Fluvial Archives Group (FLAG)

# Evolution of fluvial systems in Eurasia at different time scales

Special issue dedicated to the memory of Rob Westaway

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## 1. Introduction

The considerable diversity of environmental conditions across the Eurasian continent makes this this region an outstanding natural laboratory for studying the role of different factors (such as climatic change and tectonic activity) that control the evolution of fluvial systems.  Major developments in the research of fluvial systems in different regions of Eurasia have been achieved in recent years. The application of modern techniques in the study of alluvial archives, such as the absolute dating of terrace and floodplain deposits, has advanced understanding, at a range of timescales, of Quaternary evolution of fluvial systems, of climatic and tectonic influences on this development, and of the role of fluvial dynamics in the human occupation of river valleys (and vice versa).

The collection of papers presented in the special issue of Geomorphology, inspired by the most recent meeting of the Fluvial Archives Group (see below), is united in showing the diversity of approaches and topics in studies of the development of fluvial systems in different natural environments: mountains and lowlands, areas of recent glaciation and extra-glacial systems, areas of marine, continental and monsoon climate. The innovative research presented covers various timescales spanning from pre-Quaternary through the various divisions of the Pleistocene to Holocene sequences. The topics range from using fluvial units to reconstruct changes in palaeoenvironment, and how rivers react to climatic cyclicity, to the effect of neotectonic activity on river terraces.

The volume is dedicated to the renowned structural geologist turned fluvial geomorphologist, Rob Westaway, who died prematurely in 2021. His substantial and significant scientific contribution to the study of fluvial archives is the subject of an article by David Bridgland, which opens the special issue. Rob is a posthumous co-author of two papers in the special issue: one on tectonic uplift and climate change as forcing factors in terrace formation by the Yellow River during its incision into the Zoige Basin, NE Tibetan Plateau, and the other on the terrace sequence of the Nahr el Kebir, in NW Syria, having been completed after his death with the use of his notebooks. Other posthumous Westaway publications are envisaged, including coverage of his theories about glacio-isostatic effects, of considerable relevance to post-glacial fluvial archives.

## 2. The Fluvial Archives Group (FLAG)

FLAG is an international research group that promotes the study of past fluvial systems based on a broad range of multidisciplinary evidence: primarily geomorphological and geological, but also embracing palaeontology, archaeology and divisions of the Earth sciences such as sedimentology and geochronology. It provides a forum within which ideas can be exchanged, compared and developed (Cordier et al., 2017). FLAG was inaugurated in 1999 as a research group of the UK-based Quaternary Research Association, holding annual meetings during its three years as a funded QRA group. Its initial success led to continuation as an independent self-funded group. Its principal activities have been the organization of combined conference and field meetings, primarily in Europe, and the publication of numerous edited volumes and journal special issues (Table 1). FLAG has also participated in the organization of sessions at symposia, including the European Geosciences Union (EGU), the International Union for Quaternary Science (INQUA) and the International Association of Geomorphology (IAG). The group has also incorporated within its activities projects within the UNESCO / International Union of Geological Sciences (IUGS) International Geosciences Programme (IGCP): IGCP 449 (Global Correlation of Late Cenozoic fluvial deposits), 2000–2004 (Bridgland et al., 2007) and IGCP 518 (Fluvial sequences as evidence for landscape and climatic evolution in the Late Cenozoic, 2005–2007 (Westaway et al., 2009). At the shorter-timescale end of its activities, FLAG has engaged in fruitful collaboration with other international groups and research project initiatives, such as 'GLObal Continental PalaeoHydrology' (GLOCOPH) and 'Past Global Changes' (PAGES), the latter including 'Land-Use and Climate Impacts on Fluvial Systems' (LUCIFS).

INSERT TABLE 1 HEREABOUTS

From its inception, the activities of FLAG have been divided amongst several themes, beginning with the pairing of (1) fluvial archives as templates for long terrestrial records (e.g., spanning the whole of the Pleistocene) and (2) fluvial environments and processes in relation to external and internal forcing. This changed in 2000, upon the continuation beyond QRA funding, to a four-fold division under the following foci:

(1) Global Correlation of Late Cenozoic fluvial deposits (coinciding with the IGCP projects),
(2) Fluvial response to crustal instability,
(3) Fluvial response to rapid environmental change during the last two glacial–interglacial cycles (200 ka),
(4) Holocene fluvial system response to frequent and rapid periods of environmental change: identification and modelling of forcing factors.

