CHAPTER 11.1

NEOPROTEROZOIC TO CAMBRIAN PALAEOCLIMATIC EVENTS IN SOUTHWESTERN GONDWANA

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11.1.1. CONSTRUCTING A GLOBAL RECORD OF NEOPROTEROZOIC PALAEOCLIMATIC VARIATIONS

Since publication of the ‘Snowball Earth’ hypothesis — initially by Kirschvink (1992a) based on an apparently robust equatorial palaeolatitude for glacial strata in the Neoproterozoic Elatina Formation of Australia, and later by Hoffman et al. (1998) based on their high-resolution stratigraphic investigation of the carbonate-dominated Otavi Group in Namibia — there has been an exponential growth in the number of publications focusing on the oscillating record of extreme climate change in the Cryogenian interval (generally constrained between 750 and 635 Ma) and through the Ediacaran and Cambrian periods. Many of these studies have revealed remarkable litho- and chemostratigraphic similarities in broadly equivalent, but widely separated successions (e.g. Halverson et al., 2005a).

The lack of a rigorous biostratigraphic framework through much of this time interval and the general absence of reliable radiometric age constraints, however, has led to the use of temporal carbon isotope trends (often constructed from single and likely incomplete sections) as a means of dating Neoproterozoic sedimentary successions through


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comparison with composite curves (e.g. Jacobsen and Kaufman, 1999). This is problematic insofar as carbon isotope variations, especially across glacial divides, are inherently oscillatory, the magnitude of $\delta^{13}C$ anomalies can vary between facies, and the age models used for the composites require periodic tuning (cf. Melezhik et al., 1999). Furthermore, chemostratigraphic correlations are complicated by the discovery of multiple diamictite/cap carbonate couplets in individual sections, the incomplete nature of the stratigraphic record in glaciated marginal marine environments and tectonic factors that either omit or duplicate strata. Further complicating the interpretation of Cryogenian to Cambrian palaeoclimatic variations are suggestions that the negative $\delta^{13}C$ excursions are diagenetic artefacts, or are the result of strong surface-to-deep carbon isotope gradients in seawater (Jiang et al., 2007; Swart, 2008). If the latter is true, the profound isotopic variations documented through the strata in any of the marginal marine successions may have more spatial than temporal significance.

Our ability to reconstruct a Neoproterozoic palaeoclimatic history from southwestern Gondwana depends fundamentally on accurate regional and global correlation of Cryogenian glacial diamictites. For example, in Namibia the correlation of diamictites between the Congo and Kalahari cratons has been a long standing geological problem because of the tectonic fragmentation and reassembly of the Damaran Orogen into several tectonostratigraphic zones (Martin, 1965; Miller, 1983; Hoffmann, 1989; see Part 5).

In the absence of temporally significant fossils and radiometric constraints, carbon isotope stratigraphy was specifically applied to the correlation of carbonates above and below the Namibian glacial deposits (Kaufman et al., 1991). These early results revealed profound swings in $^{13}C$ abundances across the glacial divides with a stratigraphic pattern of strongly negative values in a ‘cap carbonate’ above diamictites on the Congo Craton in the Otavi Mountainland. The sub-Maieberg diamictite was previously thought to be associated with the Chuos Formation, but later regional correlation led to a revised subdivision of the Otavi Group that included two discrete levels of glacial deposits and the re-assignment of the diamictite/cap carbonate couplet studied in 1991 as the Ghaub and Maieberg formations (Hoffmann and Prave, 1996). Assuming the strongly negative $\delta^{13}C$ anomalies were temporally significant and reflected unusual post-glacial ocean chemistry, the isotopic results predicted the stratigraphic position of a second ice age in the Witvlei Group (Bildah and LaFraque members of the Buschmannsklippe Formation: Hegenberger, 1993) on the Kalahari Craton to the south (Kaufman et al., 1991; Saylor et al., 1998).

While the two glacial events in the Otavi Group were originally ascribed to the Sturtian epoch (Kaufman et al., 1997; Hoffman et al., 1998), the stratigraphically higher Ghaub diamictite below the Maieberg Formation cap carbonate was later re-classified as a Marinoan archetype (Hoffman and Schrag, 2002) with the carbonate containing a suite of unusual textural, sedimentologic and isotopic characteristics of supposedly temporal significance. In this context there is a general assumption that the two levels of glacial diamictite found in each of the post-rift carbonate platform successions on the Congo and Kalahari cratons are equivalent, representing Sturtian (Chuos, Blaubeker and Kaigas diamictites) and Marinoan (Ghaub, Bläskranz and Numees diamictites) events.

