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Advances in Scottish Quaternary Studies: Preface

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This Special Issue of the *Earth & Environmental Science Transactions of the Royal Society of Edinburgh* examines the advances in Quaternary science in Scotland over the last 25 years. It comprises a collection of invited papers that review the main developments in our understanding of landscape evolution and environmental history during the Quaternary and set out the authors' perspectives on future research directions and challenges. The Quaternary, the last ∼2.6 Ma of geological time, comprises the Pleistocene (2.58 Ma to 11.7 ka) and Holocene (11.7 ka to present) epochs. It has been a period of remarkable climate changes, with rapid shifts from glacial to interglacial conditions and in the accompanying geomorphological processes. These have interacted with the underlying geology and preglacial relief to play a fundamental role in shaping the great diversity of the present landforms and landscapes of Scotland. This geodiversity is an essential component of Scotland's rich and internationally important environmental assets and natural capital. As is the case for biodiversity, the key elements of geodiversity merit conservation as part of our geoheritage. This is vital for both field-based research and education that are essential to further advance geoscience, and also for the wider benefits and services provided for society. For example, learning from the past has an essential part to play in understanding and responding to pressing challenges faced by society today, such as climate change adaptation, loss of biodiversity, sea-level rise, natural hazard mitigation and sustainable economic development (Gray *et al*. 2013; Prosser *et al*. 2013; Stewart & Gill 2017).

The publication of the *Quaternary of Scotland* volume (Gordon & Sutherland 1993) in the Geological Conservation Review (GCR) series represented a benchmark in the conservation of Quaternary sites and was followed by volumes on fluvial and coastal geomorphology, mass movements, and karst and caves. Not only did these volumes provide a review of contemporary knowledge across the range of sub-disciplines of Quaternary science in Scotland, but also they documented systematically for the first time the scientific value and rationale for the selection of over 200 key localities of national and international importance. These audits have provided the scientific basis for the designation of Sites of Special Scientific Interest (SSSIs) representing Quaternary landforms, deposits and environmental records in Scotland. The assessment and documentation of these sites were primarily undertaken during the 1980s and 1990s. Since then, major advances have been made, particularly through the application of new and improved dating techniques, the establishment of systematic stratigraphic frameworks, the development of ice-sheet models and landform mapping using remotely sensed imagery, both onshore and offshore. Hence, 25 years on, it is timely to review this progress both from a scientific perspective and for the implications for the scientific underpinning of the GCR site networks and the supporting documentation.

In this Special Issue, **Hall *et al.*** highlight current understanding of the somewhat neglected Early and Middle Pleistocene and emphasise the importance of long-term landscape evolution during the course of multiple glacial and interglacial episodes. Glacial erosion modified the pre-existing terrain to varying degrees, reflecting the different modes of glaciation – mountain icefield, ice cap and ice sheet – and the spatial and temporal variations in glacier dynamics. However, widespread weathering and non-glacial erosion occurred through the Pleistocene, the effects now evident mainly in NE Scotland, the eastern Highlands and on higher elevation terrains that lack pronounced glacial bedforms. Early and Middle Pleistocene terrestrial deposits are generally poorly preserved in Scotland, and **Hall *et al.*** emphasise the value of key Middle Pleistocene sites in NE Scotland that escaped significant glacial erosion by later ice sheets.

Because of greater preservation of evidence, the Late Pleistocene has continued to be the major period of research focus. In this issue, **Merritt *et al.*** highlight the value of terrestrial stratigraphic records for elucidating the timing, sequence and patterns of glaciation and deglaciation during the last glacial–interglacial cycle and for constraining ice-sheet models. They also detail the substantial progress that has been made in understanding the age and palaeoenvironmental significance of pre-Marine Isotope Stage (MIS) 2 interglacial and interstadial deposits and their stratigraphic context through systematic re-investigation of key localities. Other lines of evidence indicate significant glacier presence in Scotland during the Early and Middle Devensian (MIS 5d-3) and multiple phases of mountain ice-cap and ice-sheet glaciation before the main expansion of the last Scottish ice sheet after ∼35 ka. They also show that earlier interpretations of ice-free terrestrial enclaves in peripheral locations are not substantiated, apart from St Kilda. Both **Merritt *et al.*** and **Ballantyne & Small** highlight the climate sensitivity and dynamic character of the last Scottish Ice Sheet. The latter show that the timing of the maximum ice extent was diachronous for different sectors and that the dynamics were strongly influenced by the behaviour of fast-flowing ice streams within the ice sheet. The application of terrestrial cosmogenic nuclide (TCN) dating has enabled much greater insights into the pattern and timing of deglaciation across Scotland. A key finding is that the last Scottish Ice Sheet lost most of its mass before the onset of rapid climate warming at the beginning of the Lateglacial Interstade at ∼14.7 ka.