In 2015, stemming from a business meeting at the INQUA Congress in Nagoya, Japan, FLAG activities were reorganized into eight foci, grouped within three key themes:

1. Natural and anthropogenic forcing at various timescales

    1.1. Fluvial response to long-term (Pleistocene) climate and sea-level change, tectonic activity and other crustal movements
    1.2. Fluvial response to Holocene climate, sea-level change and anthropogenic forcing

2. Approaches and methods for studying fluvial archives

    2.1. Study of palaeoenvironmental, biostratigraphical and archaeological data contained within fluvial archives (fluvial deposits and landforms, alluvial fans, lakes, caves), including geoarchaeology of river corridors.
    2.2. Modelling and otherwise quantifying long-term evolution of fluvial systems
    2.3. Geochronological constraints on fluvial archives
    2.4. Application of new field techniques to fluvial archives

3. Fluvial activity in relation to present and future climate and environmental change

    3.1. Applied elements of fluvial archives; e.g., economic geology (aggregates & placer deposits) or archives as sources of baseline information for river restoration.
    3.2. Using fluvial archives to inform future climate-change planning.

The key achievements of FLAG were summarized in an editorial paper for a special issue of Quaternary Science Reviews that celebrated its first two decades of activity (Cordier et al., 2017). The momentum this revealed was, however, curtailed as a result of the Covid 19 pandemic. September 2018 saw the final FLAG plenary meeting (Liege, Belgium) before the hiatus caused by Covid 19, while the final pre-Covid FLAG activities took place at the 20th INQUA Congress in Dublin in September 2019, with participation at the congress and in a pre-congress field meeting in Britain: 'The Quaternary fluvial archives of the major English rivers' (Bridgland et al., 2019; Table 1).

The planned 2020 FLAG meeting in Moscow (with a field trip to the Volga) was postponed and then cancelled because of the pandemic, being replaced by an online virtual conference in September 2021, organized from Moscow by Andrei Panin, Natalia Karpukhina and Andrei Zakharov. This present collection of papers stems from that meeting, which took place just a few weeks after the group learned of Rob Westaway's untimely passing.

## 3. Contents of the special issue

As noted already, the issue opens with a tribute to Rob Westaway's contribution to the study of fluvial archives (Bridgland, 2024), summarizing his innovative thinking in relation to the formation and preservation patterns of river terraces, the study of which has been an important theme within the activities of FLAG. Westaway's theory of lower-crustal flow as a mechanism for sustaining uplift initiated by erosional isostasy provided the first convincing explanation for the progressive fluvial incision represented by river terraces sequences. It can also explain differing patterns of fluvial-archive preservation, including records that indicate alternating uplift and subsidence and others with no net uplift.

The remaining papers are arranged according to the chronological sequence of their subject matter, beginning with three papers on the two great rivers of China. The first, by Zhang et al. (2023) reconsiders the timing of the well-known diversion of the River Yangtze from its previous course, via the Red River, to the South China Sea, an event that they demonstrate to have occurred during the Paleogene. This diversion, probably attributable to river capture (Clark et al., 2004), created the 'First Bend' of the Yangtze, at which the modern river turns sharply to the north-east. The area between the First Bend of the Yangtze and the head of the Red River coincides with the Jianchuan Basin, the sediments in which were studied by Zhang et al., who demonstrated from their K-Feldspar Pb isotopic content that the input from the Yangtze was cut off in the late Eocene, at or before 37 Ma, effectively dating the capture event with greater clarity than hitherto. Later Jianchuan Basin sediments are dominated by K-feldspars derived from local Eocene syenites, granites and tuffs. The evidence is considerably less clearcut using data from detrital zircons, an approach used in previous studies (and repeated by Zhang et al.); the authors attribute this to abundant reworking of the highly durable zircon grains from older to younger basin sediments, in contrast to the less stable feldspars, such that zircons from the Upper Yangzte (Tibetan Plateau) persisted in the basin-fill sediments after the Yangtze source had been cut off.

Next Li et al. (2023) provide a reconstruction of the middle reaches of the Yellow River (Huang he), based on studies of geomorphic surfaces, sedimentary characteristics and sediment provenance analysis, improving understanding of the Pliocene – Early Pleistocene integration of this river system.  Of key importance is the evolution of the Jinshaan Gorge, a deeply incised feature within the Yellow River valley that separates the Hetao Basin upstream (north) from the Fenwei Basin downstream (south) and which forms the final (eastern) side of the Yellow River's course around three sides of the Ordos Block.  From the Fenwei Basin the river reaches the North China Plain, across which it flows to the Pacific.  The sequence of events in the evolution of the Yellow River hereabouts, as determined by the authors, began with the Late Miocene endorheic Baode paleolake (~8.3 Ma) in the area around the location of the northern Jinshaan Gorge. By ~4.9 Ma this was part of an expanded fluvio-lacustrine system in the Hetao Basin, with a northern outlet.  A planation surface across the wider area was formed at ~3.7, into which incision began following the capture of the Hetao fluvio-lacustrine system from the south, initiating the cutting of the Jinshaan Gorge and establishing the integrated Yellow River course.

