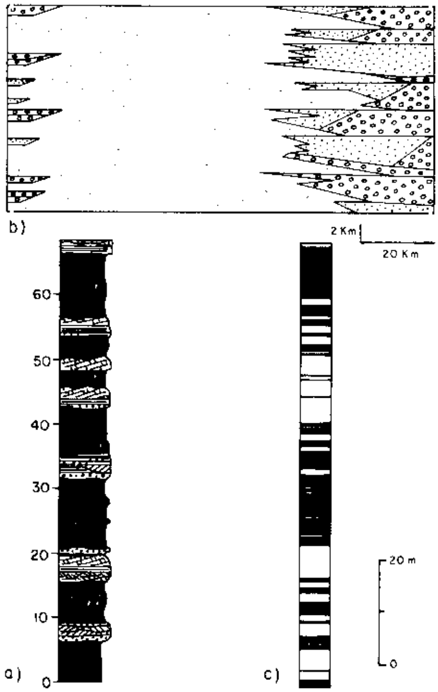


Fig 1.—Examples of architectural (cycle) analysis from the Old Red Sandstone basins. a) log of stream section, Ditton Group, Anglo-Welsh Basin, black shading indicates overbank mudstones, with pedogenic concretionary carbonate layers, sandstones units are shown with an indication of their sedimentary structures (redrawn from Allen, 1974, Fig 28); b) hypothetical vertical-plane section, representing typical cyclic architecture in the north-west and south-east areas of the Wood Bay Formation outcrop area, Spitsbergen; sandstone units are indicated with stipple distinguishing between fine and medium sandstones; the centre of the basin and the material between the sandstones is mudstone (redrawn from Friend and Moody-Stuart, 1972, Fig 20); c) log of section, K 180, W. Rodebjerg, East Greenland, showing intervals of cross-stratified sandstone (white) interbedded with flat-bedded sandstone (black) in the Sandstone Association (redrawn from Friend at al, 1983, Fig 16).

Fig. 1.—Ejemplos de análisis arquitectónico (ciclo) en cuencas de la Old Red Sandstone. a) columna del Grupo Ditton, Cuenca Anglo-Galesa, el tono negro indica limos de overbank, con niveles pedogenéticos de concreciones carbonatadas, en las unidades de arenisca se indica su estructura interna (redelineado de Allen 1974, Fig.28); b) Corte hipotético plano-vertical, representando la arquitectura típica cíclica en las áreas Noroeste y Sureste de la zona de afloramiento de la Formación Wood Bay en Spitsbergen; las unidades de arenisca están representadas con punteado, distinguiéndose entre las de grano fino y medio; el centro de la cuenca y el material entre las dos areniscas son limos (redelineado de Friend y Moody-Stuart.1972, Fig. 20); c) columna del corte K 180,W. Rodebjerg, al Este de Groenlandia, mostrando los intervalos de areniscas con estratificación cruzada (blanco) intercaladas con areniscas planolaminadas (negro) en la Sandstone Association (redelineado de Friend et al. 1983, Fig. 16).

Allen's work in this basin also resulted in important advances in the study of palaeosols (fossil soils), which, when well-developed, contain zones enriched in calcium carbonate, locally called «cornstones», or more internationally, calcretes or caliches (Allen (1986), Marriott and Wright 1993). The presence of these palaeosols was taken to indicate warm, and seasonally-arid climatic conditions (Allen, 1983).

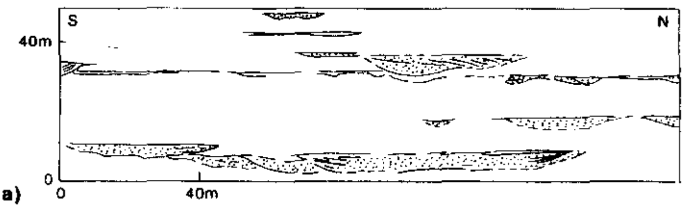
Not only did this work produce a new level of understanding of local aspects of the palaeoenvironments, but it was accompanied by systematic work that allowed a major reassessment of the regional geological setting of the deposits. Thorough work on detrital provenance, combined with systematic collection of palaeocurrent measurements confirmed the areal location of uplifting source area and subsiding basin. The AngloWelsh outcrop area was seen as one margin of a basin that thinned to the NW, and was supplied with sediment from an uplifting mountainous area that trended NE-SW, parallel to the major Caledonian orogen of the area (Fig 3a; Allen, 1974). However, the lack of good inland outcrops has, so far, made it impossible to distinguish discrete provenance or distributary systems in the basin (Fig 3a).

