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Global correlation of long Quaternary fluvial sequences: a review of baseline knowledge and possible methods and criteria for establishing a database

D.R. Bridgland[1] & D. Maddy[2]

[1] Corresponding author; Department of Geography, University of Durham, Durham DH1 3LE. email contact: d.r.bridgland@durham.ac.uk
[2] Department of Geography, University of Newcastle upon Tyne, Newcastle upon Tyne NE1 7RU

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Abstract

Fluvial sequences, particularly major terrace staircases, represent potential archives of palaeoclimatic fluctuation during the Quaternary. Such sequences can span much if not all of the Quaternary and, provided that dating is possible, can serve as stratigraphical frameworks for correlation with evidence from other depositional environments. In particular, they can provide a terrestrial lithostratigraphical framework that can be correlated with the global marine oxygen isotope record. Fluvial lithostratigraphical frameworks also provide important contexts for records of faunal evolution and human occupation, the latter largely determined from the occurrence of artefacts in fluviatile sediments.

This paper announces a new project within the International Geological Correlation Programme, devoted to fluvial sequences (IGCP 449 'Global Correlation of Late Cenozoic fluvial deposits'). It attempts to summarize existing baseline knowledge at the outset of the project and outlines the proposed methods and criteria for establishing a database of fluvial sequences.

Keywords: fluvial deposits, river terraces, biostratigraphy, geochronology

Introduction

This paper derives from oral and poster presentations at the Fluvial Archives Group (FLAG) 2000 conference in Mainz, Germany. Both of these were intended to publicize a new International Geological Correlation Programme (IGCP) project, arising from a FLAG initiative, entitled 'Global Correlation of Late Cenozoic fluvial deposits' (IGCP 449). A further aim, continued in this paper, was to review existing knowledge, illustrate ways of disseminating information on long fluvial sequences and encourage participation in the project, which is due to run for five years from 2000/01. This paper will represent a baseline statement, attempting to summarize, by way of examples, the existing knowledge onto which the IGCP project will build.

The IGCP project will be global, pooling information on long Quaternary fluviatile sequences from around the World. It is anticipated that important sequences can be recognized on all the continents, with the obvious exception of Antarctica. It is realised that little research will have been undertaken on some sequences, whereas the existence of others may as yet be undiscovered. It is hoped that the project can become the catalyst for new research designed to enhance the information available from all areas, especially those where study has thus far been at a minimal level.

Many of the best-known Pleistocene fluvial sequences are preserved in the form of terraces, recording the progressive incision of the river during the period concerned, activity that is believed to be a response to background uplift during the Quaternary

(Bridgland, 1994, 2000; Van den Berg, 1994; Maddy, 1997; Antoine et al., 2000; Maddy & Bridgland, 2000; Maddy et al., 2000; Westaway et al., 2002). Terrace sequences in some parts of the World (e.g. South Africa: Hattingh & Rust, 1999), date back to the early Neogene or even the Palaeogene; the intention to include such sequences in their entirety is the rationale for the title of the project, although it is anticipated that the majority of the data will be from the Quaternary.

Aims of IGCP 449

This will be the first time that data on Late Cenozoic fluvial sequences from around the World have been compiled systematically and made available in an easily accessible form. Emphasis will be given to assembling data in a readily understandable format, through the use of summary diagrams and tables.

Specific objectives are as follows:

- Establishment of an agreed methodology and strategy for the study and recording of fluvial sequences;
- Compilation of a database of well-dated Late Cenozoic fluvial sequences from all parts of the World;
- Designation of the best of these as regional fluvial stratotypes, with which less-well dated sequences, partial sequences and sequences from other environments can be compared;
- Correlation of fluvial sequences with the global marine record, by whatever means possible and with emphasis on a multi-proxy approach;
- Dissemination of this information by publication, including on the internet, as well as through meetings to be held both as part of the IGCP project and more widely.

Rationale: river sequences as important data archives

IGCP 449 starts with the knowledge that an ample but at present poorly coordinated supply of data exists from the temperate latitudes of Eurasia, where typically river development during the late Cenozoic has led to the formation of staircases of terrace deposits (except in areas of subsidence). These staircases have been formed in response to climatic forcing (Bull, 1991; Bridgland, 1994, 2000), which has led to cyclic incision and aggradation in synchrony with glacial/interglacial cycles, superimposed, as already noted, upon a background of progressive uplift (Bridgland, 1994, 2000; Maddy, 1997; Antoine et al., 2000). In areas that have not experienced uplift, the climatic signal is still reflected by alternations of deposition and erosion (e.g. Vandenberghe, 1995), but rejuvenation and valley incision has not occurred (e.g. the lower Rhine). Staircases of large-scale aggradational river terraces are thus a notable feature of many valleys in the temperate latitudes, particularly in areas beyond the reach of the erosive and disruptive activities of Pleistocene ice sheets. The reconstruction of longitudinal profiles represents the main tool for correlation of often very fragmentary former floodplain remnants. Correlation can be undertaken additionally using sediment composition (e.g. clast lithologies, mineralogy, erratics), biostratigraphy and geochronology (see below). All the above methods can provide correlation between different reaches of a particular river; biostratigraphy and geochronology can provide correlation between widely separated river systems. For global correlation it is desirable to compare fluvial records with the global template for Neogene - Quaternary climato-stratigraphy, the marine oxygen isotope record, optimally that from ODP 677 (Shackleton et al., 1990).

Fluvial sequences have the potential to provide frameworks for late Cenozoic stratigraphy on land. They benefit from a global distribution, being represented on all continents and across all climatic zones, with the exception of the polar regions and the driest deserts. Although the majority of readily accessible reported studies are from the temperate latitudes of Eurasia and North America, it is apparent that comparable data can be obtained from further afield: e.g. China, South America, India and Africa. An essential element of the IGCP project will be to integrate representative information from the full geographical range.