The next paper, by Yu et al. (2024) returns to the Yangtze for an assessment of the timing of river terrace formation, as well as influences on (and drivers of) this important fluvial activity, based on a sequence in the upper reaches on that river dated by the Optically Stimulated Luminescence (OSL) method.  From their findings, they note the importance of increased monsoon precipitation during interglacial and deglacial periods, which they link with fluvial incision into previous valley fills. They also observe that superimposed tectonic effects have produced responses by the river to glacial–interglacial climatic transitions that differ between the shallow headwater valleys, upstream of major tectonic activity, and deeply incised reaches further downstream within the Tibetan Plateau.

The topic of the next paper requires a move to the opposite corner of the Eurasian continent: the Iberian Peninsula.  This contribution, by Silva et al. (2024), reports on the fluvial archives from the confluence zone of the Rivers Júcar and Cabriel in eastern Spain. The authors record and illustrate a staircase of 14 well-developed terraces in this confluence area, where there is soft Miocene–Pliocene bedrock, representing a sedimentary graben-fill, the rivers flowing through gorges incised into more resistant substrates both upstream and downstream from their study area.  There is impressive geochronological control, using no fewer than four methods: Electron Spin Resonance (ESR), OSL, U-series dating of calcareous tufa deposits and K/Ar dates from volcanic materials related to the highest and oldest terrace, which show that the sequence as a whole dates back to ~2 – 1.6 Ma. This is a system that has been disrupted not only by intermittent volcanism, but also by salt diapirism, making this a most valuable example to be added to the corpus of fluvial archives.

The next paper is also from the Mediterranean region, albeit from its western extremity and from Asia. By Bridgland et al. (2024), and including Rob Westaway, this is a report of geo-archaeological work in the valley of the Nahr el Kebir, near Latakia in Syria, from which was gained an improved understanding of fluvial evolution in an area that has evidently been uplifting unusually rapidly. Like many river-terrace sequences in NW Europe, the Kebir terraces received early consideration from archaeologists, on account of the lithic artefacts found within and in association with these deposits. Indeed, the work reported here builds on substantial geoarchaeological research undertaken in the second half of the last century (e.g., Sanlaville, 1979), interpretation of which suggested marked differences in comparison with Lower Palaeolithic records from rivers further inland within the Levant. The evidence for more rapid uplift of the Latakia area implies that the Kebir terraces are considerably younger than the sequences inland, which helps explain the previously observed archaeological differences.

The next paper concerns more recent fluvial archives, from the Late Pleistocene and Holocene, the research area being in Southern Asia. This is a detailed study by Misra et al. (2024) and its location is the interfluve between the Ganga (Ganges) and Cai rivers, part of the Central Ganga Plains, characterized by a range of fluvial geomorphic features, in particular abandoned sinuous palaeochannels. Central to the research has been analysis of lacustrine deposits in an oxbow, Baraila Tal, looking at sedimentology (grain size), geochemistry (organic carbon content, carbon isotope analysis and oxygen isotopes from mollusc shells), micropalaeontology (pollen, algae and phytoliths) and AMS radiocarbon dating, from which a detailed reconstruction of chronostratigraphy, landscape evolution and palaeoclimatic has been achieved. Analysis of the local and regional geomorphological context has been aided by satellite imagery. The reconstructions shows change at the study site from an active river channel to a lacustrine environment, broadly coincident with the Last Glacial – Holocene transition, then variations in the Indian summer monsoon. The Mid-Holocene lacustrine sequence records millennial-scale weakening of the monsoon (~8.9–7.7 ka), with peak humidity during the Holocene Climate Optimum after ~7 ka.