2b. Wood Bay Formation (Early-Middle Devonian) of Spitsbergen

This Formation is the most widely exposed of a succession of Late Silurian to Middle Devonian formations outcropping in a basin in these high Arctic islands. Before the studies reported here, much of the research interest had been focussed on the fossil vertebrate interest (Friend, 1961). Subsequent sedimentological work was strongly influenced by the broadly simultaneous work of J.R.L.Allen in the Anglo-Welsh basin (see above), although the difficulty of visiting the better outcrops imposed a rather different, reconnaissance strategy on the work.

In Spitsbergen, generally flat-lying sandstone-mudstone successions can be logged in many gully and ridge sections, but lateral tracing is frequently hindered by scree- or ice-cover.The typical sandstone-mudstone alternations (cycles) were interpreted(Friend & Moody-Stuart, 1972) as the result of avulsive alternations between channel and overbank episodes, as in the Anglo-Welsh basin. Again sandstone unit thickness could be used as an indicator of river channel depth, and palaeohydraulic flood estimates of up to $600m^3/s$ were made. In much of the Wood Bay Formation, the abundance of mudstone intervals was taken (mistakenly, see above) to imply meandering channel morphology, but the question of the channel morphology of the rivers needs to be reassessed on the basis of further field examination.

Calcic palaeosol horizons (Friend and Moody-Stuart, 1970), though recognised to be similar to those of the Anglo-Welsh basin, were clearly less strongly developed.



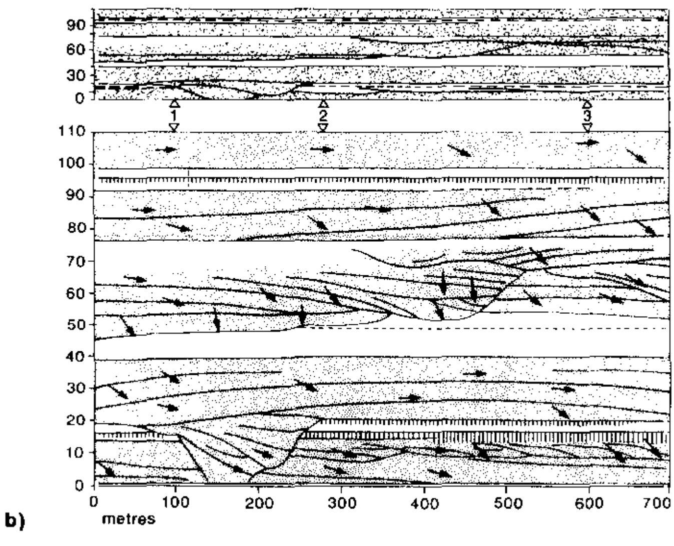


Fig 2.—Examples of architectural analysis from the Tertiary basins. a) discrete, channelfill, sandstone bodies (stippled) in mud-dominant overbank material (unmarked) of the Rio Flumen valley section, Ebro basin (redrawn from Friend at al, 1986); b) architectural analysis of major sandstone bodies (stippled) in Level C (near the top of the Nagri Formation), separated by unmarked mudstones with palaeosols (surfaces with vertical ticks) This bedding diagram (redrawn from Willis, 1993a) is presented in the upper part of the diagram without vertical exaggeration, and in the lower part with 4X vertical exaggeration. Arrows indicate sloping direction of sandstone surfaces, relative to the plane of the profile.