If river terraces can be dated, they can provide a means of gauging landscape change, since they record successive valley-floor levels. Terrace sequences can thus provide a framework for modelling fluvial incision as a part of landscape evolution (Veldkamp & Van Dijke, 1998, 2000). It is thought that incision is a direct response to crustal uplift and therefore provides an approximate measure of the amount of that uplift (Van den Berg, 1994, 1996; Maddy, 1997; Maddy et al., 2000). Evidence from deformed fluvial sequences of the Mahi River, India (Jain et al., 1998) and rivers draining northwards from the Sudaten mountains, SW Poland (Krzyszkowski et al., 1998, 2000; Krzyszkowski & Biernat, 1998), has provided records of fault movement in tectonically active areas. Such studies are of clear value to geophysical research.

Not all fluvial deposits form terraces; in subsiding sedimentary basins, grabens, aulacogens and in many continental shelf areas, thick piles of river sediments have accumulated during the Cenozoic. Study of these has not always been easy, generally relying on boreholes and geophysical techniques to determine the geometry and nature of buried and sometimes submerged (now offshore) sequences and channels (e.g. Ruegg, 1994; Yim, 1994; Bridgland & D'Olier, 1995; Alekseev & Drouchits, 1997; Veligrakis et al., 1999; Wingruth et al., 2000).

Baseline position

Table 1 summarizes the 'baseline' upon which IGCP 449 will build. It provides essential details of selected fluvial archives from around the World. The table gives an indication of the availability within each system of key evidence, such as palaeomagnetic polarity and other geochronological data, palaeontology, archaeology and the inputs from glaciations, marine transgressions and volcanic eruptions. The table indicates no more than presence/absence of selected criteria; many more lines of evidence will be explored by the project. The table is intended to be illustrative rather than exhaustive. The authors are keen to receive contributions in the form of updates and additions to the table, although it should be noted that the level of detail required for the IGCP 449 database will be considerably greater.

Eurasia

The inspiration for IGCP 449 comes from NW and central Europe, where there is a long history of research on Pleistocene fluvial sequences, providing ample data as a starting point for the project, beyond which little will be required other than translation into the chosen format, once this has been established (see below). Work on the terrace sequence and loessic overburden of the Svratka River valley, Brno, Czech Republic (Kukla, 1975, 1977) provides an early exemplar for correlation with the climatic oscillations of the marine isotope sequence and for the presentation of data in a transverse staircase diagram (Fig. 1). The recognition of palaeosols within the loess provided the principal means for the relative dating of this sequence. Evidence of this type is also indicated in Table 1.

Beyond NW and central Europe, extensive Pleistocene fluviatile records are well documented from eastern and southern Europe, Asia Minor (see Middle East), Russia, the Himalayan foreland and China. Numerous rivers in eastern Europe have impressive Pleistocene records, although much of the published work is in languages other than English. Particularly notable are the sequences from rivers flowing from the north into the Black Sea, such as the Dniestr and Dniepr (Veklich et al., 1993; Markova & Mihailescu, 1994; Matoshko et al., this volume). These sequences benefit from palaeomagnetic and biostratigraphical control; they record high-sea-level episodes in the form of evidence for marine transgressions of the Black Sea into the lower reaches of the rivers. To the north, glaciations have repeatedly injected erratic material into the upper reaches of these river systems. As well as biostratigraphical evidence from the fluvial and estuarine sediments, dating control for these Black Sea river sequences comes from loessic overburden with palaeosol horizons, as for the Svratka at Brno (Fig. 1). The use of palaeosol evidence from loessic overburden has proved valuable in areas of Eurasia as widely separated as the Somme, in northern France (Antoine, 1990; Antoine et al., 2000) and the Yellow River in China (Li, 1991; Porter et al., 1992; Table 1). In southern Europe, extensive terrace systems are documented from Iberia, where they are repositories for faunal and archaeological remains (Díaz del Olmo et al., 1989, 1993; Raposo, 1993; Raposo & Santonja, 1995; Benito et al., 2000; Table 1).

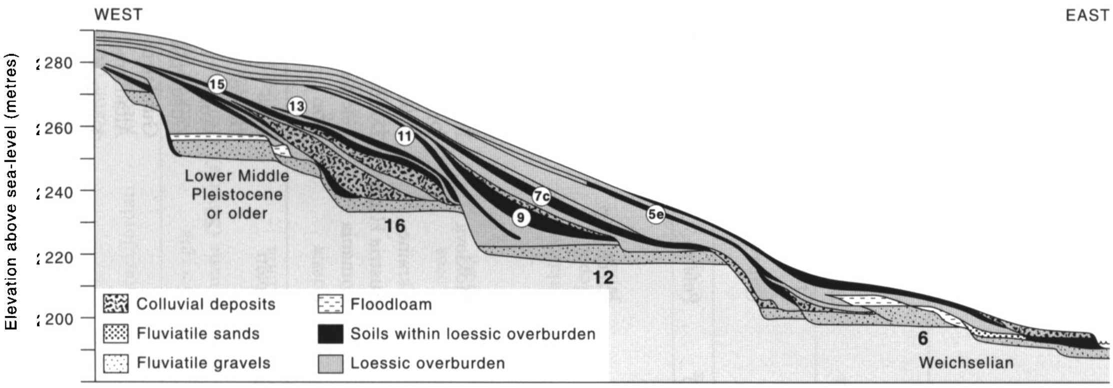

Fig. 1. Transverse section through the terraces of the River Svratka and their loessic overburden, with sequence of interglacial paleosols: The Red Hill, Brno, Czech Republic. Modified from Kukla (1975, 1977) in that suggested ages of fluviatile gravels and soils are given, using oxygen isotope stage notation where possible.

Table 1: A selection of long Quaternary fluvial records from around the World, indicating the range of evidence available from each. Coverage is by no means exhaustive.
Notes * - palaeomagnetic polarity data; g - glacial inputs; p - palaeopedology (in fluvial sediments or overlying löss sequences); s - sea-level record in lower reaches; v - volcanic inputs.