Tests of these lithologic and carbon isotope correlations in Namibia, and evaluation of the significance of sedimentary features as temporal markers require independent isotopic constraints and stratigraphically significant radiometric dates. Furthermore, it is important to correlate the low grade successions on the foreland platforms with metamorphosed equivalents in the fold and thrust belts of the Damara Orogen. In these internal mobile zones (Outjo, Swakop and Hakos) two levels of glacial diamictite have been recognised, but the scale and magnitude of thrusting and nappe displacement is poorly constrained, thus making the direct equivalence of diamictites in the metamorphosed portion of the Damara with unmetamorphosed units in the external zones problematic (Hoffman, 1989).

Correlation problems in Namibia and elsewhere are now further complicated by the recognition of diamictites from a post-Marinoan Ediacaran Period glacial epoch referred to as the Gaskiers (ca. 582 ± 0.4 Ma: Bowring et al., 2003b); these are best expressed in Newfoundland where they are overlain locally by a thin cap carbonate (Myrow and Kaufman, 1999) with $\delta^{13}C$ values as low as $-8\%$. Notably, this couplet has been tentatively correlated around the world to a profound negative $\delta^{13}C$ anomaly (to a nadir of $-10\%$ and lower) in carbonates preserved on several continents — called the Shuram event (Fike et al., 2006) — but besides the Gaskiers itself underlying glacial diamictites are currently known from only one example in Brazil (Alvarenga et al., 2007) and potentially one in Norway and the north Atlantic region (Halverson et al., 2005a) and possibly also in South Africa (Gaucher et al., 2005a).

In this review, we re-evaluate the correlation of palaeoclimatic events in the Neoproterozoic of southwestern Gondwana, including the Congo and Kalahari cratons in Africa, in light of new radiometric ages, field observations and chemostratigraphy in those regions, as well as those from the Sào Francisco, Amazon and Rio de la Plata cratons in South America. Combined with temporal constraints from Cryogenian successions external to southwestern Gondwana and recent observations of stratigraphic anomalies, this compilation of palaeoclimatic events provides insight to the number and duration of ice ages during the Neoproterozoic glacial epoch.
11.1.2. Age Constraints for Cryogenian Glacial Deposits in Southwestern Gondwana

The global distribution of Cryogenian diamictites (Harland, 1964) and their stratigraphic position within individual basins suggests that there were two main Neoproterozoic glacial epochs, which have come to be known as the Sturtian and Marinoan ice ages. When new age constraints on the Gaskiers diamictite in Newfoundland came to light, a third discrete glacial epoch was added to the Cryogenian inventory (Figure 11.1.1). Snowball Earth-like conditions have been proposed for the Sturtian and Marinoan events, but the narrow extent of Gaskiers-age glacial deposits suggests that this Ediacaran Period ice age may have been more regional in scope.

11.1.2.1. Sturtian

In Namibia on the Congo Craton, the Sturtian Chuos diamictite is constrained to be 746 Ma based on the age of a feeder dyke to a porphyry lava upon which the glaciogenic Chuos deposits in the Sumas Mountains rests (Hoffman et al., 1996).

The correlative Kaigas diamictite in the Port Nolloth Terrain is associated with felsic rift-related volcanic rocks (Rosh Pinah Formation) from which single zircon Pb-Pb and U-Pb ages of 741 ± 6 Ma (Frimmel et al., 1996) and 752 ± 6 Ma (Borg et al., 2003) have been obtained. The felsic volcanic rocks of the Rosh Pinah Formation rest above the Kaigas Formation (Frimmel, 2008) and thus provide a minimum age constraint for the Kaigas diamictite. The maximum age of sedimentation in the Gariep Basin is given by the youngest age obtained on