Fig. 2.—Ejemplos de análisis arquitectónico en cuencas Terciarias. a) cuerpos discretos de areniscas de relleno de canal (puntedo) incluidos en material de desbordamiento dominantemente limoso (blanco) del corte del valle del Rio Flumen, Cuenca del Ebro (redelineado de Friend et al. 1986); b) análisis de la arquitectura de cuerpos mayores de areniscas (punteado) en el Nivel C (próximo al techo de la Formación Nagri), separados por lutitas (sin trama) con paleosuelos (superficies con marcas verticales). Este diagrama de estratificación (redelineado de Willis, 1993a) se presenta en la parte superior sin exageración vertical, y en la parte inferior con exageración vertical 4x. Las flechas indican dirección de la inclinación de las superficies de areniscas, respecto al plano del corte.

The outcrops of the Wood Bay Formation occur between bounding fault systems that trend north-south, parallel to the Caledonian orogenic fold belts to the west and east. Systematic measurements of fluvial palaeocurrents, combined with new biostratigraphy, and provenance information from the sandstones show that the sediments were deposited in distinct fluvial distributary systems of characteristic sedimentation. The arrangement of the systems (Friend & Moody-Stuart, 1972) shows that the western boundary fault was active, to a limited extent, during sedimentation, but that there was no activity along the line of the larger eastern boundary fault(Fig 3b), which must have become active after sedimentation.

Although lithostratigraphic units both below and above the Wood Bay Formation provide evidence of marine influence, it has not been possible to establish any effects of global (eustatic) sea-level change on the general stratigraphic succession, but the lack of high-precision biostratigraphic dating means that any attempts would be highly speculative.

2c. Old Red Sandstone (Middle-Late Devonian), East Greenland

When a detailed sedimentological study began in this basin (Friend *et al.,* 1976; Friend *et al.,* 1983), much of the previous field-work had been concerned with the vertebrate fossils, which include, amongst other forms, fossils of the earliest known tetrapods. Other work had been concerned with the structural and tectonic complexity of the successions that contain several angular unconformities, as well as volcanic and plutonic igneous rocks.

As in the Spitsbergen basin, vertical logs can easily be measured in most parts of the East Greenland basin, but lateral tracing is frequently impossible due to scree, ice or fjord. The major cliff exposures neighbouring many of the fjords are often inaccessible on foot, although they can be studied from a helicopter (H. Olsen, 1990).

The sandstone-mudstone alternations (cycles) that are so characteristic of the Anglo-Welsh and Spitsbergen basins are only present very locally in East Greenland. The main formations consist either of mudstone-dominant lacustrine deposits, or of sandstone-dominant deposits, that would now be attributed to fluvial braid-plains. Because of the lack of obvious cycles, and the gradations in the sedimentary logs, a statistical classification by computer of log «samples»(each of arbitrary length of 10 m), were summarised in terms of the grain-size and sedimentary structures present. Some 31 classes of sample-types were distinguished using this approach. Further field-work on the sandstone-dominated successions(eg Fig I c) will undoubtedly yield palaeohydraulic estimates for the braid-plain material, but, little palaeohydraulic work was actually attempted.