Continent (region)	Country	River	Length of record	Geochronology (m - magnetics*)	Biostra-tigraphy	Archaeo-logy	Other evidence (see caption)	References
Europe (NW)	UK	Thames	1Ma+	✓	✓	✓	g, p, s	Gibbard (1985, 1994); Bridgland (1994)
		Severn-Avon	<0.5Ma	✓	✓	✓	g	Maddy et al. (1991), Maddy et al. (1995)
		Solent	1Ma+		✓	✓	s	Allen & Gibbard (1994); Allen et al. (1996)
	Netherlands	Maas (Meuse)	1Ma++	✓ m	✓	✓	s	Ruegg (1994), Veldkamp & Van den Berg (1993), Van den Berg (1994, 1996)
		Rhine	1Ma+	✓	✓		s	Brunnacker et al. (1982)
	Germany	Rhine	1Ma+	✓ m	✓	✓	g, v	Bibus (1980), Brunnacker et al. (1982), Klostermann (1992)
		Neckar	1Ma	✓ m	✓	✓	p	Bibus & Wesler (1995)
		Weser	0.5-1Ma	✓ m				Rohde (1989)
		Wipper	1Ma	✓	✓	✓	g	Mania (1995)
	France	Somme	1Ma+	✓ m	✓	✓	p	Antoine (1990, 1994)
		Seine	1Ma+	✓ m	✓	✓	p, s	Lautridou et al. (1983, 1999), Lericolais et al. (1997)
		Allier/Loire	1Ma+	✓			g, p, v	Pastre et al. (1997), Veldkamp (1992)
Europe (E)	Poland	Nysa Klodzka	<0.5Ma		✓		g	Krzyszkowski et al. (1998)
		Bystrzyca	<0.5Ma				g	Krzyszkowski & Biernat (1998)
		Dunajec	1Ma+	✓ m			g	Zuchiewicz & Butrym (1990), Zuchiewicz (1992)
	Czech Rep.	Svratka	1Ma+	✓	✓	✓	p	Kukla, (1975, 1977)
		Vltava	1Ma+	✓ m	✓	✓	p	Záruba (1942), Tyràcek (2001a, 2001b)
		Upper Odra	0.5-1Ma		✓			Benda (1995)
		Ohre	1Ma+	✓				Tyràcek (1983, 1995)
		Morava	0.5-1Ma				p	Zeman (1982)
	Moldova	Prut	1Ma+				p, s	Markova & Mihailescu (1994)
		Dniester	1Ma++	✓ m	✓		g, p, s	Markova & Mihailescu (1994)
	Ukraine	Dnieper	1Ma+		✓		g, p, s	Veklich et al. (1993), Matoshko et al. (in press)
	Austria Hung.	Danube	1Ma+	✓ m	✓	✓	p	Halouzka & Minarikova (1977), Blüberger (1996)
	Romania	Teleajenul	0.5-1Ma					Niculescu (1963)
	Russia	Don	1Ma+	✓ m	✓		g	Alekseev (1996)
Europe (S)	Spain	Ebro	0.5-1Ma					Raposo & Santonja (1995) , Benito et al. (2000)
		Duero	1Ma+			✓		Santonja & Villa (1990)
		Mula	0.5-1Ma					Mather et al. (1995)
		Guadalquivir	0.5-1Ma	✓	✓	✓		Díaz del Olmo et al. (1989, 1993)
		Guadalete	0.5-1Ma			✓		Giles Pancheco et al. (1989)
		Alfambra	0.5-1Ma			✓		Santonja et al. (1992)
		Tormes	1Ma+			✓		Santonja & Gonzáles (1984)
	Portugal	Tagus	0.5-1Ma	✓	✓	✓		Santonja & Villa (1990)

Asia (M.East)	Turkey	Gediz	1Ma++	✓ m	✓	✓	v	Sanver (1968), Ozaner (1992), Sarica (2000), Bunbury et al. (2001)
		Sakarya	1Ma+		✓			Ünay et al. (2001)
	Iraq	Euphrates	1Ma+			✓		Tyràcek (1987)
	Syria	Asi (Orontes)	<0.5Ma	✓	✓	✓	s	Van Liere (1960/1), Dodonov et al. (1993), Domas (1994)
		Kabir (Kebir)	1Ma+			✓	s	Bar-Yosef (1998)
	Israel/Jordan	Jordan	1Ma+	✓ m	✓	✓	v	Bar-Yosef (1998)
Asia	Georgia	Mtkvari (Kura)	1Ma+	✓	✓	✓	v	Gabunia & Vekua (1995), Bar-Yosef (1998)
	Russia (Siberia)	Kolyma	0.5-1Ma	✓ m	✓		g, s	Sher et al. (1977)
		Yenisei	<0.5Ma	✓				Yamskikh (1996)
	China	Yellow River	1Ma+	✓ m			p	Li (1991)
		You	1Ma+		✓	✓		Leng (1998)
		Ba	0.5-1Ma	✓ m		✓	p	Porter et al. (1992), Leng (1998)
		Chan	0.5-1Ma	✓ m			p	Porter et al. (1992)
		Hanshui	0.5-1Ma		✓	✓		Leng (1998)
		Sanggan	1Ma+		✓	✓		Leng (1998)
	Korea	Han, Keum, Sumjn	0.5-1Ma					J.Y. Kim (pers. comm.)
	India	Pravura	0.5-1Ma	✓		✓		Mishra (1992, 1994)
		Narmada	0.5-1Ma	✓	✓	✓	v	Acharyya & Basu (1993), Korisettar & Rajaguru (1998)
		Beas-Babganga	<0.5Ma			✓		Petraglia (1998)
	Pakistan	Indus	1 Ma+	✓				Burbank et al.(1996)
	Nepal	Babai	<0.5Ma			✓		Corvinus (1998)
	Japan	Usui	0.5-1Ma					Sugai (1993)
		Mississippi	0.5-1Ma				g, s	Fisk (1951), Saucier (1996), Blum & Straffin (2001)
N. America	USA	Susquehanna	1Ma++				s	Pazzaglia & Gardner (1994)
		Mattole	<0.5Ma	✓			s	Merritts et al. (1994)
	Canada	St Lawrence	<0.5Ma				g, s	Ochietti & Long (1999)
		Yukon	1Ma++	✓ m			g	Froese et al. (2000)
S. America	Brazil	Parana Basin	1Ma+					De Mauro & Christofoletti (1984).
	Argentina	Parana & Uruguay	1Ma+					Iriondo (1980)
	Colombia	Magdalena	1Ma+	✓			v	Kroonenberg et al. (1981)
Africa	Egypt/Sudan	Nile	1Ma+			✓		Said (1993), Salama (1999)
	Ethiopia	Omo & Gona	1Ma+	✓ m	✓	✓		Howell et al. (1988), Semaw et al. (1997)
	Niger	Niger	0.5-1Ma					Bergeing & Gilliard (1997)
	Kenya	E.Africa Rift Valley	1Ma++	✓	✓	✓	v	McBrearty (1999)
	Congo	Seliki (Rift Valley)	1Ma+		✓	✓		Harris et al. (1987)
	Uganda	Kafu	1Ma+			?✓		Wayland (1934)
	S. Africa	Sundays	1Ma+				s	Hattingh & Rust (1999)
		Vaal-Orange	1Ma+		✓	✓		Butzer et al. (1973), Helgren (1978, 1979)
Australasia	Australia	Cooper	<0.5Ma		✓			Nanson et al. (1999)
		Lachlan	1Ma++				v	Bishop et al. (1985), Bishop & Brown (1992)
		Magela Creek	1Ma++	✓			s	Nanson et al. (1993)
	N. Zealand	Charwell	<0.5Ma					Bull & Kneupfler (1987), Bull (1991)

