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Editorial: Quaternary Revolutions

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Just over 50 years ago, in April 1964, the Quaternary Field Studies group held its first meeting in Birmingham in the UK. This group became the Quaternary Research Association and, amongst other activities, established the *Journal of Quaternary Science* in 1986. It thus seems particularly apt to publish this themed set of five papers arising from a meeting celebrate the 50th anniversary of the QRA in *JQS*. Since 1964, Quaternary science has developed rapidly and become much more integrated with other areas of the environmental sciences, contributing to far-reaching debates on the Earth system and its relationship with past and future human development and society. This is perhaps most clear at the interface with climatology and meteorology in understanding natural climate variability in relation to future anthropogenically-driven climate change (Masson-Delmotte et al., 2013; and see McCarroll, 2015). There are many other developments that have been particularly important in increasing the scope, influence and thinking in relation to 'big science' problems and their relevance to society. The '*QRA@50*' meeting (Royal Geographical Society, 2014) was conceived around the notion of 'revolutions' in Quaternary science and a series of invited speakers discussed eleven themes covering a wide range of Quaternary research. The speakers were asked not just to review the science for these themes, but to focus on critical developments that have brought paradigm shifts in thinking, to examine the current state of the art, and to look forward to future potential 'revolutions'. Some speakers elected to perform 'double acts' with two speakers with differing or complementary views on the same topics, whilst others took on coverage of distinct aspects of one of the themes.

In organising the programme, and in confirmation of the vigorous and robust discussion that often characterises Quaternary science, it was clear from the start that there was no consensus on the key strands of Quaternary science that should provide the structure for such a meeting. Even the selection of themes proved controversial: Are the main revolutions in the science related to technical developments, process understanding, or theoretical underpinning? Should we concentrate on climate or organise around the atmospheric, oceanic or terrestrial realms? Do central themes in Quaternary science trump broader relevance to other areas of science and society? Is blue skies fundamental science more critical than the applications to a broader and more pragmatic set of problems? Inevitably, it was impossible to cover all topics comprehensively, but we elected to cover themes that we hoped would enable speakers to bring out the most important and widely relevant issues from the last 50 years of Quaternary science. The meeting also saw the launch of a book covering the history of the people and events of the QRA, and which also attempted to identify the key scientific contributions of one the world's most active Quaternary science organisations (Catt and Candy, 2014). The full range of the programme is archived along with the 153 abstracts from the talks and posters on the Royal Geographic Society website (RGS, 2014). The papers that appear here are based on a selection of the oral contributions given at the meeting. Three of them combine the contents of two talks, mirroring the double act structure of the meeting. They all embrace the concept of combining retrospective and prospective narratives of the topics. Some of the views are controversial and will evoke strong disagreement. This is just as we intended; we encouraged personal reflections and a clear view of the past, but also of the future of Quaternary science.

Wherever you look in Quaternary science, the need for measuring time is paramount. In the first of this themed set of papers, John Lowe and Mike Walker tackle the potentially vast and technically difficult subject of chronologies (Lowe and Walker, 2015). In reviewing the last half century of progress, they emphasise that there was rather little discussion of chronology in the early 1960s, simply because many of the methods were unavailable, poorly developed or not widely available. The vast majority of the chronological tools used routinely today had not been developed or were in their infancy. Rather than attempting an impossible detailed review of chronology, they focus on the stratigraphic templates provided by the marine oxygen isotope record and the Greenland ice cores. The significance of these records and their importance in providing a framework of environmental change and chronology through the Quaternary is beyond doubt and many other records can be fitted within these broad templates to highlight key aspects of long term climate change and Earth system response. However, we are reminded that the underlying assumptions involved in correlating or tuning records to these frameworks limit the questions that can be asked of them. Quaternary sediments record the response of the system to external forcing and the assumptions of correlation and errors in the underlying chronologies mean that we are often unable to detect leads and lags in records. For example, making assumptions about the bipolar see-saw, where the asynchrony between the poles is clearly demonstrated for the last glacial-interglacial cycle at millennial scale, at sub-millennial scale constrains the ability to perceive differences in behaviour that may point to important processes in the Earth system. Progress on these problems can only be made by improving the precision of the chronologies in the individual records, and techniques such as varve chronology, tephrochronology and high precision radiocarbon dating are now revealing such diachronous behaviour, in the Lateglacial for example. In looking forward, the authors highlight the growing importance of multiple and combined dating methods, the statistical tools to deal with them, and replication of records to more robust stacked records from multiple cores and sites. They stress that the acknowledgement of uncertainty in chronologies has been a major development across Quaternary science. Lowe and Walker comment that recognising the limitations of the chronologies is the first step; reducing this uncertainty further is a major target of next 50 years. Whilst this is undoubtedly true, it is also vital that the improved chronologies are developed with the appropriate level of precision and accuracy to answer the research question being asked. Otherwise there is a risk that Quaternary geochronology becomes an end in itself, the very danger that Lowe and Walker themselves highlight.