Most effort was put into the regional analysis of the stratigraphy, which

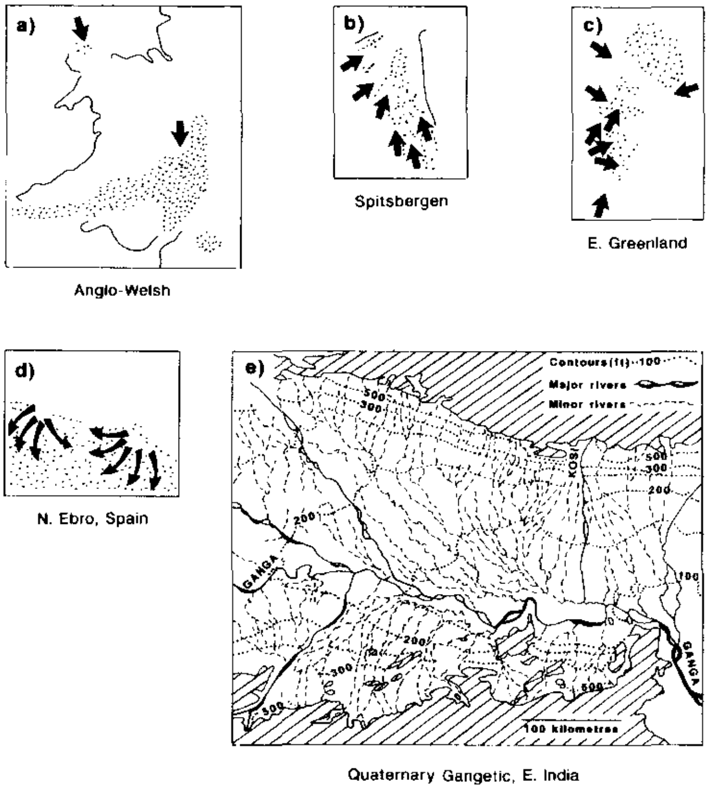


Fig 3.—Sketch maps, plotted for comparison on the same scale, showing different aspects of the five fluvial basins discussed in this paper. a) Anglo-Welsh basin (Early Devonian, redrawn from Cope et al., 1992); b) Wood Bay Formation, Spitsbergen (redrawn from Friend and Moody-Stuart, 1972, Figs 2 and 7); c) East Greenland, «Unit 5» (redrawn from Friend at al., 1983, Fig 27); Spain, northern edge of the Ebro basin (redrawn from Hirst & Nichols, 1986, Fig 9); e) Indo-Gangetic basin, showing only the East Indian segment of the basin, in order to give some idea of the scale of the basin which appears to be the present-day continuation of the fluvial basin in which the Siwalik deposits accumulated (redrawn from Willis, 1993b, Fig 14c).

Fig. 3.—Mapas esquemáticos, dibujados a la misma escala para su comparación, mostrando diferentes aspectos de las cinco cuencas fluviales discutidas en este trabajo. a) Cuenca Anglo-Galesa (Devónico inferior, redelineado de Cope et al. 1992); b) Formación Wood Bay, Spitsbergen (redelineado de Friend y Moody-Stuart, 1972, Fig 2 y 7); c) Groenlandia del Este, «Unit 5» (redelineado de Friend et al. 1983, Fig. 27); d) España, borde norte de la cuenca del Ebro (redelineado de Hirst y Nichols, 1986, Fig. 9); e) Cuenca Indo-Ganges, mostrando solamente el segmento de la cuenca correspondiente a la India Oriental, con el fin de dar idea de la escala de la cuenca, la cual parece ser la continuación actual de la cuenca fluvial en la que se acumularon los depósitos Siwalik (redelineado de Willis, 1993b, Fig. 14c).

was not easy because of lateral variations in many of the units, and the structural complexities already mentioned. However, systematic work on the fluvial palaeocurrents, and on the lithological variation, led to the definition of ten different time episodes (Friend at al., 1983). This revealed that the outcrop area contained fragments of two successive basins, overlapping but not coinciding in space; each basin started with fluvial sedimentation, often in discrete systems that were sometimes derived as fan-like radial systems from points on the basin margins (Fig.3c).

Further structural and sedimentological work has been carried out more recently on these Greenland sediments (H.Olsen, 1990; H.Olsen & Larsen, 1993). This work has resulted in important advances in both detailed sedimentology and in the general basin-scale geology. New evidence of regional synsedimentary folding has been recognised, in addition to the synsedimentary faulting previously known, and changes between fluvial and local developments of aeolian sedimentation have been attributed to climatic influences, although these may have been caused by changes of topography. Regular changes in meandering river hydraulics at one level have been interpreted (H. Olsen, 1990) as a response to astronomically forced (Milankovich) climatic cycles. This is one of the first claims that Milankovich effects have been preserved in fluvial deposits.

2d. Sariñena Formation (Oligocene-Miocene), Ebro Basin, Spain

The Ebro Basin is the Tertiary foreland basin that developed south of the Pyrenees, as the uplifted surface of the thickened orogenic crust spread southwards. Along the southernmost extent of Pyrenean thrusting, Mesozoic and Early Tertiary thrust sheets are in contact with Oligocene and Miocene fluvial sediments. Just south of this contact zone, river channel sandstone bodies, standing out clearly in profiles cut in the dominant overbank mudstones, show a clear pattern reflecting the evolving topography of the frontal thrusts (Hirst & Nichols, 1986). Two radial fluvial systems (Fig. 3d) formed with their apices where large river systems draining the axial zone of the Pyrenees were diverted around the 100 km. long emergent frontal ramp of the southernmost thrust sheet. At the same time as these large systems (radii between 40 and 60 km) formed, much smaller (radii a few km) fans of coarser (conglomeratic) material formed every few km. along the thrust ramp, draining only the ramp itself.