Again, it is anticipated that IGCP 449 will lead to the wider dissemination of these data.

North America

The terraces of the Mississippi system are probably the best known North American sequence (e.g. Fisk, 1951; Saucier, 1996; Blum & Straffin, 2001). The sediment bodies recognized are huge, but they lack the fossiliferous interglacial intercalations seen in many European rivers, of considerable value for biostratigraphical dating. Instead the sequence has been dated with reference to soil formation, often in overlying loess deposits (Rodbell & Forman, in press). Rivers on the eastern seaboard, however, have extensive Cenozoic sequences, some, such as in the case of the Susquehannah, extending back into the late Mesozoic (Pazzaglia & Gardner, 1994). Recent work is also available on rivers in N. California such as the Mattole (Merritts et al., 1994). The St Lawrence River has a well researched sequence extending back into the Middle Pleistocene (Ochietti & Long, 1999), but Late Pleistocene glaciation has prevented earlier records surviving. In the more arid Yukon, in the extreme north, a lengthy late Cenozoic sequence has been preserved, however, one that furnishes evidence for the interaction between rivers and late pre-Quaternary glaciations (Froese et al., 2000).

Middle East & North Africa

From these relatively well researched areas, the project will expand into parts of the World where relatively little is known of long fluvial sequences. The Middle East is an area that has several important rivers, some of which are known to have terrace systems. For example, Tyràcek (1987) has recorded a full staircase of terraces, suggestive of climatically-driven formation at a Milankovitch scale, in the valley of the Euphrates River, Iraq. River terrace sequences in various parts of the Levant have attracted attention as a source of Palaeolithic artefacts (see below); examples are the terraces of the Orantes and the Kabir in Syria and deposits of the Jordan (Bar-Yosef, 1998; Table 1). Terrace sequences are known from the Nile and other North African rivers, although the arid hinterland means that the Nile is the only large river draining northwards to the Mediterranean (Said, 1993). The Nile terraces, from which the origins of the river can be traced back to the late Tertiary (Said, 1993), have yielded an important archaeological record (Sandford, 1934; Wendorf & Schild, 1976; Paulissen & Vermeersch, 1987). Rivers draining the Atlas Mountains of Morocco have built terraced alluvial sequences that trace drainage history back to the Miocene, albeit with large hiatuses (A. Ait Hssaine, pers. comm.). Blum & Straffin (2001) have traced the history of wadis on the Saharan margins of Tunisia back into the Middle Pleistocene, the record being one of terraces and incised valley fills.

India & Far East

In India, as in the Middle East, fluvial deposits can be sources of Palaeolithic artifacts. For example, Middle Pleistocene alluvial deposits of the Pravara River, now between 2 and 15m above the active floodplain, have yielded Acheulian (Lower Palaeolithic) artefacts (Kale & Rajaguru, 1987; Mishra, 1991, 1994). The range of heights is suggestive of multiple terraces. Other important sources occur in Himalayan valleys in Nepal, of which the Babai system (Table 1) is just one example (Corvinus, 1998).

In China, the Yellow River has formed more than 20 terraces in response to uplift of the Tibetan Plateau by over 1km (Li, 1991). Other rivers have extensive terrace systems, amongst which the Ba and Chan are notable (Porter et al., 1992). An extensive terrace staircase, seemingly formed in synchrony with climatic fluctuation at the Milankovitch scale, is recorded from the Usui River in Japan (Sugai, 1993). In Korea, significant Quaternary terrace records are known from the Han, Nakdong, Keum, Youngan and Sumjn Rivers (Ju Yong Kim, personal communication).

Australasia

Typical Australian landscapes are not dominated by fluvial environments, but some rivers in the SE of the country have terrace sequences (Table 1). Rivers flowing into inland playa basins have also provided important records for environmental change. An example is the Cooper, which has left a sedimentary sequence representing the last two full climatic cycles, with important preservation of extinct megafauna (Nanson et al., 1999). The Charwell River in New Zealand has well documented terrace systems covering Pleistocene time-scales (Bull, 1991).