When it comes to precision and ability to directly compare events in different places, there can be few more powerful potential tools than tephrochronology. Siwan Davies addresses this topic and focuses especially on the revolution in correlation and dating of Quaternary sequences prompted by the discovery and application of cryptotephra (Davies, 2015). The number of papers documenting the search and discovery of volcanic ash layers invisible to the naked eye has grown rapidly since the discovery of Icelandic ash in Scotland (Dugmore, 1989). Davies documents the development of the critical underpinning methodologies used to improve the detection and identification of crypototephra, and stresses the need to understand taphonomic processes so that the full potential of the use of tephra isochrons can be realised. In exploiting cryptotephra as a chronological tool, Davies also refers to the necessity of multiple dating techniques for chronological development. Whilst correlation using the same tephra layers is precise, absolute age estimates for tephra are often based on dates from the sediments in which they are found and chronological models often include tephra alongside other age markers.

It is clear that this is a science still in its early development. Much has been gained, but there is clearly much more to come in future, as more locations and sediments are explored and techniques for detection improve. A key challenge is one of complexity of the growing number and range of tephras discovered. The problems of data quantity and management are surely surmountable as long as data are available and properly archived, but the technological challenges in separating ashes of similar composition are more problematic. Davies concludes by returning to the ultimate purpose of tephrochronology; the application to Quaternary records that are directed at key questions of environmental and climatic science. Whilst it is easy to be enthused by the very process of discovery of new tephras in a growing number of locations and sedimentary contexts, it is only in the application to wider Quaternary science problems that the full value of this burgeoning area of Quaternary science will be realised.

In turning from chronologies, two areas of Quaternary science are reviewed and discussed by two of the double act speakers at the meeting. The first is a wide ranging review that identifies four important revolutions in the science of Quaternary sea-level change (Gehrels and Shennan, 2015), with a critical commentary on past and future possibilities in this field. Their first point is on the concept of eustasy and the identification of a single globally applicable sea level curve. The search for such a curve has been productive in many ways but the concept has clearly been misapplied in many studies. The second issue addressed is the need for proper account to be taken of the resolution of sea-level reconstructions. As with chronology (see above and Lowe and Walker, 2015), it is difficult to see how changes with an amplitude smaller than that of the precision of the proxy record can be reliably identified. Gehrels and Shennan convincingly dispel the notion that rapid mid- and late-Holocene fluctuations in sea level are detectable in many of the records, as some previous authors have suggested. Perhaps more importantly, they question whether such fluctuations are physically plausible. Larger magnitude sea-level change can be reliably detected and three types of rapid change are evaluated; sea-level rise associated with melt water pulses from the collapsing ice sheets, rapid changes over very short time scales associated with seismic and tsunami events, and storm surges over a single tidal cycle. The final part of the discussion covers the integration of Quaternary sea level data with models of the earth-ocean-cryosphere and the need to exploit this synergy to a greater extent. In concluding the paper, Gehrels and Shennan highlight some 'inconvenient truths' about sea-level science that could equally well apply to other areas of Quaternary science. As all good reviews should do, they remind us that many ideas are not new and we need to build on these concepts, not reinvent them (beware dependency on Web of Science and the internet search engine!). They also suggest humility; respect the complexity of the system, be realistic about precision of proxy-based sea-level estimates, replicate to generate more robust records, and adopt multiple working hypotheses in interpreting the data.