In contrast with the truncated and discontinuous onshore sedimentary evidence, a significant part of the Scottish Quaternary record lies in the offshore sedimentary archives on the continental shelf and adjacent deep-water areas and in the seabed geomorphology. The application of detailed seabed mapping of glacial and other landforms, high-resolution seismic surveys, multibeam echo sounding and coring is now enabling a fuller and more integrated understanding of the extent and timing of glaciation and deglaciation, ice-sheet

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dynamics and climate change over the duration of the Quaternary (Phillips *et al*. 2017). For example, there is now evidence of repeated ice-sheet glaciation in the North Sea basin from early in the Pleistocene (Rea *et al*. 2018), while the dynamics and pattern of deglaciation of the last Scottish Ice Sheet have been shown to be strongly influenced by marine processes and bathymetry (Bradwell & Stoker 2015; Callard *et al*. 2018; Bradwell *et al*. 2019). The responses of the Scottish palaeo-ice sheets and palaeo-ice streams to different forcing factors have the potential to help better understand the longer-term dynamics of contemporary ice sheets in Greenland and Antarctica, whose future stability is a matter of concern under conditions of global warming, sea-level rise and possible changes in ocean circulation (Stokes *et al*. 2015).

The Lateglacial period, between ∼14.7 ka and 11.7 ka, was a time of rapid and pronounced environmental and geomorphological changes, reviewed by **Walker & Lowe** and by **Ballantyne**, respectively. **Walker & Lowe** highlight the advances in the different types of proxy evidence (pollen and plant macrofossils, coleoptera, chironomids and diatoms) used to reconstruct the spatial and temporal patterns of environmental change, and the application of new dating methods (using accelerator mass spectrometry (AMS) radiocarbon, tephrochronology and TCN methods) to establish an event stratigraphy. They emphasise the potential links between records in Scotland and the Greenland ice core isotopic records and the importance of placing Scotland in the context of climate change in the wider North Atlantic region. **Ballantyne** highlights, in particular, the progress in understanding rock-slope failures, debris-flow activity and the evolution of bedrock river channels. The paraglacial concept has provided an important new framework for understanding rock-slope failures and the release, reworking and re-deposition of glacigenic sediment stores by slope and fluvial processes. While the role of some paraglacial processes has declined during the Holocene, large sediment stores remain on hillslopes and under floodplains, so that the period of postglacial paraglacial landscape modification may ultimately extend well into the future. **Ballantyne** notes, however, the lack of a consistent trajectory of Holocene landscape evolution since the effects of declining sediment supply and climate change are overprinted by more local factors, notably extreme climatic events and anthropogenic effects.

Edwards *et al.* examine the contribution of palaeoecology in studies of environmental changes during the Holocene, and they highlight the progress and challenges in understanding woodland and blanket peat dynamics and the role of human impacts on the landscape. More is now known about the time-transgressive expansion of woodland species and the altitudinal variation in woodland extent, as well as the decline in woodland cover after about 6 cal ka BP as blanket peat spread in N and W Scotland and human impacts on the landscape increased in the S and E. Nearly a quarter of Scotland is covered by blanket peat, but the timing of the formation processes and the factors underlying its spread continue to remain a matter of debate. In a recent development, palaeoecological evidence is helping to inform conservation of plant biodiversity, which has declined over recent centuries. In particular, palaeoecological evidence can be used to provide baselines and assess restoration targets, to improve understanding of how ecosystems have changed over time and their resilience to climate change and other stresses, and to help identify situations where modern conditions have no past analogues.

Relative sea-level (RSL) changes have been a longstanding theme in Scottish Quaternary research. **Smith *et al.*** highlight our greatly improved knowledge of RSL changes particularly through the investigation of the detailed sedimentary records from isolation basins on the coasts of W and NW Scotland, as well as from estuaries elsewhere, based on improved field and analytical methods. The use of new microfossil proxies, combined with studies of sediments and stratigraphy, has enabled better understanding of changing environmental conditions, tidal levels and depositional processes, and provided new detail on Late Devensian and Holocene RSL change, as well as indications of global meltwater pulses from far-field sources. There has also been improved understanding of storms and extreme events, both recently and historically, and of the Holocene Storegga Slide tsunami (∼8.1 cal ka BP). Progress has also been made in the study of rock shoreline processes, although erosion histories during the Quaternary remain uncertain. The development of quantitative glacial isostatic adjustment (GIA) models is also enabling better understanding of the pattern and timing of land uplift during and following deglaciation of the last Scottish Ice Sheet.