South America

In South America, significant sequences are known from the Parana and the Uruguay rivers of Argentina and the Magdalena/La Plata in Colombia (Table 1). Rifting has fashioned basins on the eastern side of the continent that have received fluvial sediments from the late Mesozoic onwards (Campbell et al., 1985; Andreis et al., 2000; Iriondo, 2000).

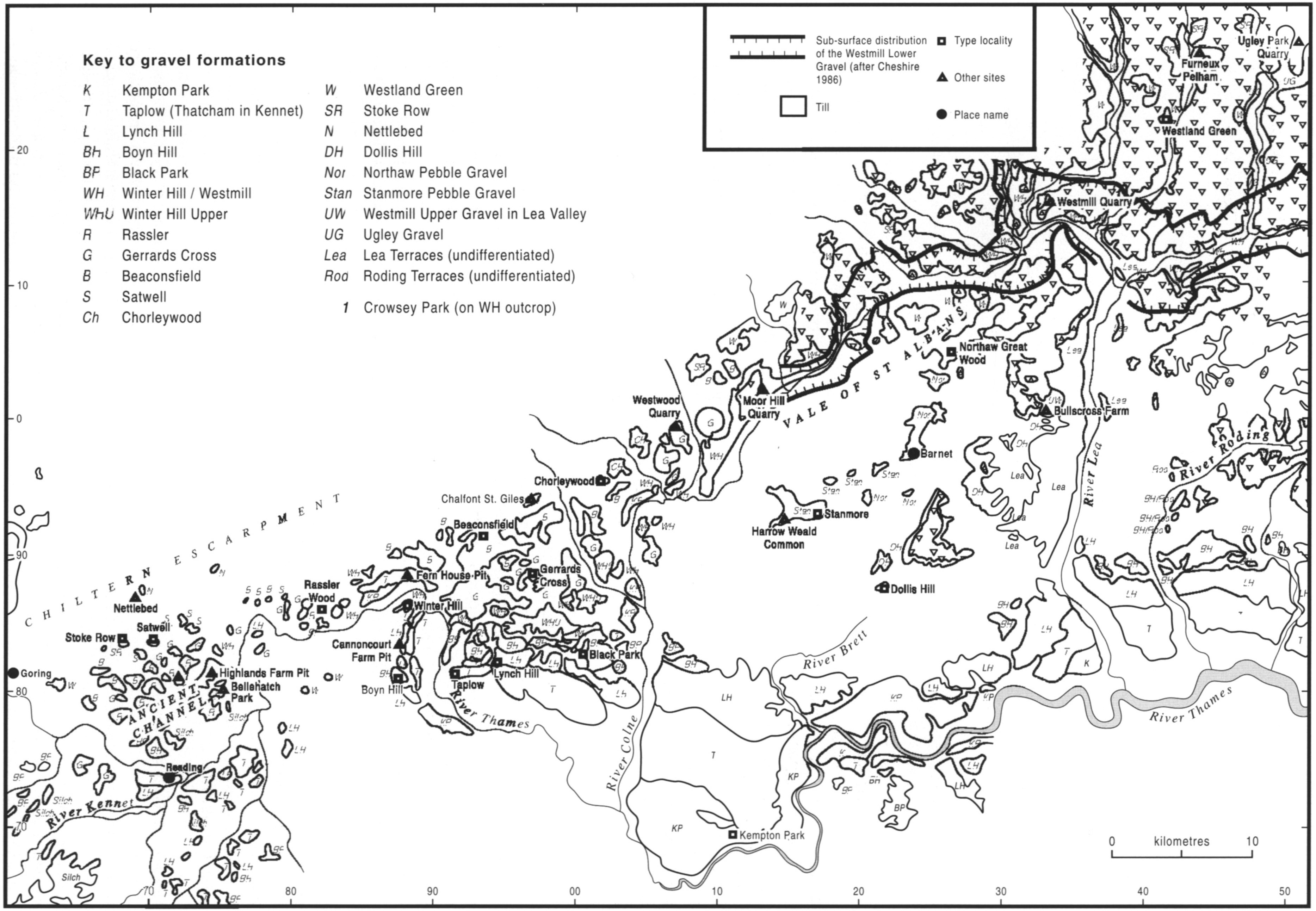

Fig. 2. Map of terrace deposits of the Middle Thames. The subsurface form of the buried pre-diversion route of the Thames is also indicated. After Bridgland (1994).

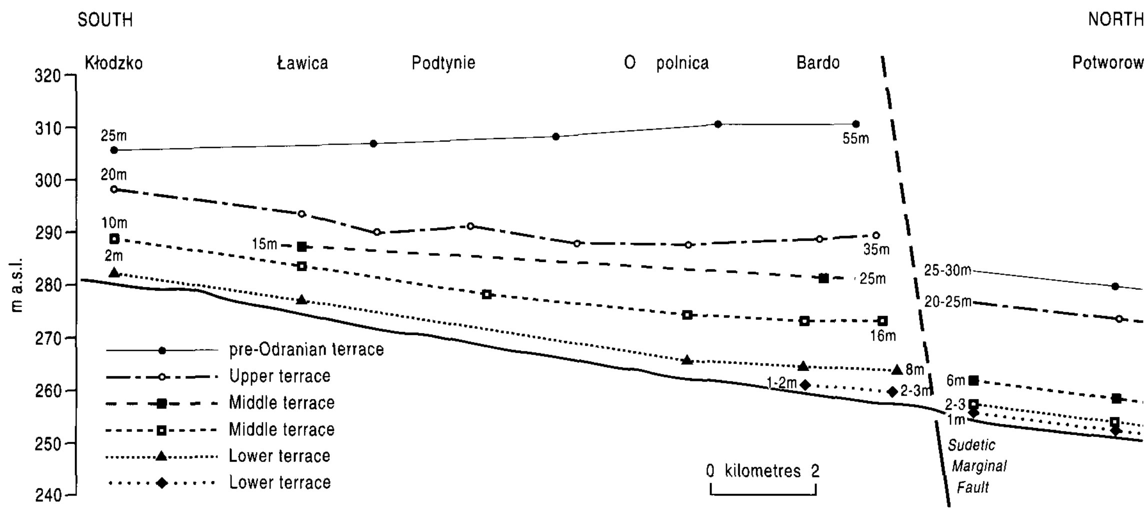

Fig. 3. Longitudinal profiles of terraces of the River Nysa Kłodzka, Sudeten Mountains and Sudetic Foreland, Poland. The effects of late Quaternary movement on the Sudetic Marginal fault are clear (after Krzyszkowski et al., 1998).