The sandstone bodies in the large fluvial systems were interpreted as channel plugs, or laterally-linked amalgamated channel plugs, and therefore provided evidence of the bank-full size and hydraulics of the channels (Friend *et al*, 1986: Hirst, 1991). These systems were obviously large terminal systems, because the channels died out altogether as the mud, carbonate and sulphate lacustrine sediment of the basin centre was approached.

These Ebro-basin studies contributed immediate knowledge of the geomorphology and hydraulics of the river systems. When coupled with systematic work on the palaeocurrents, and pebble and sandstone petrology, they provide a vivid picture of the interaction of regional and local tectonics in the source area with the sedimentation in the basin. The location of this study area on the active, compressional, margin of the foreland basin is clearly a major reason why these studies were dominated by tectonic considerations.

Careful pedogenic studies have shown only a limited degree of soil horizon formation (Marriott, S.B., personal communication, 1993), and at the moment, the best indications of palaeoclimatic seem to be based on interpretation of the rodent faunas. There is no evidence that the fluvial sediments of Oligocene and Miocene age were influenced by changes of sea-level, and all the general stratigraphic information suggests that the sea was excluded completely from the basin during this period.

2c. Siwalik Group (Miocene), northem Pakistan

The Siwalik Group is the youngest major bed-rock stratigraphic unit filling the foreland basin of the Himalayas. It has long been famous for its abundant fossil faunas, particularly its Miocene mammals. The foreland basin is still active and being filled at the present-day by the Indo-Gangetic river systems.

In parts of northern Pakistan, the semi-arid climate, recent uplift and relatively gentle folding, related to the continuing crustal convergence have produced exposures that are ideal for lateral tracing, as well as «vertical» logging. Techniques for analysing these excellent outcrops have been refined (Willis, 1993 a, b), and provided a new standard of success in palaeohydraulic and geomorphological analysis. For example (Willis, 1993 a), estimates of bank-full discharges of 310-3390 m^3/s, have been made for «Level C» (Fig. 2b), along with many other estimates of hydraulic and morphological variables.

At the same time, palaeocurrent data are available in great quantity from work of this intensive kind, and tend to show relatively uniform flow directions.

Attempts to examine basin-fill variation pose special problems in a basin some 2000km long and 1-200km wide. The major recent programme, directed by Dr. J.S.Bridge, involved a strategy of selecting three distinct, spaced areas, each for a PhD study of sedimentological detail. Palaeomagmetic reversal correlation has been used to provide information about regional trends of variation between the three localities.

The abundance of the fossil material and its evolutionary interest have led to consideration of the ecology of the fluvial environments generally, and also the taphonomy of the fossils (eg. Behrensmeyer, 1987). This has also led to extended research on the palaeosols (Behrensmeyer, Willis, & Quade, 1995), which provide frequent markers between the main channel sandstone bodies. The palaeosols normally show an upper decalcified horizon, and lower horizons with calcareous, iron or manganese nodules. Work on the oxygen and carbon isotopes of the soil carbonates has exciting potential in distinguishing types of plant cover, and thus ultimately the climate and terrestrial ecology of the floodplain (Quade and Cerling, 1995).

3. DIRECTIONS AND STRATEGIES OF FLUVIAL STUDIES

3a. Local palaeoenvironmental results

Considerable advances have been made in interpreting the hydrology and geomorphology of ancient rivers, using their deposits.

These advances have required the development of very time-consuming observational routines (eg. Willis, 1993a), involving high standards of systematic measurement. Much of this work also requires two, or even three-dimensional information, and is largely impossible if only one-dimensional logs can be measured.

The distinction between braided and meandering river morphologies that was often the end point of early sedimentological studies, must now be based on more careful analysis of channel sandstone-body internal structures, and cannot be based on the absence or presence of mudstone intervals.

