Glacial deposits provide a long-term record of climate and sea level changes on Earth. Detailed study of sedimentary rocks deposited during and immediately after glacial episodes is paramount to accurate paleoclimatic reconstructions and for our understanding of global climatic and eustatic changes. This book presents new information and interpretations of the ancient glacial record, looking in particular at the Late Proterozoic and Late Paleozoic eras. The influence of global tectonics on the origins and distribution of ice masses and the character of glacial deposits through geologic time is emphasised. Sequence stratigraphic techniques are applied to glaciogenic successions, and explanations are put forward for possible low-latitude glaciation during the Late Proterozoic era and the association of carbonate deposits with glaciogenic rocks. Early interglacial conditions, represented by dark-grey mudrocks and ice keel scour features, are discussed. These studies, from key workers in International Geological Correlation Program Project 260, will aid the understanding of Earth's climatic history.

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Earth's Glacial Record

EDITED BY
M. DEYNOUX, J. M. G. MILLER,
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Preface

An IGCP contribution

This volume represents the final contribution of the International Geological Correlation Program Project 260 'Earth's Glacial Record'. The project was active from 1987 until 1991. It succeeded IGCP Project 24 'Quaternary Glaciations in the Northern Hemisphere', and Project 38 'Pre-Pleistocene Tillites'. Thus, its goal was to promote further research on glaciations, whatever their age and location, and to encourage geologists working in Modern or Quaternary sequences and those working on Pre-Pleistocene rocks to share their experience and different approaches. In this way we hoped to emphasize and illuminate global aspects of glacial phenomena in addition to facies description and regional problems. Participants in the project were encouraged to consider the tectonic versus climatic control on sedimentation in glacially influenced basins, the nature of the feedback between plate positioning, tectonics, and climate, and the paleoenvironmental significance and distribution of specific rock types (e.g. black shales, carbonates, iron formations, etc.) during and immediately after glacial periods.

These ambitious objectives were addressed by three subgroups that were in charge of, respectively, geodynamic setting, paleomagnetic reconstructions, and significance of specific rock types. Yearly meetings and field trips were held in various countries (10 field trips in Canada, Brazil, USA, UK, Mali), covering a vast variety of structural terranes (active and passive margins, intracratonic basins) from Proterozoic up to Modern in age. This clearly demonstrated the interest in and necessity for such a comprehensive approach among geologists. We do not pretend that all objectives were perfectly met, but aspects have been clarified and progressively more communications on global climatic or tectonic implications were presented during the successive meetings. This awareness of the importance of a global approach is certainly one of the most significant results of the project.

A second outcome of the project is a definite improvement in communication among workers on ancient and modern deposits leading to more sophisticated facies interpretation. Such interaction, as well as the idea of submitting a common IGCP project, began at the Till Mauretania 83 Symposium (Deynoux, 1985*a*), when Quaternary and 'paleo' geologists examined West African Late Proterozoic glacial deposits. The final decision to submit the project, which was encouraged and supported in particular by J.C. Crowell and N.M. Chumakov, was made after an informal meeting during the 1986 International Sedimentological Congress in Canberra.

Content of the volume

The present volume complements the largely descriptive compilation made by Hambrey and Harland (1981) for IGCP 38. It is less encyclopedic and more interpretive. It reflects results of research on the IGCP 260 project themes outlined above.

One of the most puzzling climatic phenomena in the Earth's history is the possibility of glaciations at low latitudes, inferred from low paleomagnetic inclinations in many Late Proterozoic (Neoproterozoic) strata containing glacial deposits. In response to this paradox, a glacial origin for most alleged Late Proterozoic 'tillites' was denied by Schermerhorn (1974) in an excellent and somewhat provocative paper. Among his arguments was the occurrence of diamictites in active tectonic settings, implying that many diamictites may be explained better as deposited by debris-flow processes or in association with mountain glaciations, and the association of these diamictites with rocks generally indicative of warm climate, such as carbonate or iron deposits. Such an extreme position has in many cases been undermined by field evidence (Hambrey and Harland, 1981). However, Schermerhorn's paper forced reappraisal of arguments in terms of plate tectonic activity and reinforcement of those arguments which concern the glaciogenic origin of diamictite-bearing facies associations. IGCP Project 260 extended these themes by investigating the effect of tectonic setting upon the distribution and type of sedimentary facies in proven glaciogenic successions. The first nine papers of this volume address these themes.