Sub-Saharan Africa

In southern Africa, some large rivers such as the Vaal - Orange have significant terrace systems. The Vaal has an important archaeological record extending back considerably further in time than any of the better known NW European sequences (Butzer et al., 1973; Helgren, 1978, 1979; Hattingh & Rust, 1999). The long-term stability of the African landcape has led to the preservation in this area of sequences that extend back into the early Neogene (Table 1). For example, the terraces of the Sundays River, eastern South Africa, have provided important evidence of post-Palaeogene uplift history (Hattingh & Rust, 1999).

Much less is known from tropical and equatorial Africa. In Rwanda, fluvial sequences have yielded important evidence for palaeohydrological evolution and the influence on drainage of volcanic eruptions (Schmidt & Neuffer, 1995). The sequence in the Mukungwa valley, Rwanda, includes sediments yielding faunal and archaeological remains (Schmidt, 1996). Fluvial deposits are included amongst the sedimentary fill of the East African Rift Valley (Feibel et al., 1999; McBrearty, 1999), of great significance as the source of fossils charting early human history. Important archaeological records are also known from fluvio-lacustrine sequences in the rift valley in Congo (Harris et al., 1987).

Proposed IGCP449 database

Perhaps the most important aim of IGCP 449 is the compilation of an international database of information and evidence from fluvial sequences. The final specification of this database has yet to be decided, but it is already clear that certain types of data will be included. It is also intended that summary diagrams of various types will be archived.

Three main types of diagram are envisaged:

1. Maps showing distribution of outcrops and subsurface data where available (Fig. 2).
2. Longitudinal profile diagrams, which can reveal differences in gradient between different terrace levels, perhaps the result of differential crustal movements (Fig. 3).
3. Idealized transverse sections (in the case of terrace sequences these can be termed 'staircase diagrams'), which probably represent the greatest aid to understanding particular sequences (Fig. 1).

The accuracy of such diagrams, and any interpretations and age estimates that go into compiling them, is dependent upon the quality of the basic data. This can only be assessed through access to the data itself, so it is important that this is archived in some detail, which is the role of the main database. It is intended that the database will be disseminated via the Internet. It is likely that the content will include information such as follows below.

Lithostratigraphy

A sound stratigraphical framework is fundamental to the recording of data from fluvial archives. Formal lithostratigraphy (cf Hedberg, 1976) has been seldom undertaken in the case of river terraces except in a few countries, such as the Netherlands, the UK and North America, workers elsewhere preferring informal geomorphology-based nomenclature. An alternative would be to use allostratigraphic units (North American Commission on Stratigraphic Nomenclature NACSN, 1983), which were specifically designed to overcome the difficulties in applying formal lithostratigraphical nomenclature to fluvial sequences. Effectively, however, it will be both necessary and desirable to make use of nomenclature already well established and this will be the normal policy.

Under this heading will be recorded basic information such as sediment types, height of sedimentary units above sea-level, downstream gradient and relation to adjacent non-fluviatile deposits. Thus the mapping of terrace geomorphology, an aspect of geological mapping, is subsumed here under the heading of lithostratigraphy, although others might wish to give it greater prominence.

Biostratigraphy

This is a traditional and well-tried method for establishing relative chronologies for fluviatile sequences. Applicable only where fossiliferous sediments have been preserved, the method has proved valuable in many parts of the World. The most useful fossil groups are those that can be identified readily to species level and those that have undergone significant evolutionary change within the late Cenozoic. Others may provide valuable palaeoenvironmental data that can be fed into climato-stratigraphical reconstructions. The most useful fossil groups are as follows:

Vertebrates

Recent work suggests that mammalian fossils offer a powerful tool for correlation of fluvial sequences with the global marine ($\delta^{18}O$) record of glacials and interglacials (Van Kolfschoten & Turner, 1996; Preece & Parfitt, 2000; Bridgland & Schreve, 2001; Schreve, 2001). The bones and teeth of large mammals are commonly found in fluviatile deposits, rarely at sufficient frequency for any systematic samping strategy, although substantial collections from the days of manual quarrying survive in museums. Vertebrate remains from river deposits sometimes include hominid fossils, such as at Swanscombe, UK, in the Thames sequence (Conway et al., 1996), and Steinheim, Germany, within sediments of the River Murr (Adam et al., 1995). Mammals are especially valuable biostratigraphically, as they have undergone considerable evolution and numerous extinctions during the Neogene and Quaternary (Horáček, 1990). Small mammals and other small vertebrates are readily obtained from systematically collected samples by means of sieving (Rabeder, 1974, 1981; Fejfar & Heinrich, 1983).

Molluscs

With freshwater, brackish and marine representatives, molluscs can record nearby land habitats as well as, in the lower reaches of rivers, the transition from the fluvial to the marine environment. Thus they allow sea-level changes to be detected at the downstream ends of river courses (e.g. Markova & Mihailescu, 1994). The Mollusca supply important biostratigraphical and palaeoenvironmental information (Lozek, 1964a, 1964b; Horacek & Lozek, 1988; Keen, 1990; Kovanda et al., 1995; Preece, 1995, 1999; Meijer & Preece, 2000) and, in recent years, have provided the raw material for the powerful geochronological method based on the racemization of amino acids within mollusc shells (Miller et al., 1979; Bowen et al., 1989; Bates, 1994). Molluscs are also extremely important climato-stratigraphical tools, since they provide reliable evidence for palaeoclimate and palaeoenvironmental conditions.