The second double act presentation giving rise to a paper is that of Terry Brown and Ian Barnes on ancient DNA (aDNA) (Brown and Barnes, 2015), a field that is very clearly completely new in the last 50 years, with a history covering only just over half that period following its beginnings in the mid-1980s. Whilst clearly a technological revolution in the way we access past biological information, and a spectacular start to the science, initial development was marred by a realisation that many of the early and most spectacular results were false positives arising from contamination with modern DNA. A complete rethink on methodology and establishment of strict protocols partly addressed the problem, but technological development was the real key to reliable aDNA analysis. Brown and Barnes summarise this most recent revolution in the field, Next Generation Sequencing (NGS), which is now leading to the new subfield of palaeogenomics. This is the analysis and reconstruction of entire genomes from fossil material and is still a challenging field, but with a growing number of results being published. Not least amongst the challenges is the removal of the sequences derived from the bacteria associated with fossil material. Whilst not as serious a problem as contamination with modern DNA, this remains an issue in contexts where the abundance of the target DNA is very low. Palaeogenomic work over the last few years has provided spectacular insights into the contribution of ancient hominins such as Neanderthals and Denisovans to the modern human gene pool. The potential of palaeogenomics of non-human species is also tremendous, although as yet not explored in any depth. Equally tantalising is the potential of analysis of sedimentary DNA, revealing the presence and genetic makeup of species not even present as preserved macrofossils. It is hard not to be inspired by the potential of such an enormously powerful technique, but the authors conclude with a reminder that excitement over potential applications and results has to go hand in hand with more sober assessment and development of reliable methodologies and technological progress.

The final paper in the series is one that will no doubt stir some debate. Given the challenge of future anthropogenic climate change, Danny McCarroll critically evaluates the existing and potential extent to which Quaternary science has contributed to climate change prediction (McCarroll, 2015). He explores this over a range of timescales in terms of understanding climate dynamics, the future principal drivers of climate change, quantifying climate sensitivity to increased greenhouse gas forcing, and climate model evaluation. He argues that we have to adapt our approach to Quaternary science if we are to improve our contribution to the science of climate modelling and the prediction of future climate change. In particular, he suggests that traditional, often inductive, approaches to interpreting palaeoenvironmental records limits our ability to target research on testing critical hypotheses of climate change. He also suggests that this approach has hampered efforts to fully understand important natural forcing factors such as solar variability. A third area of criticism is that we have placed too much emphasis on the role of the North Atlantic as a driver of climate variability, when set against experimental and monitoring data of modern ocean processes. His over-riding message is that given the importance of future climate change and the imperative to understand and mitigate it better, more of our science needs to be carefully directed at this as a problem. When we invited Danny to give a lecture at the meeting, we did so precisely to generate this type of contribution; wide ranging, critical and somewhat polemic in approach, but consequently thought provoking and likely to stimulate debate and critical reflection amongst the community. There are certainly areas one could argue over. For example, how would the large scale climate reconstructions important for testing general circulation models be built up if it were not for the hundreds of ‘climate narratives’ on which they are based, which were developed by past research for other purposes? Clearly indiscriminate future data collection is not to be recommended, but the targeted collection of data from data poor regions or a larger range of climate variables may be critical to testing hypotheses on past climate variability other than those which arise directly from climate modeling. Equally, over-emphasis on a single time period may not provide the most robust test of some aspects of climate dynamics, especially as the next few hundred years will undoubtedly see a shift towards climate variability that exceeds the envelope of change that has occurred in the last millennium. Notwithstanding the criticisms that could be levelled at aspects of the argument presented in this paper, we very much hope that readers will take it constructively and that the work will encourage more Quaternary researchers to think carefully about the scientific motivation and methodological approach in their work. If this collection of papers serves to stimulate some of these thoughts and promote new ideas on the future direction of our science, we will have achieved our aim in celebrating the last fifty years of the QRA and looking forward to the next fifty.

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