For the next paper, there is a return to the Yellow River, in this case to consider its more recent history. This is related to the headward expansion of that river by the progressive capture of formerly endorheic basins at its upstream limits on the Tibetan Plateau (e.g., Pan, 1994; Bridgland et al., 2020). By Mo et al. (2024), this is the second of the papers in the special issue to include Rob Westaway as a co-author, based on his participation in a field season in the study area during 2019. The paper concerns the geomorphology and geochronology of terraces of the Yellow River and its tributary, the Xike River, within the Zoige Basin, the most recent to be added at the upstream end of the integrated Yellow River. Capture of this basin was instigated by incision of the Lajia Gorge, through which the river flows en route to the next lowest Xinghai–Tongde Basin. The timing of the Zoige Basin capture was around the Last Glacial Maximum (LGM), so Accelerator Mass Spectrometry radiocarbon dating has been used to constrain the ages of the terraces, which are cut into basin-fill (fluvio-lacustrine) sediments and marginal bedrock.

The next contribution, by Yorke et al. (2024), sees a return to Europe, it being a study of the post-LGM (Last Glacial Maximum) record of the River Tyne, NE England. The rivers in this region show unusually deep post-glacial incision, especially in their lower reaches, a phenomenon that Rob Westaway (in Bridgland et al., 2010; Bridgland and Westaway, 2014) attributed to glacial isostatic uplift enhanced by lower-crustal compensation that was especially effective because of the hot and dynamic crust in this region. Yorke et al., working on the entirety of this catchment, which has important North Tyne and South Tyne headwaters, confirm the importance of incision, providing discussion of potential drivers for it, and document a terrace sequence that reveals the fluvial response to deglaciation and subsequent Holocene changes. They recognize nine alluvial terraces lying between 20 and 2 m above present river level and constrain the geochronology of this sequence with OSL ages from T1, the oldest and highest (12.9 ± 1 ka), T4 (10.7 ± 1 ka) and T7 (3.2 ± 0.5 ka). Furthermore, they suggest that this sequence can be divided into four phases, (i) a deglacial phase, marked by proglacial outwash terraces, (ii) a Lateglacial phase of high level alluvial terraces, (iii) an early to mid-Holocene phase of alluvial terraces and (iv) a mid- to late Holocene phase that represents a major period of landscape instability and reorganization, with upland mobility resulting from increased precipitation and anthropogenic disturbances.

Continuing the evaluation of natural (climatic) versus anthropogenic influences on Holocene fluvial activity, the next paper, by von Suchodoletz et al. (2024), is a study of floodplain sedimentation in the Weiße Elster River of Central Germany. To pursue their research aims, the authors analysed three Holocene floodplain transects, looking at sedimentology and micromorphology and using numerical dating to provide age constraints. They also compiled a spatio-temporal database of former human activity within the catchment from the Neolithic to the ‘Early Modern’, for comparison with paleoclimatic data. The outcome raises doubts about the significance of anthropogenic drivers, at least in the Central German lowlands study area, which the authors suggest might have high sensitivity, in terms of landscape dynamics, to climatic influence.

The final paper is by Innes and Zong (2024), who investigated the potential of non-pollen palynomorph assemblages, primarily algae, as indicators of hydrological conditions and depositional environments in mid- and late Holocene sediment sequences of the Yangtze deltaic coastal lowlands. The authors analysed nine sediment profiles of differing age and wetland sediment type from various areas of the coastal plain, identifying the relative frequencies of algae, fungal spores and wetland pollen taxa indicative of open, limnic freshwater of various depth, marshland, fen, reed-swamp and semi-terrestrial habitats. Allied to a review of previously published literature on the wetland environmental history of the area, they were able to reconstruct hydrological changes across the mosaic of the coastal lowland wetland system, including flood events but also more subtle fluctuations, low-amplitude changes in aquatic systems that were not apparent in the lithostratigraphy, such as variations in water depth and trophic status, as well as factors such as temperature and eutrophication. It was also possible in many cases to correlate water-level fluctuations revealed by the microfossil data with the regional climate record. A more detailed understanding of the Holocene spatial development of the Yangtze coastal wetlands has been achieved, and the major potential of non-pollen palynomorph research in such studies confirmed.

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Table 1. Principal FLAG meetings and outputs. This includes IGCP projects that ran within FLAG but excludes early participation in symposia unless specific published outcomes resulted.

