Chapter 1

The geological record of Neoproterozoic ice ages

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The IUGS- and UNESCO-funded International Geoscience Programme Project #512 (Neoproterozoic Ice Ages) was conceived to contribute towards a global synthesis of current geological data on the number, duration, extent, causes and consequences of glacial episodes during the Neoproterozoic Era. IGCP 512 attracted more than 200 scientists from over 30 countries, many of whom provided their regional and specialist expertise on Neoproterozoic successions around the world to the realization of this volume. IGCP 512 focused on integrating various aspects of Neoproterozoic geology: geochronology, geochemistry, sedimentary geology, biostratigraphy, palaeomagnetism and economic geology. At its inaugural meeting on 27 August 2005 during the International Association of Sedimentology conference on glacial processes and products in Aberystwyth, Wales, IGCP 512 members decided to produce a volume that summarized existing data sets in a form similar to *Earth's Pre-Pleistocene Glacial Record* by Hambrey & Harland (1981).

An enormous amount of work has been carried out in the 12 years since the publication of Hoffman *et al.*'s (1998) paper on the Snowball Earth hypothesis for Neoproterozoic glaciation (Fairchild & Kennedy 2007). The Snowball Earth hypothesis and, more generally, Neoproterozoic climate, have been the topic of numerous special volumes, special sessions, a dedicated conference in Ascona (Switzerland) in 2006 (Shields 2006), and numerous documentaries. Motivated by this intense worldwide interest in the Neoproterozoic glaciations and an exploding body of research into the topic, this volume synthesizes the state-of-the-art in this now highly multidisciplinary research field. It is intended to facilitate the integration of data sets, inspire new research projects, and inform ongoing work into the definition and subdivision of the Neoproterozoic timescale, including selection of the Global Stratotype Section and Point (GSSP) for the base of the Cryogenian Period. Despite such lofty aims, any book such as this cannot claim to be complete, and there are indeed many gaps in our knowledge and also in this book's coverage, some of which are outlined in this Introduction and throughout the volume.

Book organization, format and terminology

This book contains ten introductory overview chapters followed by 60 site- or succession-specific chapters. The multidisciplinary overview chapters provide reviews of the study and interpretation of Neoproterozoic glaciations. The first chapter by **Hoffman** reviews the history of research (1871–1997) into late Precambrian glaciations from the first recorded discovery of Neoproterozoic glaciogenic rocks at Port Askaig on Islay, SW Scotland in 1871 to just before the renewal of interest in their significance after 1998. **Arnaud & Etienne** provide a 'user's guide' to the identification of glacial influence in the rock record, with emphasis on the processes and sedimentary products found in various glaciated basins as well as some common issues encountered with determining the palaeoclimatic significance of commonly used indicators of glacial palaeoenvironmental conditions. Geochemistry, in particular, isotope chemostratigraphy, has been key to the recent revival of interest in Neoproterozoic climate change and underpins models of both glaciation and global correlations. **Halverson & Shields-Zhou** review Neoproterozoic chemostratigraphic records with a focus on how they have been applied to palaeoenvironmental studies and to constrain both the number and relative timing of glacial events.

Hoffman *et al.* then review the occurrence of chemical sediments and their depositional environments associated with the Neoproterozoic glaciations. In particular, the role of the enigmatic, post-glacial 'cap carbonates' and the reoccurrence of iron formations after a billion-year hiatus are explored here. Climate affects how rocks are weathered, and this in turn influences the global carbon cycle, a key factor in modulating global climate change. **Bahlburg & Dobrzinski** offer in this regard a more specific review of the application of the Chemical Index of Alteration (CIA) to Neoproterozoic glacial deposits. If the Snowball Earth hypothesis remains contentious, the following chapter should at least dispel any doubt that Neoproterozoic glaciation reached the tropics. In their review of palaeolatitudes of Neoproterozoic glacial deposits, **Evans & Raub** contribute a comprehensive compilation of locations and available palaeomagnetic data for Neoproterozoic glacial deposits worldwide. **Condon & Bowring** also provide a much needed user's guide to Neoproterozoic geochronology, with emphasis on the most commonly used techniques, their strengths and weaknesses and the source of uncertainties that should be considered when using these data to constrain the timing of climatic changes. In addition, Condon & Bowring provide a summary of the key geochronological constraints on the timing and duration of glaciations and other significant Neoproterozoic events related to isotopic excursions and biological evolution. **Grey *et al.*** tackle the Neoproterozoic fossil record, and in particular the question of how climate change affected life on Earth. In their detailed review, they formulate a Cryogenian biostratigraphy based on Australian data, which can potentially be used as a template for such studies, generally still in their infancy, in other regions and for other Proterozoic time periods. In the final overview chapter, **Goddéris *et al.*** provide a critical review of the widely differing climate models that have been used to investigate the onset and melting of a Snowball Earth and highlight that whereas initiation of a Snowball Earth is

From: Arnaud, E., Halverson, G. P. & Shields-Zhou, G. (eds) *The Geological Record of Neoproterozoic Glaciations*. Geological Society, London, Memoirs, **36**, 1–16. 0435-4052/11/$15.00 © The Geological Society of London 2011. DOI: 10.1144/M36.1

not difficult to accomplish in many models, how the Earth escapes from the icy grip of a snowball requires more study from a modelling perspective.

The remaining chapters, organized by current geography, address specific sites from around the world where Neoproterozoic deposits have been studied. The purpose of these chapters is to provide a summary of available data and key references; they are not comprehensive reviews. Each chapter was intended to follow a consistent format in order to cover concisely the following topics and to facilitate cross chapter comparisons: structural framework, regional stratigraphy, sedimentary characteristics of glacial strata and associated deposits, boundary relations with non-glacial strata, chemostratigraphy, palaeomagnetism and palaeogeography, geochronology and a discussion outlining interpretations that can be inferred from these data. The *structural framework* section was designed to include a description of the overall structural and tectonic setting (such as cratons, types of sedimentary basin, regional-scale folds and faults) as well as the degree to which the sections have been modified by post-depositional tectonism and metamorphism. Authors were also asked to discuss the history of basin development in the region. The *stratigraphy* section was meant to provide an overview of the relevant stratigraphic units with comments about any lateral variations. The *glaciogenic and associated strata* section was designed to include descriptions of typical sedimentary characteristics of the glaciogenic and associated strata such as ironstones and carbonates, with the nature of contact with the overlying and underlying non-glacial units described in the following *boundary relations* section. The *chemostratigraphy* section was meant to include geochemical data within a stratigraphic context, including CIA values, $\delta^{13}C$, $\delta^{18}O$, $\delta^{34}S$, $^{87}Sr/^{86}Sr$, and other available isotopic data. Some authors also included analyses of Rare Earth Elements, whole rock geochemistry, major and trace elements, Nd data, and Ce, Eu and Ir anomalies. The *other characteristics* section was designed to cover economic deposits, biomarkers or any other notable feature not covered in the other sections. The *palaeolatitude and palaeogeography* section was primarily designed to discuss the palaeomagnetic data available for that succession in order to consider palaeogeographic location of the deposits at the time of deposition. Some authors also included provenance data in the context of palaeogeography based on lithology or geochemistry. The *geochronological constraints* section was designed to report any available radiometric or biostratigraphic data that constrains the minimum or maximum age of the succession. These dates could come from the glacial deposits themselves or from associated strata. Authors were also asked to discuss regional stratigraphic correlations based on radiometric data, chemostratigraphy, lithostratigraphy and/or biostratigraphy. Global stratigraphic correlations were discouraged as these are discussed in the introductory chapters by **Condon & Bowring** (geochronology) and **Halverson & Shields-Zhou** (chemostratigraphy). Lastly, the *discussion* section was designed to include interpretations of available datasets with respect to palaeoenvironmental conditions, timing of climate change and palaeogeography, showing how