N. Eyles and G.M. Young (p. 1) give an overview of glaciations in Earth's history and focus on the role of plate tectonic processes in the production and preservation of glaciogenic deposits. They demonstrate that strong uplift in active collisional margins or on the flanks of basins undergoing regional extension, and the resultant enhanced weathering that causes drawdown of atmospheric

CO_2, provide first-order controls on glaciations. Many points that they discuss are fleshed out in papers later in the volume. The paper by P.K. Link, J.M.G. Miller, and N. Christie-Blick (p. 29) may serve as an illustration of the Eyles and Young hypothesis on the origin of glaciations. They present well-documented examples of Late Proterozoic glacial-marine sedimentation along the margin of differentially subsiding basins that developed during an episode of rifting in western North America. They provide careful descriptions of diamictite-bearing facies associations and emphasize the common occurrence of relatively deep-water facies in most of the Late Proterozoic sequences of inferred glacial origin. In contrast, J.M.G. Miller (p. 47) illustrates the merits of Schermerhorn's arguments in an excellent example of Late Proterozoic diamictite-bearing facies associations in a continental rift system in eastern North America. She proposes that diamictites were deposited in a lacustrine environment under the influence of a local alpine glaciation.

The next two papers show the influence of local tectonics upon glacial sedimentation patterns during the Late Paleozoic. V. Von Brunn (p. 60) proposes a Permo-Carboniferous model in which glacial-marine deposits, including a large amount of diamictite, were formed within and on the flanks of a subsiding trough which developed over a failed rift. Depositional architecture appears largely controlled by pre-existing topography and glacially related sea-level changes. A.B. França (p. 70) presents an overview of the stratigraphy and hydrocarbon potential of the Carboniferous-Permian Itararé Group in the whole Brazilian Paraná Basin. The Itarare Group forms a continuous and thick record of a temperate glacial-marine environment in which the distribution and thickness of sedimentary units were affected by structural lineaments. This contribution is original because it concerns an economic aspect of the glacial sequences. According to structural setting and proximity of source rocks, the Itarare Group constitutes an excellent model for petroleum exploration.

Difficulty determining the origin of massive diamictites was frequently discussed at IGCP 260 meetings, J.N.J. Visser (p. 83) addresses this problem using four examples from the Permo-Carboniferous Dwyka Formation in South Africa. He proposes well-defined criteria, based on clast fabric and facies context, for the absolute identification of mechanisms of deposition of these diamictites in a glacial marine environment. Harking back to Schermerhorn (1974), Lu Songnian and Gao Zhenjia (p. 95) questioned the origin of two superposed Late Proterozoic diamictite-bearing formations in West China. Both formations were previously interpreted as glacial. Using stratigraphic and sedimentologic arguments, the authors demonstrate that the 'lower diamictite' corresponds to non-glacial debris-flows, the 'upper diamictite' to continental glacial deposits. Zheng Zhaochang and Li Yuzhen (p. 101) report Late Proterozoic glaciogenic successions in north-western China, which consist of massive to bedded diamictite layers deposited subglacially or as subaqueous debris flows, overlain by transgressive post-glacial, thinly bedded siltstones and shales. They emphasize the importance of regional and local facies context in inferring the glaciogenic origin of the diamictite.

Lastly, the paper by M.R. Gipp (p. 109) provides sedimentological models for the large-scale architecture of glaciated shelf and slope systems in Late Cenozoic active (Gulf of Alaska) and passive (Nova Scotia) margins. Processes of deposition appear identical on both active and passive margins, but the gross depositional architecture of glacial marine deposits differs depending on the preservation potential of sediments, which is controlled by tectonics and relative sea-level changes.