In a remarkable paper, Cotter (1978) examined evidence for the idea of Schumm (1968) that the evolution of land vegetation might have been responsible for a change in the pattern of rivers during Phanerozoic time. Unfortunately, most of the literature available at the time of Cotter's work used the incorrect sand- or mud-dominant distinction for the different river patterns, so requires careful re-assessment. In this paper, my comparison of the three Devonian with the two Tertiary fluvial formations shows such major differences, due particularly to the tectonic settings of the basins, that it is not possible to recognise differences due to the expected increase in vegetation. Much more detailed work will be required before the influence of this change is likely to be detected.

Palaeosol work involving textural and mineralogical analysis has great potential for providing information on both local climates and ground-water conditions. The use of soil carbonate isotope work (Quade and Cerling, 1995) as an indicator of different vegetation types offers a powerful independent tool in local environmental studies.

3b. Basin-scale, regional results

The importance of the study of fluvial deposits in providing independent information on basin evolution is very clear from the examples cited. It is particularly important to stress that much of this information on the topography and kinematics of the crust can be dated with a precision that, though not as good as generally associated with marine sediments, is still likely to be better than that available from the structures or petrology of the basin surroundings.

In general, regional tectonic advances have come from fluvial deposits because of the systematic and intensive way that their palaeocurrents and petrology have been studied in recent years. This work has led to the recognition of discrete fluvial systems in which specific source areas have provided sediment to defined depositional areas. It may be that measurements of sediment flux in these relatively simple systems of direct sediment transfer can provide important information on rates of source area exhumation in future. When these data are combined with source area studies of exhumation using fission-track and other mineral dating methods, then well-constrained source area uplift histories will be reconstructed as well as basin-fill, subsidence histories.

Over the last twenty years, many basinal studies have been dominated by considerations of the influence of sea-level change. Much of this work, under the general heading of sequence stratigraphy has resulted in recognition of patterns of stratigraphic change that are best interpreted in terms of marine transgressions and regressions, However independent dating of these events is often not available to distinguish global (eustatic) changes from more local (broadly tectonic) change. Because of the common lack of precise dating in fluvial successions, few studies have, so far, been succesful in this, even where the fluvial deposits interdigitate with coastal sediments (eg. Shanley & McCabe, 1993). Of course, basins that lack clear evidence of river connections with the sea, eg. the Old Red Sandstone of East Greenland and the Oligocene and Miocene of the Ebro Basin, Spain, would not be expected to show evidence of any influence by sea-level change.

One research development that offers exciting possibilities is based on the recognition that some marine basins show evidence of Milankovich, astronomically-driven, climatic oscillations in sedimentation. When coupled with palaeomagnetic reversal stratigraphy, this work offers the prospect of dating some marine basin-fills with a precision of 20,000 years, back as far as the Miocene (Hilgen, 1995). It seems doubtful, at the moment, whether this work can be extended widely into the non-marine stratigraphic record, but the marine results are so promising, that much work will be directed to this end, and optimistic claims have already been made in Devonian fluvial strata, as mentioned in the Greenland review above (Olsen, 1990). Lacustrine sediments clearly have great potential for recording regular climatic oscillations, and claims that these are astronomically-driven , Milankovich-scale, 20- 100,000 year oscillations have been made for many lake basins as far back as Triassic (eg. P.Olsen, 1986) and Devonian (Astin, 1990) in age.

It is proving very difficult to extract absolute climatic information from fluvial successions. Palaeosols provide relatively promising local evidence, although it is difficult to interpret this in basins where actively changing topography, and changing disposition of land and sea, may have produced local climatic changes. Palaeohydraulic information is even more difficult to utilise, partly because of the preservational bias towards extreme flood events, but also because hydraulic work relates to individual channels, and complete drainage networks would have to be reconstructed to make meaningful assessments of basinal water flux, and therefore precipitation.

All the approaches outlined in this review can clearly lead to the greater understanding of particular situations which itself can lead to understanding of the basic processes and interactions involved. Most of the results obtained in these studies have been acheived by investing increasing amounts of time making the field observations, or laboratory analyses involved. The new possibilities for electronic storage and handling of the large and complicated sets of information being gathered in this work, must be used in order to make the maximum use of all the new data becoming available. New technical developments in the electronic handling of map data appear to offer exciting possibilities for improved basin-scale studies.

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