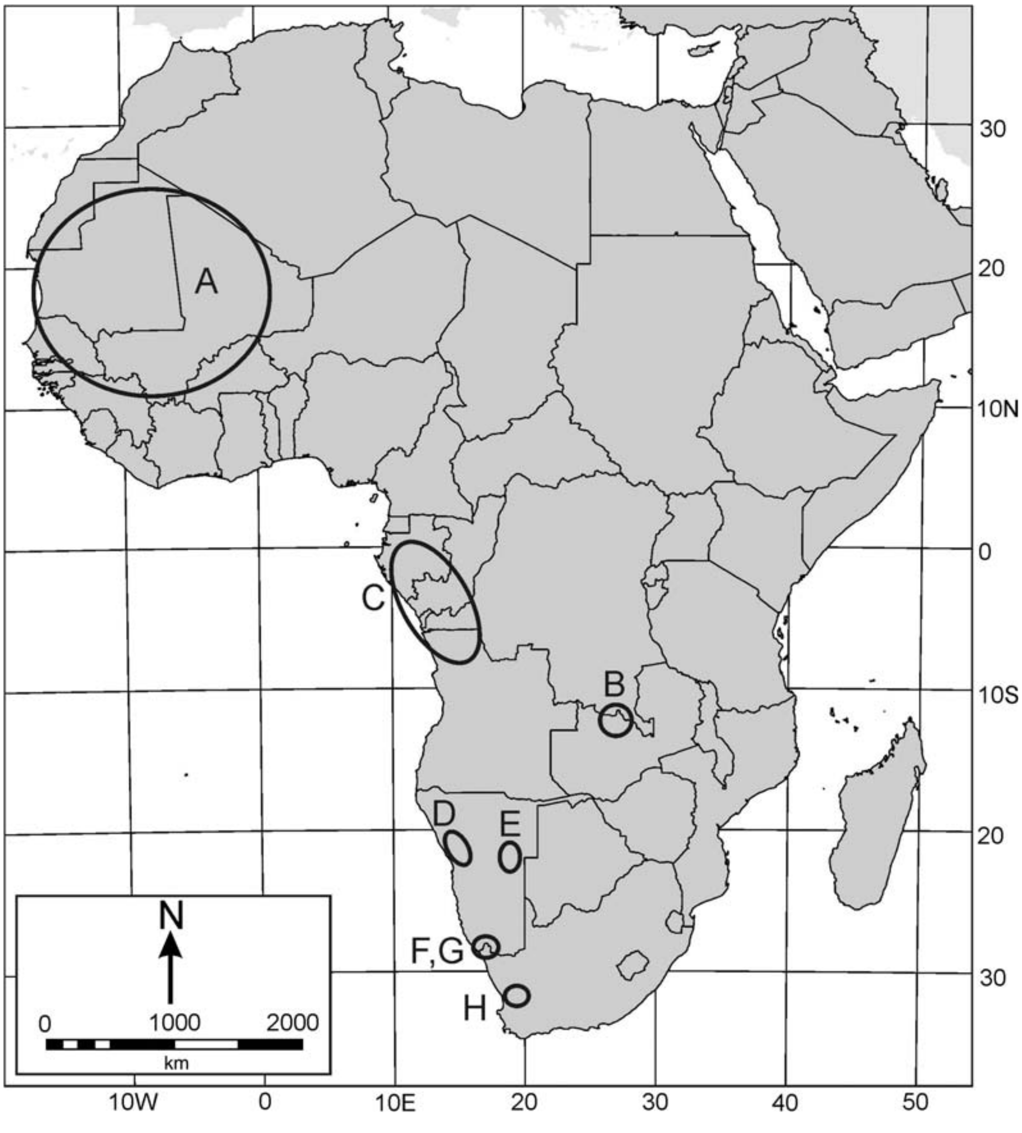

Fig. 1.1. Map showing distribution of Neoproterozoic glaciogenic successions within Africa, as covered in this volume. (**A**) Taoudeni Basin, NW Africa; (**B**) Katanga Supergroup, central Africa; (**C**) West Congo and Lindi/Ubangi Supergroups, central Africa; (**D**) Otavi Group, northern Namibia; (**E**) Witvlei Group, East-Central Namibia; (**F**) The Chameis Gate Member, Namibia; (**G**) The Kaigas and Numees formations, South Africa and Namibia, (**H**) Karoetjes Kop and Bloupoort formations, South Africa.

Table 1.1. *Summary of Neoproterozoic data sets from Africa*

Lead author	Glaciogenic strata	Structural framework	Chemostratigraphy					Geobiology	Economic	Palaeomagnetism	Geochronology		
			$\delta^{13}C$	$\delta^{18}O$	$\delta^{34}S$	$^{87}Sr/^{86}Sr$	Other				U–Pb detrital	U–Pb direct	Other
Shields-Zhou	Basal diamictite of the triad sequence, Taoudeni Basin, diamictite of the triad sequence, Volta Basin	Foreland basin	Y	Y	Y	Y		Scarce	Barite, BIF, petroleum source rocks			Y	K–Ar, Rb–Sr
Master	Grand Conglomerat Fm., Petit Conglomerat Fm.	Synrift, foreland basin	Y				Ir	Y	Fe, Cu–Co, Zn–Pb–Cu–Ge–Ga, Cu–Au, Ba–Fe, Pb–Zn	Y	Y	Y	
Tait	Lower and Upper Diamictite Formations, West Congo Supergroup; diamictites of the Lindi/Ubangi Supergroup	Passive margin	Y			Y					Y	Y	Ar/Ar
Hoffman	Chuos Fm., Ghaub Fm.	Passive margin	Y	Y	Y	Y	[Fe, Mn, Ba], $\delta^{11}B$, $\delta^{44}Ca$					Y	
Prave	Blaubeker Fm.	Rift to passive	Y		Y			Y		Y reset		Y	
Frimmel	Kaigas Fm., Numees Fm.	Failed rift; passive; back-arc?	Y	Y		Y		Y	Pb, Zn		Y	Y	Pb/Pb, Ar/Ar
Frimmel	Chameis Gate Mb., Chameis Group	Back-arc?	Y	Y		Y	Limited trace elements						Pb/Pb, Ar/Ar
Frimmel	Karoetjes Kop Fm.; Bloupoort Fm.	Rift; pasive margin?	Y	Y		Y	Limited trace elements		Calcitic marble; Cu, Fe, Mn; Fe oxides				

Note: 'U–Pb direct' means dates from volcanic intrusions or tuffs anywhere in the succession, not necessarily from the glaciogenic strata itself. 'U–Pb detrital' means dates from detrital zircons from within the succession. Data in presumed correlative successions were not included.

the tectonic, stratigraphic, sedimentological, isotopic, palaeomagnetic and geochronological data outlined in previous sections support such interpretations. Whereas authors clearly favoured certain interpretations, they were encouraged to discuss competing interpretations and continued controversies. In an attempt to avoid redundancy and maintain consistency, photographs were omitted from site-specific chapters, and are made available in a companion online photo atlas (http://neoproterozoic-glaciations.weebly.com). Although this format was generally followed, some flexibility was required to accommodate the complexity of certain areas and the widely differing perspectives that reflect the diversity of authors contributing to this volume.

Authors were asked to avoid interpretive terms, such as tillite, varvite, and cap carbonate, in preference to descriptive terms, except in the discussion section where interpretations are presented. More specifically, the non-genetic term diamictite was meant to be used to describe poorly sorted materials that contain a mixture of gravel-, sand- and mud-sized particles. For example, the term tillite was meant to be used in the discussion section in referring to poorly-sorted materials that were demonstrably deposited by ice without subsequent disaggregation and flow. The use of the term varvites or varves for rhythmically laminated mudstone that record seasonal fluctuations in ice cover was discouraged considering the lack of chronological control on Neoproterozoic successions and the inability to demonstrate seasonal cyclicity. In the discussion section, authors were asked, where possible, to distinguish between the cap carbonate sequence that overlies the glacial deposits and the cap dolostone that occupies the basal transgressive tract of the post-glacial sequence.

Although the focus of the book is on Cryogenian glaciation, these glacial deposits and associated strata are best understood within the context of their overall stratigraphic successions. Therefore, several site chapters also review associated later Neoproterozoic, Ediacaran-age deposits to highlight the carbonate strata associated with the late Cryogenian glacial deposits and the evolution of early animals that followed the late Cryogenian and mid-Ediacaran glaciations.

Every effort was made to include all the sites where Neoproterozoic glaciogenic successions have been studied. In some cases, multiple distinct glaciogenic successions within a single region were grouped into a single chapter, whereas in others, they were treated in separate chapters. For the Adelaide rift-basin in South Australia, where extensive work has been done on each of the older (Sturtian and equivalent) and younger (Elatina and equivalent) glacial successions, the reviews are split into two chapters – one for each glaciation.