Note * SEQS = Symposium of European Quaternary Stratigraphy (INQUA)

| **Meeting (Location, month and year)** | **Published outcomes** |
|---|---|
| FLAG 2025, Tubingen, Germany | First post-Covid FLAG plenary meeting |
| FLAG session, INQUA 2023 (Rome, Italy) | |
| FLAG 2020/21 Meeting, online (Moscow) | This special issue (Geomorphology), 2024 |
| INQUA 2019 (Dublin, Ireland) – Pre-Congress excursion, London – Stratford-on-Avon, July 2019 | Field Guide (Bridgland et al., 2019) |
| FLAG 2018 Meeting, Liege, Belgium September 2018 | Special issue in Geomorphology (Twenty-five years of FLAG activity: Concepts, foci, trends in research), 2021 ((Cordier et al., 2021) |
| FLAG – QRA – Geologists' Association meeting in Lanzhou and the Yellow River, China | Field Guide (Hu et al., 2017) |
| FLAG 2016 Meeting, Kielce-Suchedniów, Poland (20th Anniversary Meeting, September 2016 | Special issue in Quaternary Science Reviews (The Fluvial Archives Group: 20 years of research connecting fluvial geomorphology and palaeoenvironments (Cordier et al., 2017). |
| FLAG 2014 Meeting, Mojacar–Tabernas, Spain, September 2014 | |
| FLAG Session (S10A) at the 8th International Conference on Geomorphology, International Association of Geomorphology, Paris, August 2013 | Special issue in Quaternaire (26, 1), Research on fluvial archives: from diversity to multidisciplinarity (Cordier et al., 2015) |
| FLAG 2012 Meeting, Remich, Luxembourg, September 2012 | Special issue in Boreas (Fluvial archives from past to present), 2014 (Cordier et al., 2014) |
| FLAG/GLOCOPH Session within 28th INQUA Congress, Bern, Switzerland, July 2011 (Palaeohydrological archives, fluvial environments and surface–groundwater flow processes) | Special issue, Geomorphologie, Paris (from fluvial geomorphology to fluvial archives); Cordier and Bridgland (2012) |
| FLAG 2010 Meeting, Castelo Branco, Portugal, September 2010 | Special issue, Geomorphology (165–166), Techniques for analyzing Late Cenozoic river terrace sequences (Stokes et al., 2012) |
| FLAG 2008 Meeting, Budapest, Hungary, September 2008 | Special issue, Proceedings of the Geologists Association, 2010 (Vandenberghe et al., 2010) |
| IGCP 518 Plenery Meeting, Nanjing (session of CHINQUA) and excursion to Middle Yangtze, October 2006 | Included within special issue of Global and Planetary Change (Vol. 68, issue 4 of 2009; Westaway et al., 2009) |
| FLAG 2006 Meeting, Izmir, Turkey, September 2006 | |
| IGCP 518 Plenery Meeting, Şanlıurfa, Turkey, September 2005 | Special issue, Global and Planetary Change (Vol. 68, issue 4 of 2009; Westaway et al., 2009) |
| European geoscience Union (EGU) Symposium, Vienna, April 2005; FLAG co-sponsored session | Special issue, Geomorphology (Issues 3–4 of 2008); papers published online in 2007 (Vandenberghe and Vanacker, 2008) |

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| Final IGCP 449 Plenary Meeting, Malaga, Spain, December 2004 | Special issue, Quaternary Science Reviews (Vol. 26 Parts 22–24 of 2007; Bridgland et al., 2007) |
| FLAG 2004 Meeting, Sienna, Italy, September 2004 | FLAG/SEQS* special issue, Quaternary International (Vol. 181 of 2008) |
| 4th IGCP 449 Plenary Meeting, Belem, Brazil, June 2003 | Papers in South American Journal of Earth Sciences, 2006 |
| 3rd IGCP 449 Plenary Meeting, Agadir, Morocco, December 2002 | |
| FLAG 2002 Meeting, Clermont-Ferrand, France, September 2002 | Special issue, Quaternaire, 2004 (Volume 15, No. 1–2) |
| FLAG / GLOCOPH / IGCP 449 meeting (Wollongong, Australia, August 2002) | |
| 2nd IGCP 449 Plenary Meeting, Kanpur, India, December 2001 | Collection of papers, Current Science, New Delhi, 2003 (Volume 84, Number 8, 25 April 2003) |
| Inaugural IGCP 449 Plenary Meeting, Prague, Czech Republic, April 2001 | Collection of papers, Proceedings of the Geologists Association, 2004 (Bridgland et al., 2004) |
| FLAG 2000 Meeting (Mainz, Germany, March 2000) | Special issue, Netherlands Journal of Geosciences, 2002 (Bridgland and Sirocko, 2002) |
| FLAG 1998 Meeting (Cheltenham, UK, September 1998) | Edited volume, Balkema (Maddy et al. 2001) |
| FLAG 1997 Meeting (Arcen, Netherlands, September 1997) | |
| Inaugural Discussion Meeting (Durham, UK, December 1996) | |