Recent years have seen the introduction of the exciting new concepts of sequence stratigraphy. Such ideas are particularly relevant to glaciogenic successions because of the associated rapid and large-scale sea-level changes. However, sequence stratigraphy remains scarcely used in glacial rock successions owing probably to local effects related to the common occurrence of glacigenic deposits in tectonically active areas. J.N. Proust and M. Deynoux (p. 121) propose a sequence stratigraphic model based on the definition of a depositional genetic unit and its evolution through space and time in the marine to continental transitional zone of an intracratonic glacially influenced basin. Their model is developed from detailed field analysis of Late Proterozoic glacially related deposits on the West African platform. These genetic units and their different development in a stacking pattern lead to the definition of different orders of stacked sequences that are interpreted in terms of short-term climatically (glacially) controlled and long-term tectonically driven baselevel fluctuation cycles.

As shown by the papers quoted above, geologists have strong arguments which confirm the glacial origin of several Late Proterozoic successions. However, this does not solve the problem of low latitude glaciations (Chumakov and Elston, 1989). Hypotheses such as fast-moving plates (Crowell, 1983) or global glacial climate (Harland, 1964) have been proposed but are difficult to support on paleomagnetic and geologic grounds. Astronomical causes have also been proposed (Williams, 1975, Sheldon, 1984), and in this volume G.E. Williams (p. 146) again addresses this problem which 'challenges conventional views on the nature of the geomagnetic field, climatic zonation, and the earth's planetary dynamics in Late Proterozoic time'. Williams gives new evidence (paleomagnetic and time-series analysis of tidalites, and paleoclimatic interpretation of periglacial structures) supporting his previous hypothesis of a large obliquity of the ecliptic ($>54°$) leading to a reverse climatic zonation and marked seasonality.

Although still used as an argument against glaciation, the co-occurrence of carbonate rocks and glacial deposits is common. However, there are many facets of the association. Skeletal carbonates are common in high latitude seas today but they do not have exact equivalents in Proterozoic rocks. As reviewed by Fairchild (1992) the extensive ice sheets of Late Proterozoic times appear to have encroached onto previously warm carbonate-forming environments which returned following glaciation. Glacial deposits are carbonate-rich primarily because of the incorporation of detrital carbonate. Subglacial redistribution of detrital carbonate by dissolution and reprecipitation by stress-related melting–freezing processes was proposed for some Late Proterozoic terrestrial tillites (Deynoux, 1985*b*). The discovery of marine recrystallization of

Late Proterozoic glacially transported rock flour in Svalbard (Fairchild *et al.*, 1989) gave new insight to the problem. Following this discovery, Crossing and Gostin (p. 165) investigated examples of diamictites in the Adelaide geosyncline of south Australia and found geochemical evidence from the composition of the matrix for deposition in a sea diluted by meltwater. Additionally, correlation between high Fe and reduced δ^{13} C values in the matrix suggests that bacterial activity accompanied the diagenesis of the rock flour. In order to gain a better understanding of the chemical processes involved when carbonate rock flours interact with fluids in glacial systems, investigations of carbonate-rich Quaternary glacial systems have been started, and I.J. Fairchild, L. Bradby, and B. Spiro (p. 176) report their preliminary conclusions. Although they stress the importance of postglacial processes in controlling lithification of the sediments, evidence is also found for the precipitation of calcite in the matrix of a refrozen meltout till. Since this article was prepared they have found similar material in unfrozen meltout till and basal ice.