Unfortunately, not every site known to preserve evidence of Neoproterozoic glaciation is included in this volume. These

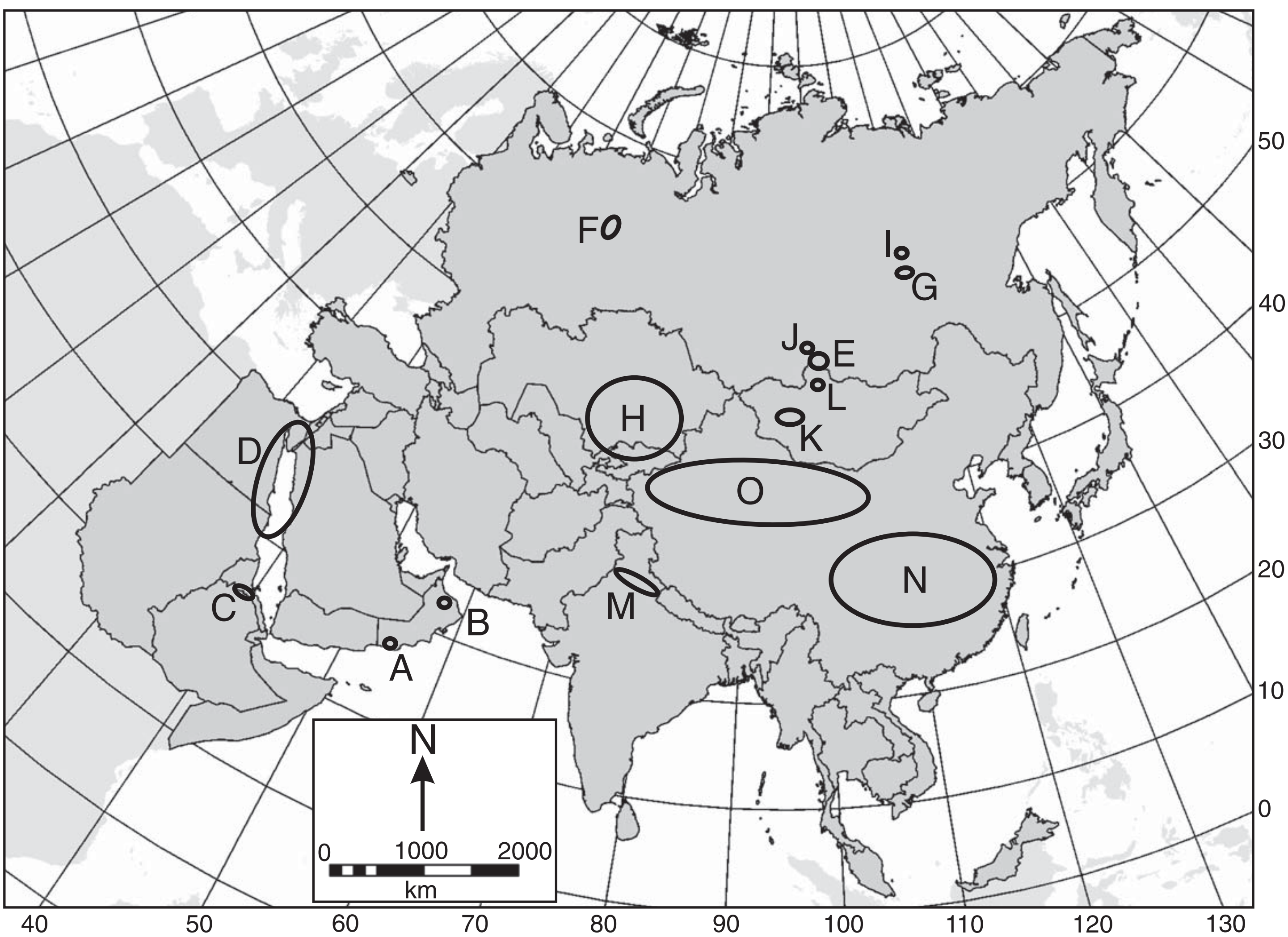

Fig. 1.2. Map showing distribution of Neoproterozoic glaciogenic successions within Eurasia and the Nubian Shield, as covered in this volume. (**A**) Ayn Fm., Oman; (**B**) Abu Mahara Group, Oman; (**C**) Tambien Group, northern Ethiopia; (**D**) northern Arabian–Nubian Shield (Egypt, Sudan and western Arabia); (**E**) Bokson Group, East Sayan Mountains, Russian Federation; (**F**) North and Middle Urals, Russian Federation; (**G**) Nichatka Fm., central Siberia; (**H**) Baykonur Fm., Kazakhstan and Kyrgystan; (**I**) Bol'shoy Patom Fm., central Siberia; (**J**) Marnya Fm., foothills of East Sayan mountains; (**K**) Tsagaan Oloom Fm., SW Mongolia; (**L**) Khubsugul Group, northern Mongolia; (**M**) Blaini Fm., NW India; (**N**) Yangtze region, China; (**O**) Tarim Block, NW China.

Table 1.2. *Summary of Neoproterozoic data sets in Eurasia and the Nubian Shield*

Lead author	Glaciogenic strata	Structural framework	Chemostratigraphy					Geobiology	Economic	Palaeomagnetism	Geochronology		
			$\delta^{13}C$	$\delta^{18}O$	$\delta^{34}S$	$^{87}Sr/^{86}Sr$	Other				U–Pb detrital	U–Pb direct	Other
Allen	Ayn Fm., Shareef Fm.	Rift	Y				CIA, MIA			Y, unreliable	Y		Rb–Sr, K–Ar
Allen	Ghubrah Fm., Fiq Fm.	Rift	Y				CIA, MIA			Y, unreliable	Y	Y	
Stern	Meriti Gp.?, Mahd Gp.?, Atud & Nuwaybah diamictites	Arc–back-arc, oceanic basin					REE, Ce, Eu		BIF, Au, Cu, Zn, Ar,			Y	
Miller	Didikama Fm., Matheos Fm. (Tambien Gp.)	Arc, intra-oceanic platform	Y	Y		Y	CIA, PIA, $\delta^{13}C$_TOC, Sr				Y	Y	Sm–Nd, Pb/Pb, Rb–Sr
Chumakov	Zabit Fm., Kushatay Fm. (Bokson Gp.)	Foreland basin	Y	Y				Y	Bauxite, Phosphorite				Rb–Sr
Chumakov	Churochnaya Fm., Tany/ Koyva/Wil'va formations, Lower Starye Pechi Subformation	Passive margin	Y	Y				Y				Y	K–Ar, Sm–Nd, Rb–Sr, Pb/Pb
Chumakov	Nichatka Fm.	Passive margin	Y	Y		Y							
Chumakov	Baykonur	Unknown	Y					Y	Vanadium, phosphorite			Y	
Chumakov	Bol'shoy Patom Fm.	Passive margin	Y			Y		Y		Y, reset			K–Ar,Rb–Sr
Sovetov	Marnya Fm. (Oselok Gp.)	Foreland basin	Y	Y		Y		Y		Y, overprinted			Ar/Ar
Macdonald	Tsagaan Oloom Fm.	Passive margin?	Y			Y	Ce	Y		Y		Y	
Macdonald	Ongoluk Fm., Khesen Fm. (Khubsugul Gp.)	Rift?	Y			Y			Phosphorite				
Etienne	Blaini Fm.	Passive margin	Y	Y				Y		Unreliable	Y	Y	
Zhang	Chang'an/Fulu Fm (Jiangkou Gp); Nantuo Fm.	Rift	Y		Y		TOC	Y (Biomarker)	Manganese, BIF	Y		Y	Nd (t_{DM})
Zhu	Polong Fm. Yutang/ Yulmeinak diamictite (Tarim Basin); Beiyixi, Altungol, Tereeken and Hankalchough diamictites (Tarim Block); and others	Foreland basin	Y					Y		Y		Y	

Note: 'U–Pb direct' means dates from volcanic intrusions or tuffs anywhere in the succession, not necessarily from the glaciogenic strata itself. 'U–Pb detrital' means dates from detrital zircons from within the succession. Data in presumed correlative successions were not included.

lacunae are due either to the inability to find an appropriate author or because little or no work has been published in that region since the publication of Hambrey & Harland (1981). In such cases, readers are referred to that earlier volume for more information or, where appropriate, to more recent literature referenced in chapters covering neighbouring basins. Where possible, these overlooked successions were incorporated into chapters covering nearby regions or related deposits. Most are also listed in Evans & Raub's review of the palaeomagnetic database.