An example of valuable biostratigraphical constraints provided by the study of molluscs is the occurrence of *Corbicula fluminalis* in British fluvial sequences, in which this bivalve occurs in deposits attributed to the OIS 11, 9 and 7 interglacials, but is absent from those representing the last interglacial, OIS 5e (Keen, 1990; Bridgland, 1994; Preece, 1995, 1999). Recent reinvestigation of the record of this bivalve from the Netherlands suggests a similar pattern of occurrence there, with *Corbicula* absent from Eemian deposits, excepting reworked specimens (Meijer & Preece, 2000).

Palaeobotany

This includes the study of pollen and spores, as well as macroscopic plant remains. Pollen, recognized as the most widespread source of environmental and stratigraphical evidence since the study of the Pleistocene interglacials began (Pike & Godwin, 1953; West, 1956; Zagwijn, 1985), is often present in organic fluviatile sediments, such as those representing infilled channels (Maddy et al., 1998; Urban, 1995; Thomas, 2001). However, these generally record only a fragment of the time represented by any particular interglacial, although they may indicate in which part of the climatic (glacial-interglacial-glacial) cycle a sediment was laid down and contain key elements that may be of value for distinguishing between particular temperate-climate episodes (Tzedakis et al., 1997).

Macroscopic plant fossils provide valuable additional information, as they allow higher taxonomic resolution than is generally available from palynological data. Species that are poor pollen producers can also be represented. However, it is more difficult to undertake quantifiable studies and much less work has been carried out on macrofossils than on pollen.

Ostracods
These provide important palaeoenvironmental information, particularly in relation to marine influences at the downstream ends of rivers (e.g. Dykan, 1999). However, they are of limited value for biostratigraphy (Griffiths, 2001; cf. Bridgland et al., 2001).

Beetles
Beetles have proved to be perhaps the most sensitive of the fossil groups for the reconstruction of palaeoclimate. The Mutual Climatic Range Method can provide limits of palaeotemperature based on coleopteran assemblages (Atkinson et al., 1987). This method is of obvious importance to climato-stratigraphy, but the biostratigaphical value of Coleoptera is equivocal, given the minimal evolution shown by the group during the late Cenozoic (cf. Coope, 2001).

Geochronology

Geochronological methods have already been applied widely to fluvial sequences in Europe, Asia and North America, and to the hominid-bearing deposits of the East African rift system, but less extensively elsewhere. The IGCP project will be a catalyst for this type of new research undertaking, which will be promoted where potential for dating has yet to be realized. It is anticipated that the following methods will be the principal sources of age estimates.

Palaeomagnetism
This method is valuable in providing isochrons. Location of the Matuyama-Bruhnes magnetic reversal is particularly important as a marker for the base of the Middle Pleistocene (780,000ka). This marker is an important element in the dating of the Somme (Antoine, 1994, Antoine et al., 2000) and Alpine (Fink et al., 1979) terrace sequences and has also been recognized in the Dniestr sequence (Markova & Mihailescu, 1994). In some valleys (the Rhine and Danube are examples) it has been identified in both fluvial deposits and in aeolian overburden. Records in which magnetic reversals have been identified are indicated in Table 1.

Amino acid geochronology
This has proved to be one of the most effective geochronological techniques for application to fluviatile sequences in north-west Europe, although its potential has yet to be realized elsewhere. The method is applicable in temperate latitudes over the last 0.5Ma, although higher racemization rates in warmer climates will reduce this range. Recently the development of new preparation techniques has greatly enhanced the reliability of this method (Stathopolos & Hare, 1993; Sykes et al., 1995). The amino acid method has proved effective in the Thames, UK (Miller et al., 1979; Bowen et al., 1989, 1995), the Severn-Avon, UK (Maddy et al., 1991), the Somme, France (Bates, 1994), the Danube (Zöller et al., 1994; Oches & McCoy, 1995) and the Dnieper, Ukraine (Oches et al., 2000). It can be applied to any fluviatile sequence in which molluscan fossils are commonly preserved, the shells providing the raw material for dating.

Luminescence dating
Luminscence methods, in particular IRSL (infrared stimulated luminescence) and GLSL (green light stimulated luminescence) applied to grains of quartz and feldspar, present perhaps the most exciting possibilities for the dating of fluvial sequences. Systematic dating of fluvial sequences using these methods has been shown to produce well constrained chronologies for sites unsuitable for dating by other techniques. These methods are applicable to sediments within the age range up to 200ka; for example, using GLSL, Perkins and Rhodes (1994) dated coarse-grained, fluvially deposited sands at Tattershall, Lincolnshire, to beyond 100ka. Thermoluminesence (TL) and optically stimulated luminescence (OSL) methods have also been applied to loess overlying river terrace deposits. For example, OSL has been used to date Pleistocene sediments of fluvial and aeolian origin in the valley of the River Luni, India (Jain et al., 1999).

Uranium Series Dating
This method is well suited to dating travertines within fluvial sequences, such as those in East Germany and France, where the technique has been applied in the valleys of the River Ilm, at Weimar-Ehringsdorf (Blackwell & Schwarcz, 1986), the River Wipper, at Bilzingsleben (Schwarcz et al., 1988), and the River Allier (Veldkamp & Kroonenberg, 1993). Travertines within River Danube sequences in Hungary have also been dated using this method (Hennig et al., 1983).

Potassium-Argon (^{40}K /^{40}Ar and ^{40}Ar/^{39}Ar) Dating
The K-Ar dating technique has been widely applied for the dating of igneous rocks with recent developments, particularly in ^{40}Ar/^{39}Ar dating, allowing the possible dating of Quaternary materials with relatively high temporal resolution (Richards & Smart, 1991). In many areas fluvial sediments are intercalated with tephras and lava flows etc. (Table 1), allowing the possibility of utilizing these techniques to constrain the ages of fluvial sequences. This method has been used the date the Rhine terraces with reference

to ash layers from volcanism in the Eifel region (Boogard et al., 1989), providing geochronological control within important sequences such as that at Kärlich (Van Kolfschoten & Turner, 1996). It has also been claimed as a measure of uplift, when used to date Pleistocene basalt flows that have invaded and diverted the Kula River in western Turkey, lavas of progressively younger ages occupying successively lower altitudes as a result of incision by the river (Bunbury et al., 2001).