The succession of glacial deposits in Late Paleozoic sequences across much of Gondwana is punctuated by a sharp contract between diamictites and overlying late- or post-glacial dark- to black-colored mudstones (Domack *et al.*, 1992). Such a sharp contact has also been described in intracratonic Late Proterozoic and Late Ordovician glacial sequences on the West African platform (see Deynoux and Trompette in Hambrey and Harland, 1981). The diamictite–black mudstone transition is important in that it is widely believed to represent the end of glacial climates within the regional extent of the basins in which it is found. Hence these rocks preserve a record of global warming associated with an apparently rapid 'glacial' to 'interglacial' transition. A similar hypothesis was also proposed for certain Proterozoic carbonate horizons capping glacial deposits (e.g. Williams, 1979). Depositional mechanisms for the dark to black mudstones are varied. J.N.J. Visser (p. 193) describes the conditions that prevailed in a shallow to moderately deep Late Carboniferous foreland basin (Dwyka glaciations of the Karoo Basin) after self-destructive collapse of a marine ice sheet resulting from a relative sea-level rise. The syn- to post-glacial dark to black mudrocks, which overlie the glaciogenic deposits, were deposited by suspension settling of mud and mud turbidites. Basin tectonics, oceanic circulation, and climate controlled the organic-rich black mud deposition. D.I. Cole and A.D.M. Christie (p. 204) also describe Early Permian black mudrocks overlying diamictites (debris and turbidity flows) deposited by a retreating tidewater glacier during the final phase of the Dwyka glaciation. The black mudrocks are the product of pelagic mud settling proximal to the ice front where freshwater plumes mixed with basinal saline water. They account for a sudden increase in organic productivity, indicating that the rapid termination of the Dwyka glaciation was accompanied by a sharp rise in temperature. M.F. Miller and J.W. Collinson (p. 215) describe the processes and environments that characterize the filling of a large Lower Permian post-glacial inland sea in Antarctica. Deposition in relatively shallow water was dominated by turbidity currents carrying fine-grained sediments in channel-overbank systems. The glacial environment allows the definition of a model in which a fine-grained turbidite system is paradoxically fed by a coarse-grained braided stream of the outwash plain.

Recent years have seen increasing interest in the sedimentary record of ice scours on continental shelves and lakes. Such structures and associated diamict deposits are widespread on Pleistocene shelves but are rarely known from the rock record. The paper by A.C. Rocha-Campos, P.R. dos Santos, and J.R. Canuto (p. 234) describes Early Permian iceberg scours. These scours are encountered on bedding planes of rhythmites inferred to be varves in a relatively deep freshwater body. C.M.T. Woodworth-Lynas and J.A. Dowdeswell (p. 241) argue that many striated surfaces, and associated diamictites found in ancient successions may have been produced by marine (or lacustrine) ice keel scour and report a modern analogue from the Greenland shelf. The need for a more critical examination of ancient glacial striated surfaces and associated facies is clearly indicated. Qui Rui Zhang (p. 260) describes periglacial indicators such as iceberg scours and dropstones, ice wedge casts, and glaciotectonic structures. These structures indicate that, instead of an abrupt erosional unconformity, the glaciogenic deposits of the Nanhua Ice Age (Late Proterozoic) of South China are locally conformably underlain by rocks that mark a progressive climatic transition from warm to cold.

Significance

The results of IGCP Project 260 are very relevant to current concerns about global change. As more details of the present climate and the climate of the Pleistocene are revealed, the interplay of ocean, atmosphere, biosphere and lithosphere with the internal heat engine of the Earth is being revealed as something of great complexity. We are still far from a complete understanding of the Earth's climatic system but glaciogenic deposits provide critical palaeoclimatic data. In spite of recent suggestions that some tillites/diamictites may be the ejecta of large planetesimal impacts (Rampino, 1992; Oberbeck *et al.*, 1993), extensive research and field studies demonstrate that the vast majority of documented ancient glaciogenic deposits correctly record periods of cold climate during Earth history. The discovery of mechanisms governing the appearance and disappearance of glaciers on Earth is paramount to the understanding of long-term climatic change, and the only long-term record of climatic change is the geologic record. The rock record of glaciation has been catalogued (Hambrey and Harland, 1981) but still has not been perfectly described. Since the 1983 Mauritanian meeting (Deynoux, 1985*a*), good facies descriptions of ancient glacial deposits have been proposed, and lately sequence stratigraphic concepts have developed. Now glacial sedimentology has joined the mainstream of sedimentology. In the near future, because most ancient glacial evidence is preserved in marine sequences, we must achieve a better understanding of the workings of glacially related marine basins.

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