The current knowledge base

General trends

Many of the successions and regions covered in this book were reviewed in Hambrey & Harland (1981). Since that time, the greatest advances in our knowledge have come from the fields of geochemistry, palaeomagnetism and geochronology, although palaeoenvironmental interpretations of many glaciogenic and overlying units have also been variably reinforced and challenged in recent years. One of the novel aspects of the Snowball Earth hypothesis was its integration of various geological data sets, specifically bringing attention to the geochemical signatures associated with the Neoproterozoic glacial deposits. As a result, geochemical analyses of associated carbonate rocks proliferated from the late 1990s onwards. Although the main focus has been in acquiring traditional stable isotope (namely $\delta^{13}C$ and $\delta^{34}S$) and $^{87}Sr/^{86}Sr$ data sets to reconstruct ocean compositions and terrestrial weathering processes (Halverson & Shields-Zhou 2011), these rocks have also proven fertile grounds for novel isotopic approaches such as Ca and B isotopes, and multiple O isotopes (e.g. Kasemann *et al.* 2004; Bao *et al.* 2008). In addition, the hypothesis generated renewed interest in the idea of global synchronous glaciation, its onset and initiation, which in turn prompted focused efforts to provide additional geochronological constraints. The development of new techniques such as the use of Re–Os in dating organic shales, the proliferation of SHRIMP and LA-ICP-MS analyses, and the refinement of the ID-TIMS U–Pb dating technique have simultaneously refined some age constraints and seriously challenged conventional age models for key Neoproterozoic successions, particularly in Australia. The glacial deposits themselves, as the most direct record of the global glaciations, have come under much greater scrutiny, and many units have been re-evaluated using facies and sequence stratigraphic analysis, incorporating advances in our understanding of glaciated basins made in the last 30 years. The role of tectonics in modulating climate change during this time period and the role of basin setting in controlling the preservation and nature of the sedimentary record has also been explored further (e.g. Eyles & Januszczak 2004; Allen 2007; Stern 2008).

Some workers have focused on sites that previously had relatively little to no data, such as Mongolia, Alaska, Ethiopia, Egypt and western Arabia and some parts of Australia, Russian Federation and South America, while some of the classic Neoproterozoic sections have been the subject of additional study by several

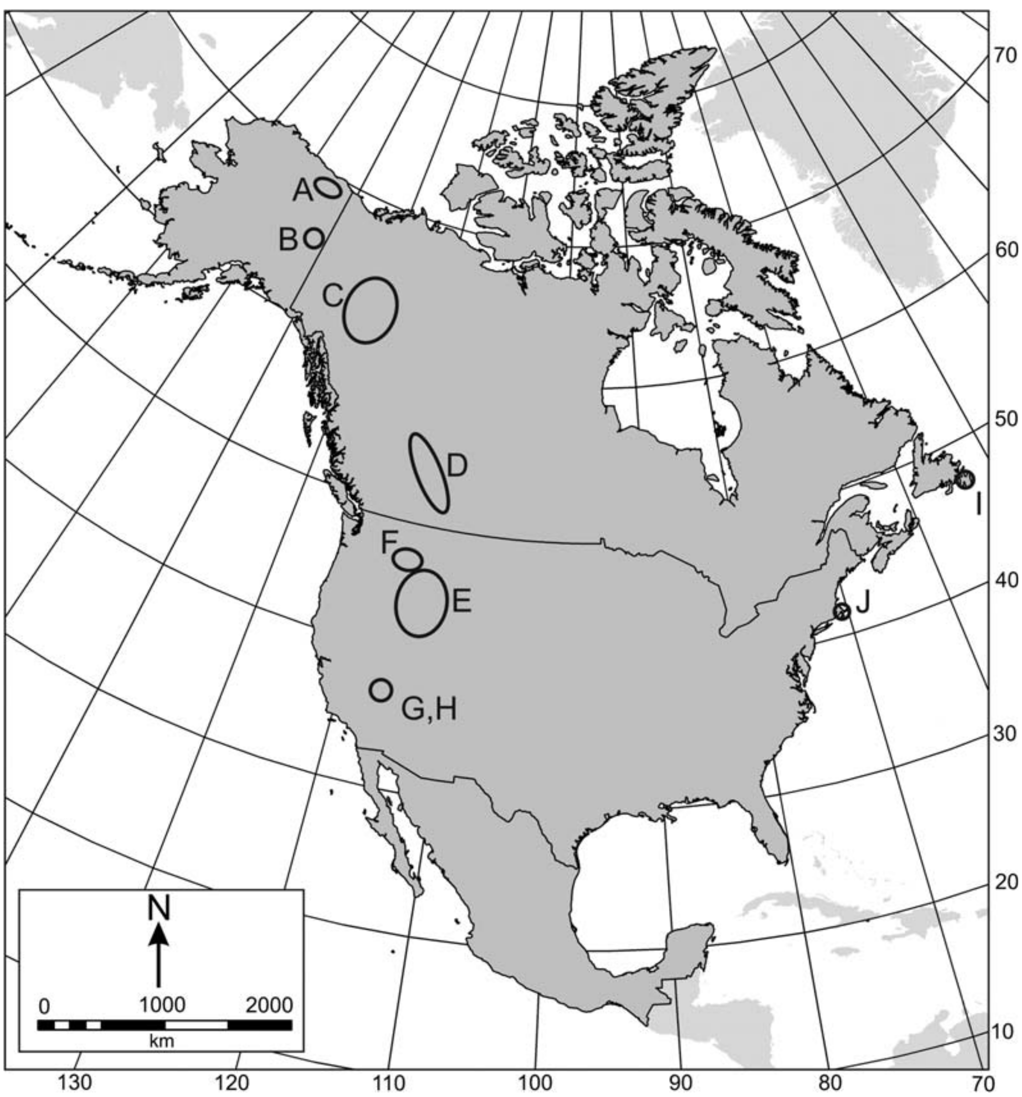

Fig. 1.3. Map showing distribution of Neoproterozoic glaciogenic successions within North America, as covered in this volume. (**A**) Hula Hula diamictite, Arctic Alaska; (**B**) Tatonduk Inlier, Alaska–Yukon border; (**C**) Windermere Supergroup, Mackenzie Mountains, Canada; (**D**) Windermere Supergroup, southern Canadian Cordillera; (**E**) SE Idaho and Utah, USA; (**F**) Edwardsburg Fm., central Idaho, USA; (**G**) Kingston Peak Fm., eastern Death Valley region, USA; (**H**) Kingston Peak Fm., Panamint Range, USA; (**I**) Gaskiers Fm., Newfoundland, Canada; (**J**) Squantum Member, Boston Basin, USA.

Table 1.3. *Summary of Neoproterozoic data sets in North America*

Lead author	Glaciogenic strata	Structural framework	Geochemistry					Geobiology	Economic	Palaeomagnetism	Geochronology		
			$\delta^{13}C$	$\delta^{18}O$	$\delta^{34}S$	$^{87}Sr/^{86}Sr$	Other				U–Pb detrital	U–Pb direct	Other
Macdonald	Hula Hula Diamictite	Unknown	Y					Y					Pb/Pb (detrital), Rb–Sr
Macdonald	Rapitan Gp.; Hay Creek Gp.	Rift to passive	Y			Y		Y				Y	Ar/Ar
Hoffman	Rapitan Gp.; Ice Brook Fm. (Stelfox Mb.)	Rift to passive	Y	Y	Y	Y	$\delta^{57}Fe$, Ce/Ce*, $\delta^{44}Ca$, Elemental analysis, REE	Y	Fe	Y (Rap. Gp.)			Pb/Pb
Smith	Toby Fm., Vreeland Fm (Windermere Supergroup)	Rift; controversial upper WSG	Y	Y	Y		TOC, Mo, V/Cr	Y	Cu			Y	Re–Os, Sm–Nd
Link	Pocatello Fm. (Idaho), Mineral Fork Fm. (Utah)	Rift to passive	Y				CIA, TOC, Nd, Sr	Y			Y	Y	
Lund	Edwardsburg Fm., Moores Lake Fm.	Extensional (inferred)					Whole-rock geochem.					Y	
Mrofka	Kingston Peak Fm. (Eastern Death Valley)	Extensional	Y	Y	Y			Y					
Petterson	Kingston Peak Fm. (Panamint Range)	Rift	Y						U, U–Th, Iron ore				
Carto	Gaskiers Fm.	Arc	Y				FeHR/FeT	Y		Y	Y	Y	
Carto	Squantum Mb.	Extensional-rift, intra-arc					CIA	Y		Y	Y		Pb/Pb

Note: 'U–Pb direct' means dates from volcanic intrusions or tuffs anywhere in the succession, not necessarily from the glaciogenic strata itself. 'U–Pb detrital' means dates from detrital zircons from within the succession. Data in presumed correlative successions were not included.

research groups, notably Svalbard, northern Norway, Scotland/Ireland, the North American Cordillera (Death Valley, Idaho and western Canada), Namibia, various regions in Australia, and China. As a result, some of these classic localities have become 'type' localities for investigating Neoproterozoic glaciations and their aftermath.