Cosmogenic Isotopes

This method is based upon the modelling of cosmogenic isotope (^{26}Al, ^{36}Cl and ^{10}Be) uptake on newly exposed rock/boulder surfaces. Although to date there have been relatively few fluvial studies using this technique (e.g. the Indus: Burbank et al., 1996), it has considerable potential, especially for use in sequences that include strath (erosional) terraces and where there are gorges cut into bedrock.

Archaeology

In north-west Europe, where some of the best-known studies of river terrace sequences have been carried out, many fluviatile deposits are an important repository for Palaeolithic artefacts, from which a record of early human occupation can be reconstructed (much more readily than from rare occurrences of hominid fossils). Indeed, in Europe, river terrace deposits have provided the bulk of the artifactual evidence for the presence of Lower Palaeolithic hunter-gatherers (e.g. Wymer, 1968, 1988, 1999; Mania, 1995; Tuffreau & Antoine, 1996; Roebroeks & Van Kolfschoten, 1995).

Fluvial sequences in the Near East, Middle East and parts of Asia and Africa are also important sources of artefacts. The records of Lower Palaeolithic artefacts from the sediments of the Pravara River in India and the Mukungwa River in Rwanda have already been cited. Artefact discoveries from fluvial sequences in southern Africa record the activities of early humans in that area during and since the Early Pleistocene, perhaps even the late Tertiary (Butzer et al., 1973; Helgren, 1978, 1979; Beaumont & Morris, 1990). As already mentioned, some of the evidence for the earliest known phases of human history also comes from fluvial sequences, within the infill of the Turkana and Baringo Basins of the East African rift systems (Feibel et al., 1999). The progression of humans northwards from Africa into Eurasia is likely to be charted in fluvial sequences across these areas, with the earliest appearances in the regions closest to the African origins.

Event stratigraphy

In many parts of the world, particularly the mid-latitudes of the Northern Hemisphere, detailed stratigraphical sequences are recognized on the basis of the interpretation of glaciogenic and lacustrine sedimentary archives that have been independently dated and correlated. Whereas the lacustrine sequences generally reflect short-lived basins (most became infilled within a single climatic cycle) that are stratigraphically isolated from other Quaternary sediments, glacial deposits often interdigitate with fluvial sequences and can provide important markers, particularly where glaciation had a significant effect on the river system concerned. Glacial diversions of rivers in northern Europe provide useful examples (e.g. Gibbard, 1988), visible in fluvial sequences as a result of changes in sediment provenance and composition. Rivers can also be diverted by the process of river capture (Bishop, 1995; Pastre & Leroyer, 1997; Pissart et al., 1997), with changes in catchment again providing markers within fluvial sequences.

Marine transgressions provide further significant markers, usually at the opposite (i.e. lower) ends of fluvial systems to glacial markers. The highest marine transgressions will generally record the warmest interglacials, although the severity of preceding glaciation can be a significant factor, through delayed isostatic recovery (Kukla & Cílek, 1996). The overprinting of high-sea-level events onto background uplift is the basis for the best sequences, in which fluvial sediments may interdigitate with estuarine sequences or even raised beaches. A good example of the latter is seen in the Sussex coastal plain, UK (Bates, 2001). The record from the northern margins of the Black Sea is an excellent example of the important palaeoclimatic archives that can be derived from river systems repeatedly affected by marine transgressions (Markova & Mihailescu, 1994; Matoshko et al., this volume).

Volcanic eruptions, already seen as a provider of datable layers interbedded within fluvial sequences, can also provide important markers. In extreme cases they might be a further cause of diversions (Kroonenburg et al., 1981; Pastre et al., 1997); less drastically, they can introduce new material into a catchment that can be recognized in sediments that post-date the eruption, a good example being the augite from eruption in the Eifel at c. 480 ka (Van Kolfschoten & Turner, 1996).

Discussion

A key aim of the IGCP project is to cross-correlate fluvial sequences by correlating the record from each river system with the oceanic oxygen isotope record, which will be achieved with reference to all available data. This will principally constitute applying biostratigraphical and geochronological evidence, using the established lithostratigraphy as a framework (see above). Thus by building on regional models, established early on, it should be possible to progress towards the main objective of this project: the global correlation of fluvial sequences. The resultant data will be valuable for comparison of landscape evolution between different areas.

The correlation programme will also provide better understanding and dating control for those fluvial sequences that are the context for archives of mammalian evolution and human occupation during the late Cenozoic. A significant proportion of the data on both of the above comes from fluvial sequences. Even where key sites occur in other environmental contexts, a better dated regional fluvial sequence could provide an improved framework for correlation. Thus cave and lacustrine sequences, generally isolated within the landscape and within the geological record, might be correlated with the regional fluvial sequence by means of biostratigraphy. The established regional fluvial sequence would provide a framework into which the 'floating' lacustrine or cave sediments could be fitted. Conversely the cave sediments might provide an independent geochronology based on the uranium series dating of speleothems (Smart, 1991), providing an important cross-check for the dating of the fluvial sequence. Lacustrine sequences can provide a more complete record of interglacial cycles than is likely to be found in fluvial sediments, so again, if these can be linked into the regional stratigraphical framework of fluvial sediments, the palaeoclimatic record as a whole will be much enhanced (cf Thomas, 2001).

It is hoped that many will want to contribute information to the IGCP 449 database, in which case they should contact one of the authors or visit the project's internet site (*http://www.qra.org.uk/FLAG/IGCP449.htm*). It is anticipated that subgroups will develop to promote particular strands of the project, some regionally based, but including thematic groups working on mammals, molluscs and archaeology from fluvial sequences.

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