Looking to the future, a number of important research directions and challenges emerge from these reviews, some of which are highlighted here. Dating and chronology remain crucial. Application of TCN dating has significantly advanced our understanding of the timing and pattern of the last ice sheet and its deglaciation, as outlined in the review by **Ballantyne & Small** and in publications from the BRITICE-CHRONO project. This should greatly improve identification of the links between climate, ice-sheet dynamics, glacio-isostasy and sea-level change. Also, as noted by **Hall *et al.***, there is great potential to extend TCN dating and other emerging techniques to establish long-term rates of erosion for both glacial and non-glacial processes over the full duration of the Pleistocene and to redress the neglect of the Early and Middle Pleistocene. Continued work to link offshore records with terrestrial landforms and stratigraphy will be crucial. **Merritt *et al.*** comment that improvements in landform mapping through use of digital surface models and applications of three-dimensional modelling based on borehole data should help to improve links between morphostratigraphy and lithostratigraphy, and combined with detailed field mapping, excavations and coring in areas with potential for survival of extended sedimentary records, should help particularly to resolve the pre-MIS 2 stratigraphic record, including RSL changes.

In the context of the Lateglacial, but equally applicable across other timeframes, **Walker & Lowe** emphasise the need for multi-proxy, hypothesis-testing approaches and methods that are most sensitive to climate shifts to help distinguish more immediate and lagged responses to climate forcing. They highlight the importance of extending and refining the tephra record for Scotland, more targeted application of AMS radiocarbon dating using identifiable terrestrial macrofossils and possibly pollen grains, and the potential for varve chronology and use of TCN chronologies to augment patterns of regional environmental change established by other methods. **Ballantyne** also highlights the importance of hypothesis-based research design to build on our much improved but still incomplete understanding of postglacial geomorphological processes and the stratigraphic record to realise the potential of the many new analytical methods and techniques available to further our knowledge of landscape changes. Among the challenges he identifies are improved understanding of lowland periglaciation during the Lateglacial, the processes and triggering factors underlying rock-slope failures, the potential for representation of fluvial and slope processes in lake sediments and the timing and patterns of floodplain incision and aggradation. At the coast, **Smith *et al.*** identify as priorities: (i) better understanding of the offshore record of RSL changes; (ii) determination of the age of inherited rock shorelines; (iii) acquisition of RSL

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records from areas peripheral to the centre of isostatic uplift; (iv) investigation of the comparability of sea-level records derived from isolation basins and estuaries; (v) the need for more records and better understanding of RSL changes during the last 2 ka to help inform assessment of likely future changes and adaptation strategies; (vi) discrimination between tsunami and storm events as sources of extreme coastal flooding in the sedimentary record; and (vii) further refinement and validation of GIA models. With regard to land cover, **Edwards *et al.*** highlight issues regarding the establishment and modification of the altitudinal zonation of vegetation and particularly woodland cover, the estimation of vegetation openness, the interrelationships between human activity and changing land cover, and the improved integration of palaeoecological data into conservation planning.

All these studies depend on the availability of field sites, not only to provide new or extended records but also to test new hypotheses and apply new analytical methods. They include type or reference localities for particular time periods or events; reference sites for sediments, landforms, deposits or fossils indicative of past environmental conditions; sites with extended stratigraphic records; sites with features representative of particular time periods or events or particular geomorphological processes or landforms, or that are unusual or distinctive; and classic textbook features and landscapes. While several authors mention the importance of searching for new sites, it is critical that the most scientifically valued existing sites are recognised and protected for further study and education. We are fortunate in Scotland, as in the rest of Great Britain, to have the GCR, which provides the scientific basis for the statutory protection of SSSIs for geoheritage. In the final contribution to this Special Issue, **Gordon *et al.*** examine progress in geoconservation and consider the implications of recent advances for the GCR. As they note, the principal phase of site selection was completed in the early 1990s, but the site lists and the supporting site documentation now require updating as part of an ongoing process to reflect the advances in scientific knowledge. The review papers in this Special Issue provide a starting point for the necessary revisions. In addition, **Gordon *et al.*** also reflect on the wider values of geoconservation and the need for its better integration in the developing nature conservation agenda. There is growing emphasis on the role of protected areas in connecting people and nature and the contribution of natural capital in delivering ecosystem services and benefits. The latter include natural solutions to hazard mitigation as exemplified in recent studies in fluvial and coastal geomorphology. These wider values are not incorporated within the GCR process and criteria but are vital to help gain wider support for geoconservation. This may require developing alternative approaches to conservation management at the landscape scale, which also recognise the wider biodiversity, cultural, aesthetic and geotourism values of Scotland's geodiversity and geoheritage.

Finally, as **Walker & Lowe** observe, 'the more we know the more there is to know'. The next 25 years will hopefully see many more new advances as well as many new questions about the Quaternary in Scotland.

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