With the increasingly global focus in research into the Neoproterozoic and ongoing efforts to define and normalize chronostratigraphic units in the Neoproterozoic, the terminology used to refer to Neoproterozoic glaciations and, implicitly, their age and global correlations has significantly evolved. For example, now largely absent from the international lexicon are such previously mainstream terms as *Sinian*, *Vendian* and *Varangerian*, which refer to overlapping subsets of Neoproterozoic time spanning glacial epochs. Because these intervals were defined based on regional stratigraphic sequences with little basis other than the occurrence of glacial deposits, their use was inconsistent and often confusing. New informal terms have emerged in their place and partly as a result of the intense efforts to determine the number of Neoproterozoic glacial epochs. Specifically, the Neoproterozoic glaciations are now commonly identified by their relative timing and assumed correlation with well-studied localities. Mid-Ediacaran glacial deposits are widely referred to as *Gaskiers*, based on the eponymous glaciogenic formation on the Avalon Peninsula of southeastern Newfoundland, which occurs just below the first appearance of Ediacaran fossils *c.* 575 Ma (Narbonne & Gehling 2003). Older, Cryogenian-aged glacial deposits are commonly referred to as *Sturtian* (older) and *Marinoan* (younger) (e.g. Kennedy *et al.* 1998; Halverson *et al.* 2005) in an adaptation of terms originally intended for specific sequences in the Adelaidean rift-basin of South Australia (Preiss 2000). Despite their proliferation and appeal, the application of these terms usually hinges on inferred inter-regional correlations that are commonly controversial and often poorly backed up by radiometric data. Although biostratigraphy (Grey *et al.* 2011), chemostratigraphy (Halverson & Shields-Zhou 2011) and magnetic stratigraphy (Evans & Raub 2011) are increasingly able to resolve relative age assignments and correlations, we have favoured reference to the emerging Neoproterozoic timescale (i.e. Cryogenian and Ediacaran) over the terms Sturtian, Marinoan

Fig. 1.4. Map showing distribution of Neoproterozoic glaciogenic successions within South America, as covered in this volume. (**A**) Chiquerio Fm., Peru; (**B**) Puga Fm., Paraguay Belt, Brazil; (**C**) Serra Azul Fm., Paraguay Belt, Brazil; (**D**) Bebedouro Fm., Brazil; (**E**) São Francisco Craton, Brazil; (**F**) The Macaúbas Group, SE Brazil; (**G**) Moema laminites, São Francisco basin, Brazil; (**H**) Jequitaí Fm., SE Brazil; (**I**) Playa Hermosa Fm., Uruguay; (**J**) Last Ventanas and San Carlos formations, Uruguay; (**K**) Tandilia system, Argentina.

Table 1.4. *Summary of Neoproterozoic data sets in South America*

Lead author	Glaciogenic strata	Structural framework	Chemostratigraphy					Geobiology	Economic	Palaeomagnetism	Geochronology		
			$\delta^{13}C$	$\delta^{18}O$	$\delta^{34}S$	$^{87}Sr/^{86}Sr$	Other				U–Pb detrital	U–Pb direct	Other
Chew	Chiquerío Fm.	Extensional, not well constrained	Y	Y					Fe, Cu, Au		Y	Y	
Alvarenga	Puga Fm., Cuiabá Gp, Jacadigo Gp.	Extensional	Y	Y		Y		Y	Fe (BIF), Mn	Y		Y	Pb/Pb, Nd
Figueiredo	Serra Azul Fm.	Passive margin											Ar/Ar, K–Ar, Sm–Nd
Guimaraes	Bebedouro Fm.	Extensional	Y			Y			Barite nodules; phosphate			Y	Pb/Pb
Misi	Bambuí Gp., Una Gp., Vazante Gp., Vaza Barris/Miaba Gp.	Not well constrained	Y			Y		Y (ltd)	Fe–Mn, Phosphorite, fluorite, barite, Pb–Zn, Zn			Y	Re–Os, Pb/Pb, Sm–Nd
Pedrosa-Soares	Serra do Catuni Fm., Nova Aurora Fm., Lower Chapada Acaua Fm.	Rift to passive margin							Mn, Fe, diamonds		Y	Y	
Rocha-Campos	Moema Laminites	Intracratonic basin					Major and trace elements, REE, Eu, Ce,		Kaolinite (ceramic)				
Uhlein	Jequitaí Fm.	Cratonic/intracratonic?	Y	Y		Y						Y	Rb–Sr, Pb/Pb
Pazos	Playa Hermosa Fm.	Not well constrained								Preliminary			Ar/Ar, K–Ar, Rb–Sr
Pecoits	Las Ventanas Fm., San Carlos Fm.	Strike–slip basin						Y			Y	Y	K–Ar, Rb–Sr, Ar/Ar
Pazos	Sierra del Volcán Fm.	Not well constrained	Y					Y		Y?	Y		Rb–Sr

Note: 'U–Pb direct' means dates from volcanic intrusions or tuffs anywhere in the succession, not necessarily from the glaciogenic strata itself. 'U–Pb detrital' means dates from detrital zircons from within the succession. Data in presumed correlative successions were not included.

and Gaskiers in this volume in recognition that ages and correlations of the Neoproterozoic glacial deposits remain controversial. This said, the fact that the lower boundary of the newly defined Ediacaran Period is defined as the contact between the glaciogenic Elatina Fm. (=Marinoan) and the overlying Nuccaleena cap carbonate (Knoll *et al.* 2006) is suggestive of the chronostratigraphic importance of at least one of these Neoproterozoic glaciations.

The definition of this boundary was bolstered by several new, well placed and precise radiometric ages on basal Ediacaran *cap dolostones* (i.e. the lower, transgressive, dolomite facies of the *cap carbonates*; Hoffman *et al.* 2011) that strengthen the case for their global age equivalence. The trickle of new radiometric ages is generally tightening the age constraints on this *late Cryogenian* glaciation and the other glacial epochs and at the same time calibrating and helping to refine the secular evolution of seawater geochemical proxies (Halverson & Shields-Zhou 2011). New ages have demonstrated that some putative 'Cryogenian' glacial deposits are in fact post-Cryogenian in age, such as the Gaskiers unit in Newfoundland, while the purported 'Cambrian' glaciation in the Taoudeni Basin is now regarded unequivocally as Cryogenian in age. Recent U–Pb and increasingly Re–Os data (Condon & Bowring 2011) confirm the division of Cryogenian glaciations into two main episodes (*c.* 720–*c.* 660 Ma and *c.* 650–635 Ma), although older diamictites of unconfirmed origin may hint at localized earlier Cryogenian glaciation. In contrast to the now reasonably well constrained late Cryogenian glaciation, the wide range of dates obtained from older Cryogenian glacial deposits long thought to be correlative (mainly in Australia and the North American cordillera), have called into question their equivalence and have been used to argue against global glaciation. Whereas the available data allow for a single, long-lived earlier Cryogenian glaciation, it is clear that the implications and interpretations of these many new ages are contentious and rapidly evolving. Therefore, references throughout the book to early, earlier or middle Cryogenian glaciation should not be assumed to indicate synchronous glaciation.

In recent years, with resource exploitation reaching unprecedented peaks, there has also been increasing interest in the economic potential of Neoproterozoic strata. Ediacaran rocks comprise petroleum source rocks in China and Oman, and this has triggered interest in correlative post-glacial successions in Africa, India, Australia, Brazil and Russia. Phosphorus resources have also become a vulnerable commodity worldwide as Moroccan deposits

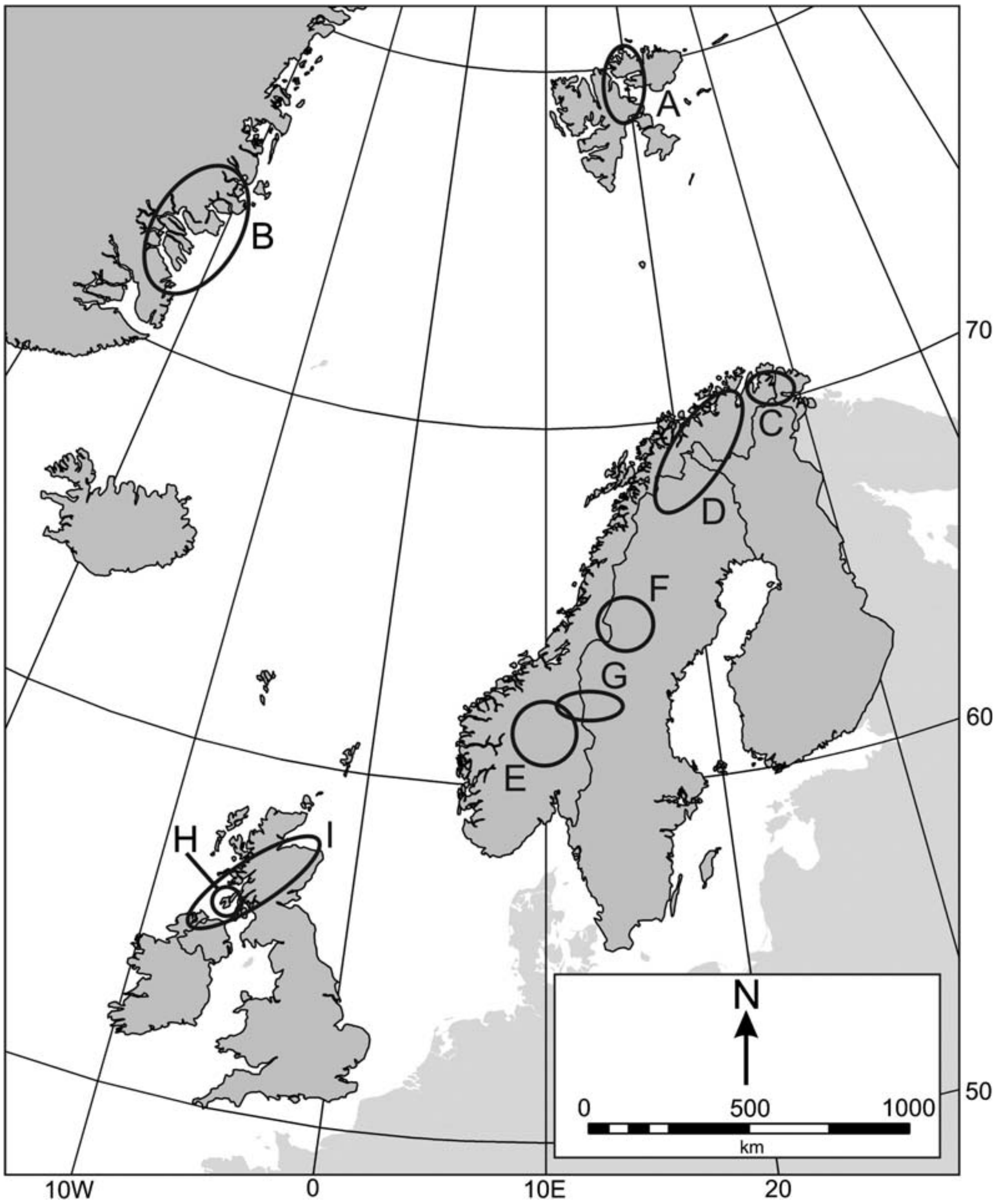

Fig. 1.5. Map showing distribution of Neoproterozoic glaciogenic successions within Europe, as covered in this volume. (**A**) Polarisbreen Group, NE Svalbard; (**B**) NE Greenland; (**C**) Smalfjord and Mortensnes formations, Finnmark, Norway; (**D**) Caledonides, NW Scandinavia; (**E**) Moelv and Koppang formations, southern Norway; (**F**) Caledonides, central Scandinavia; (**G**) Lillfjället Fm., southern Swedish Caledonides; (**H**) Port Askaig Fm., Scotland; (**I**) Scotland and Ireland.

Table 1.5. *Summary of Neoproterozoic data sets in Europe*

Lead author	Glaciogenic strata	Structural framework	Chemostratigraphy					Geobiology	Economic	Palaeomagnetism	Geochronology		
			$\delta^{13}C$	$\delta^{18}O$	$\delta^{34}S$	$^{87}Sr/^{86}Sr$	Other				U–Pb detrital	U–Pb direct	Other
Halverson	Petrovbreen Mb., Wilsonbreen Fm. (Polarisbreen Group)	Thermally subsiding margin	Y	Y		Y	$D^{17}O$	Y					
Stouge	Ulvesø Fm., Storeelv Fm. and Støvfanget Fm.	Rift to passive	Y				TC, TOC, TS	Y		Y/unreliable?			
Rice	Smalfjord Fm., Mortensnes Fm.	Rift to passive	Y					Y		Y			Rb–Sr
Stodt	Possible correlatives of the Mortensnes Fm.	Passive margin	Y (ltd)					Y					
Nystuen	Moelv Fm., Koppang Fm.	Rift; pericratonic shelf	Y (ltd)	Y (ltd)			Lu–Hf				Y	Y	Rb–Sr, Re–Os
Kumpulainen	Längmarkberg Fm., Risback Gp. Diamictite?	Rift to passive margin											
Kumpulainen	Lillfjället Fm.	Rift to passive margin?											Ar/Ar
Arnaud	Port Askaig Fm.	Extensional	Y			Y	CIA	Y	Pb–Zn, magnetite			Y	Pb/Pb, Sm–Nd
Prave	Dalradian Supergroup overview-Port Askaig Fm.; Stralinchy-Reelan; MacDuff/Loch na Cille/Inishowen boulder beds	Rift	Y			Y					Y	Y	

Note: 'U–Pb direct' means dates from volcanic intrusions or tuffs anywhere in the succession, not necessarily from the glaciogenic strata itself. 'U–Pb detrital' means dates from detrital zircons from within the succession. Data in presumed correlative successions were not included.

become the only widely traded source of phosphorus for fertilizer. Ediacaran-age phosphorites of China are the only other world-class phosphorite resource, sparking interest in possibly correlative, glacially associated phosphorites in West Africa, South America and Australia. In addition to being an oceanographic curiosity of the Cryogenian Period, the widespread deposition of iron and manganese deposits may also have economic implications for those regions where they are found (South America, northwestern Canada, India, China and Australia; Hoffman *et al.* 2011).

Significant advances have been made in all regions since the publication of Hambrey & Harland (1981). However, with new data always come new questions and controversies. Some of the notable advances and contentious issues are highlighted below. Readers interested in specific glaciogenic successions are encouraged to read chapters from neighbouring sites as controversies are sometimes most apparent when viewing the geological record from a regional vantage point.

Africa

Neoproterozoic glaciogenic successions reported from Africa are located primarily in the NW, central and southern regions, with a cluster of sites in Namibia (Fig. 1.1, Table 1.1). These occur in a wide range of tectonic settings, with few sites containing biostratigraphic or palaeomagnetic data. Geochemical and geochronological studies have been carried out at most sites, with the most complete data sets found in the Taoudeni Basin in NW Africa and the Otavi Group of Namibia. The glacial deposits in the former (Shields-Zhou *et al.* 2011) remain significant for being among the few to preserve unequivocal terrestrial glacial deposits, which are now known to be age-equivalent to other end-Cryogenian glaciogenic units around the world. Robust geochronological constraints spanning the two glaciogenic intervals of the Otavi Group are particularly notable. The Otavi Group has been the subject of intense study over the past two decades, and despite lingering controversy over interpretation of glacial deposits in the succession (Hoffman 2011), plays a central role in debates over the Snowball Earth hypothesis. Prave *et al*. (2011) have provided a useful review of the hitherto poorly documented Witvlei Group in east-central Namibia (northern Kalahari craton), which provides a firmer basis for correlation with the numerous Neoproterozoic glacial deposits elsewhere on the Kalahari craton (see the chapters by Frimmel). Whereas few geochronological or geochemical data had been available from the West Congo belt until recently, new research has provided key data that strengthen glacial interpretations and correlations across the belt and elsewhere on the Congo craton (Tait *et al.* 2011), such as the Katangan Supergroup, best known for its world class Cu deposits (Master & Wendorff 2011).

Eurasia–Nubian Shield

This region encompasses Neoproterozoic glaciogenic successions found throughout the Russian Federation, Mongolia, China and India, as well as those from Oman, the shores of the Red Sea and Ethiopia (Fig. 1.2, Table 1.2). Excellent preservation of Cryogenian glacial deposits in northern Oman have allowed detailed sedimentological and sequence stratigraphic analysis to be carried out over the last several decades. The results have shed light on the environmental conditions during Neoproterozoic glaciations, with some more recent geochemical and geochronological analyses contributing a relatively comprehensive data set for this region. Unfortunately, palaeomagnetic studies in Oman have thus far yielded no reliable palaeolatitudes. In contrast, studies in Ethiopia and the shores of the Red Sea have focused on geochemical and geochronological aspects of Neoproterozoic geology, making this region an ideal candidate for future work in sedimentology and stratigraphy to confirm glaciogenic conditions existed in these regions and maximize the impact of these new radiometric ages. The basins of the Arabian–Nubian Shield are unique in that they occur in arc or back-arc basins, a relatively rare tectonic setting for glaciated Neoproterozoic basins.

Glaciogenic successions in the Russian Federation and neighbouring Mongolia, Kazakhstan and Kyrgyzstan are found within primarily passive margin and foreland basin settings, with

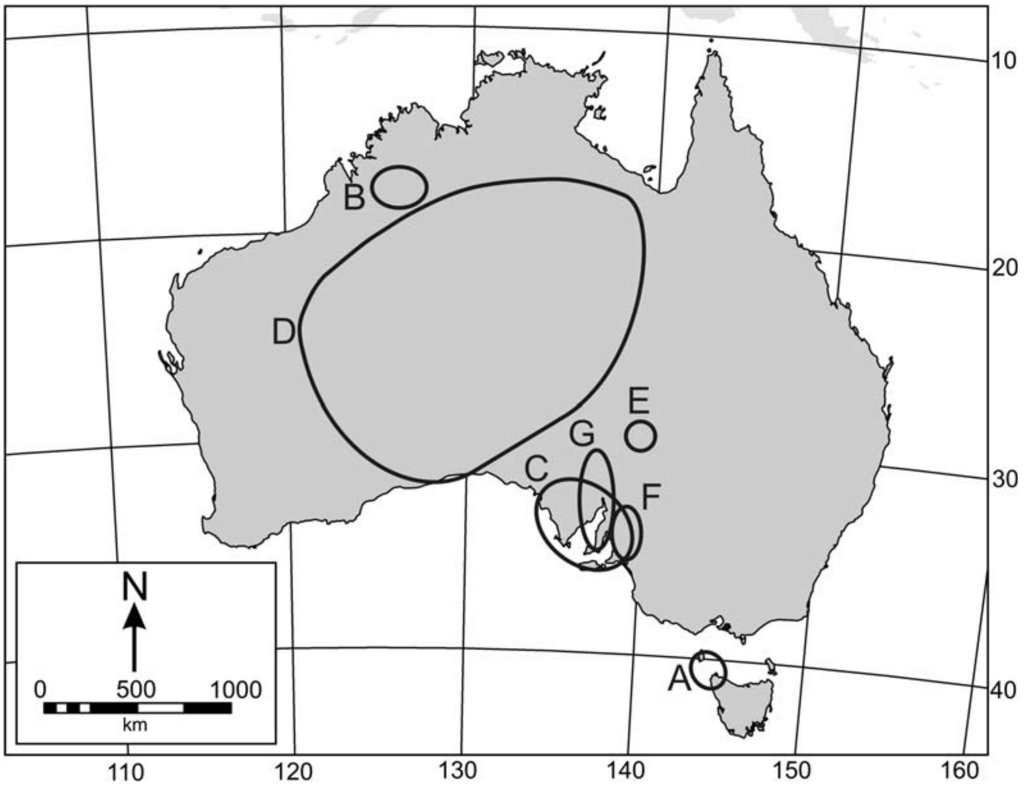

Fig. 1.6. Map showing distribution of Neoproterozoic glaciogenic successions within Australia, as covered in this volume. (**A**) Tasmania; (**B**) the Kimberly region and NW Northern Territory; (**C**) Mid-Ediacaran ice rafted deposits, Adelaide Geosyncline and Officer Basin; (**D**) Central Australia; (**E**) Billy Springs Fm.; (**F**) Yudnamutana Subgroup (Sturtian); (**G**) Elatina Fm.

Table 1.6. *Summary of Neoproterozoic data sets in Australia*

Lead author	Glaciogenic strata	Structural framework	Chemostratigraphy					Geobiology	Economic	Palaeomagnetism	Geochronology		
			$\delta^{13}C$	$\delta^{18}O$	$\delta^{34}S$	$^{87}Sr/^{86}Sr$	Other				U–Pb detrital	U–Pb direct	Other
Calver	Cottons Breccia, Julius R. Mbr., Croles Hills Diamictite; Wedge R. beds, Cotcase Ck. Fm.	Rift, epicratonic basin	Y	Y		Y		Y	Calcic scheelite skarns	Unpublished	Y	Y	Re–Os, Nd–Sm
Corkeron	Walsh Fm., Landrigan/ Egan Fms., Fargoo/ Moonlight Valley Fm.	Unknown	Y	Y		Unreliable				Y		Y	Rb–Sr
Gostin	Bunyeroo Fm., Dey Dey Mudstone	Thermally subsiding basin; platformal	Y				Atomic H/C ratios	Y		Y	Y		Rb–Sr
Hill	Glaciogenic deposits of Central Australia (Officer, Amadeus, Ngalia, Georgina Basins	Intracratonic sag basin	Y			Y		Y		Y	Y		Re–Os
Jenkins	Billy Springs Fm.	Rift complex	Y		Unpub.			Y			Y (ltd)		
Preiss	Yudnamutana Subgroup (Sturt and correlatives)	Rift	Y	Y	Y	Y	Elemental analysis, REE, Ironstone geochemistry					Y	Rb–Sr, Re–Os
Williams	Yerelina Subgroup, Elatina Fm.	Rift	Y	Y						Y	Y	Y	Re–Os

Note: 'U–Pb direct' means dates from volcanic intrusions or tuffs anywhere in the succession, not necessarily from the glaciogenic strata itself. 'U–Pb detrital' means dates from detrital zircons from within the succession. Data in presumed correlative successions were not included.

geochemical data (primarily carbon, but also oxygen and strontium isotopes in some cases) as well as important biostratigraphic data. Interestingly, these studies have led to some contradictory stratigraphic correlations across neighbouring basins (see chapters on the Bokson Group and Khubsugul Basin). Chumakov (2011) suggests that two diamictite-bearing horizons within the Bokson Group in the East Sayan Mountains are likely Ediacaran in age based on biostratigraphic data, whereas Macdonald & Jones (2011) suggest that the two horizons in the neighbouring Mongolian basin correspond to an early and late Cryogenian glacial episode. Dispute also remains over the glacial origin of the younger Mongolian diamictite-bearing unit. Nonetheless, the tectonic setting of the region makes these basins suitable targets for future geochronological studies, which may help to resolve these stratigraphic inconsistencies. The chapter on the Marnya Fm. in the East Sayan Mountains (Sovetov 2011) is notable for its review of regional stratigraphic correlation and useful comparison of the Russian stratigraphic scheme with that of the more widely used International Subcommission on Stratigraphy (see also Table 27.2). Palaeogeographic reconstructions in northern Eurasia are hampered by the lack of reliable palaeomagnetic data, although ongoing studies in Mongolia show some promise.

The Blaini Fm. of India did not receive much attention until the more recent studies reported in this volume, which include new sedimentological and geochemical data. In contrast, the glaciogenic successions of the Yangtze region (rift setting) and Tarim Block (foreland basin) have a long history of Neoproterozoic research that has resulted in extensive data sets for geochemistry, geobiology and biostratigraphy, palaeomagnetism and geochronology. Notably, a U–Pb zircon age from an ash bed in the Yangtze region has provided a definitive date for the end of the late Cryogenian glaciation (*c.* 635 Ma), whereas maximum and syn-glacial ages in China and elsewhere have shown that this late Cryogenian glaciation lasted <10 Ma (Condon & Bowring 2011). In addition, palaeomagnetic data indicating low palaeolatitudes for the Nantuo diamictite have one of the highest reliability ratings of available palaeomagnetic data, as discussed by Evans & Raub (2011). Lastly, novel geobiological and biostratigraphic studies have demonstrated the preservation of animal embryos in the Ediacaran-age Doushantuo Fm. of the Yangtze region (Hagadorn *et al.* 2006).

North America

Many of the Neoproterozoic glaciogenic successions in North America are found along the length of the North American Cordillera in rift basins and passive margin settings, whereas others are found on exotic terranes in Arctic Alaska and along the eastern margin of North America (Fig. 1.3, Table 1.3). The Cordilleran sections generally have a long history of research, but have enjoyed renewed interest and have been the source of much new data. While many researchers have attempted to correlate these widely separated sections, recent studies have highlighted the possible diachroneity of Neoproterozoic glaciations and rifting related to Rodinian break-up. New additions to the North American database include the preliminary results of ongoing multidisciplinary studies in Alaska and the Yukon including geochronological and palaeomagnetic data (Macdonald 2011; Macdonald & Cohen 2011); new geochronological data from Idaho (Link & Christie-Blick 2011; Lund *et al.* 2011) and the Canadian Cordillera (Smith *et al.* 2011; Macdonald *et al.* 2010); detailed mapping and geochemical data from the Death Valley region; a better understanding of the tectonic development of the southern Cordillera margin based on work in Idaho, Utah and Death Valley; the analysis of a deepwater 'cap' carbonate in the southern Canadian Cordillera; and influential studies on the impressive Ediacaran biota and ocean redox in Newfoundland.

South America

Neoproterozoic glaciogenic successions in South America are primarily clustered in the Paraguay Belt and on the São Franscisco craton of Brazil, with other sections reported from Uruguay, Argentina and Peru (Fig. 1.4, Table 1.4). The Araras Group in the northern Paraguay Belt, in particular, has been the subject of interdisciplinary studies and preserves some of the best evidence for Ediacaran glaciation in South America (Figueiredo *et al.* 2011). New entries to the South American database include the sections in Peru, Uruguay and Argentina as well as the Moema laminites in Brazil. Despite some new geochronological data, there remain significant challenges in regional stratigraphic correlation schemes, limited information regarding palaeolatitude, and uncertainty regarding tectonic setting and glacial origin of some of the units described herein. These challenges are manifested in significant controversies over the correlation and ages of Proterozoic glacial deposits across Brazil (Misi *et al.* 2011). Despite uncertainties in age, the correlations between the Bambuí and Una groups have been strengthened (Guimarães *et al.* 2011).

Europe

The Neoproterozoic glaciogenic successions of Europe described here are primarily those found in extensional and passive margin basins of Scandinavia, Svalbard, Greenland and the British Isles (Fig. 1.5, Table 1.5). Although most of these sites were described in Hambrey & Harland (1981), new data have become available in recent decades, including additional geochemical data from most of these successions, additional information on associated carbonate strata and some additional geochronological constraints. Most successions in the region have been significantly impacted by Caledonian tectonics and hence lack reliable palaeomagnetic data directly related to the glacial deposits. Robust geochronological constraints are also largely lacking, making regional stratigraphic correlations relatively tenuous, despite some advances using chemostratigraphic data. Interestingly, ongoing studies in Greenland have led some researchers to propose that the Greenland and Svalbard sections are not as intimately connected palaeogeographically as was previously proposed.

Australia

The Neoproterozoic glaciogenic successions in Australia covered in this volume are very similar to the entries found in Hambrey & Harland (1981) over 30 years ago (Fig. 1.6, Table 1.6). Recent advances include the collection of additional geochemical and biostratigraphic data, continued state-of-the-art palaeomagnetism research with confirmation of low-latitude glaciation, and additional geochronological constraints that have prompted abundant discussion about the duration and timing of the older Cryogenian glaciation. Entries for South Australia are focused on individual glacial events (Preiss *et al.* 2011; Williams *et al.* 2011), with new evidence for Ediacaran-aged glaciation within the Adelaidean rift-basin (Gostin *et al.* 2011; Jenkins 2011). Corkeron, Hill *et al.* and Calver provide timely and useful syntheses of the separate Neoproterozoic successions in the Kimberly region, 'Centralian Superbasin' and Tasmania, respectively.

Calibrating Neoproterozoic change

One of the prominent developments in stratigraphy over the last decade has been the attempt to establish consistent, rock-based periods of geological time beneath the Cambrian Period. Neoproterozoic glaciation played a pivotal role in this when the Ediacaran

Period, which was the first period of the geological timescale to be established for a hundred years, was defined as beginning directly after the widespread, end-Cryogenian (= Elatina or Marinoan) glaciation. Now, international efforts are under way to further subdivide the Ediacaran Period and define the underlying Cryogenian Period. In this endeavour, the integrated approach taken by many of the authors in the present volume will be key as a global stratigraphic framework can only be established in the Precambrian by meshing together sparse fossil information with high-resolution chemostratigraphy, strategically placed age constraints and lithostratigraphic markers.

At present, the base of the Cryogenian Period is defined chronometrically at 850 Ma, but few age constraints exist to identify this level in sedimentary successions from around the world. Although, the base of a new chronostratigraphically defined Cryogenian Period is yet to be established, any GSSP is likely to be placed 'beneath the oldest clearly glaciogenic deposits in a Neoproterozoic succession' at an outcrop horizon with 'proven potential for global C- and Sr-isotope stratigraphic correlation and preferably be amenable to microfossil biostratigraphy, isotope geochronology and other forms of global correlation such as magnetostratigraphy' (Neoproterozoic Subcommission 2009 Annual Report). This emphasis on glacial strata will likely lead to a shorter Cryogenian Period more in line with its Phanerozoic counterparts, and with a base close in age to the Dunn *et al.* (1971) estimate of *c.* 750 Ma. The unique Neoproterozoic palaeoclimate, which underpins this volume, has already cemented the place of Neoproterozoic ice ages in the international geological timescale (Ogg *et al.* 2008) and will continue to be central in the subdivision of Proterozoic time.

Future work

This memoir was inspired by *Earth's Pre-Pleistocene Glacial Record* (Hambrey & Harland 1981), and it is hoped that it can serve similarly as a long-lasting reference work that provides useful summaries of most Neoproterozoic glacial successions, while also highlighting the state-of-the art in the study of these rocks. The large number of chapters and impressive list of contributors highlight the extraordinary interest in the Neoproterozoic and the vast amount of research carried out over the past 30 years. At the same time, the results of this research have revealed gaping holes in our understanding of the Neoproterozoic and aroused compelling new questions. Many glaciogenic units described in Hambrey & Harland (1981) have received little or no attention since that time, such as the widespread diamictites of the Sino-Korean craton, which are still of uncertain age and origin. Radiometric age constraints on most glacial units remain sparse or non-existent, which poses a persistent challenge to inter-regional correlations. Many important advances have been in the biostratigraphy of Cryogenian and Ediacaran successions, but most sections remain poorly studied. In addition, a welter of exciting new geochemical methods, such as the Δ_{47} palaeothermometer and transition-metal stable isotopes, await rigorous application to the Neoproterozoic. Clearly, much remains to be done, but in almost every region of the world there are now interdisciplinary teams of scientists at work in what has become a global endeavour not only to explore the extremes of past climate change, but also to evaluate the link between eukaryotic evolution and global glaciations.

We wish to thank all the authors who made this collection possible, for agreeing to write these contributions amidst many other writing commitments, and patiently awaiting the completion of the volume. We particularly thank N. Chumakov and Q. R. Zhang for promptly contributing to the original template papers that were essential in establishing the format for all subsequent regional chapters. We are also especially grateful to P. Hoffman, F. Macdonald, M. Zhu, R. Stern and J. Tait for acquiescing to last-minute requests for contributions. We would also like to thank all the reviewers (see list of reviewers) who provided meaningful and constructive comments and improved the individual chapters. I. Fairchild kindly provided the cover photo and the historical photograph for the dedication.

E. Arnaud would also like to thank those who provided guidance in developing the instructions for authors with suggested content required of specific sections: namely D. Condon, N. Eyles, G. Halverson, B. MacGabhann, P. Martini, T. Raub, G. Shields-Zhou & R. van der Voo. The following regional coordinators also assisted in tracking down authors and names of Neoproterozoic glaciogenic successions in their regions: P. Allen, C. Calver, N. Chumakov, M. Corkeron, N. Eyles, V. Gostin, P. Hoffman, C. Hoffmann, G. Jiang, K. Kristiansen, R. Kumpulainen, P. Link, U. Linnemann, J. Meert, N. Miller, P. Pazos, T. Prave, Q. R. Zhang, H. Rice, T. Rocha Campos, S. Stouge, M. Wendorff and S. Xiao. We thank J. Howe for his contribution as the Society Books Editor and for his timely review of this chapter. Angharad Hills at the Geological Society of London Publishing House kept us on track and provided editorial assistance throughout the project. This memoir represents a contribution of the IUGS-UNESCO sponsored International Geoscience Programme (IGCP) Project # 512.

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