![Figure 11.1.1](stratigraphic subdivision of the proposed Cryogenian and Ediacaran periods. Glacial units within selected late Neoproterozoic succession and their radiometric age constraints are shown to scale (Gaucher et al., 2005a). Except for Ghaub, Ghaub and Gaskiers that have been directly dated (Brasier et al., 2000; Bowring et al., 2003b; Hoffmann et al., 2004), correlations for all other glacial units is interpretative (modified from Gaucher et al., 2005a and references therein). ECAP, Ediacaran Complex Acanthomorph Palynoflora (Grey et al., 2003). Sources: (1) Frimmel et al. (1996c); Folling et al. (2000); Grotzinger et al. (1995); (2) Hoffmann et al. (2004); (3) Ireland et al. (1998), Preiss (2000); (4) Grey and Corkeron (1998); (5) Zhou et al. (2004a); (6) Brasier et al. (2000); (7) Myrow and Kaufman (1999); Bowring et al. (2003b); (8) Vidal and Nyestuen (1990).)
basement rocks, i.e. $771 \pm 6$ Ma (Frimmel et al., 2001b) and the best age estimate for the Kaigas deposits is approximately 750 Ma. This is supported indirectly by a Pb-Pb double spike carbonate age of $728 \pm 32$ Ma (Folling et al., 2000), which dates early diagenesis of the overlying cap carbonates. While it is possible that the Kaigas diamictites are slightly older than those of the Chuos, the available age data overlap within error and the most parsimonious interpretation is that these are equivalent units.

In the Lufilian Arc on the northeastern margin of the Congo Craton (Democratic Republic of Congo and Zambia), two Neoproterozoic glacial levels are preserved and ascribed to the Marinoan and Sturtian glacial epochs (Bodiselitsch et al., 2005). The older of the two diamictites, the Grand Conglomerat, is constrained by a U-Pb SHRIMP zircon age for a volcanic unit that intrudes the Ngumba Group to be younger than $760 \pm 5$ Ma (Key et al., 2001).

On the conjugate São Francisco Craton in Brazil a similar Sturtian age ($740 \pm 22$ Ma 11 point isochron with MSWD = 0.66; Babinski and Kaufman, 2003; Babinski et al., 2007) was determined by Pb-Pb carbonate techniques on exceptionally preserved seafloor precipitates in the Sete Lagos Formation (Pedro Leopoldo facies), which is interpreted as a cap carbonate on sedimentologic and isotopic evidence (Misi et al., 2007). Notably, the Sturtian age constraints from Namibia, Congo and Brazil are significantly older than those determined elsewhere, including South Australia where the Sturtian was first defined. There, a U-Pb SHRIMP zircon age of ca. 660 Ma was assigned to the Sturtian Meninjina Formation, which is a tuffaceous bed sandwiched between massive iron-formation bearing diamictite and dropstone-bearing sandstone and conglomerate. A Re-Os date of 643.0 $\pm 2.4$ Ma for overlying shale of the Tindelpina Shale Member of the basal Tapley Hill Formation (Kendall et al., 2006) supports the younger age for the type deposit. Similarly, the 723 $\pm 16/\pm 10$ Ma U-Pb zircon age for the Ghubrah diamictite in Oman (Brasier et al., 2000), U-Pb SHRIMP age constraints for the Scout Mountain Member diamictite in Idaho, USA between 717 $\pm 4$ and 667 $\pm 5$ Ma (Fanning and Link, 2004), and a 702–705 Ma intrusive volcanic into the Mechum River diamictite in the Blue Ridge of Virginia (Tollo and Hutson, 1996) predict an $\sim 100$ myr interval of Sturtian glaciations.

Where detailed carbon isotope trends have been determined for these successions it appears that ocean chemistry returned to pre-glacial conditions (recording significant $^{13}$C enrichments in seawater proxies) before each of the Sturtian epoch ice ages, which were likely separated in time by tens of millions of years. For this reason it is unlikely that the ice ages were diachronous over an extended interval (Kendall et al., 2006) and more plausible that these represent multiple discrete events driven by oscillations in ocean chemistry and biology. The wide range of Sturtian ages is consistent with the prediction of multiple Sturtian events — including the Ghaub diamictite — based on integrated carbon and strontium isotope stratigraphy (Kaufman et al., 1997).

11.1.2.2. Marianoan

While multiple ash layers have been discovered and collected from the Ghaub on the Otavi platform, including one at the feet of Galen Halverson in the quintessential photograph of the Ghaub/Maieberg contact, none have yielded reliable and publishable ages. However, an age constraint for the Ghaub is permissible, if the lithostratigraphic correlation proposed by Hoffmann et al. (2004) for the two Swakop Zone diamictites to the Chuos and Ghaub diamictites on the Otavi platform is valid (see discussion below). U-Pb geochronology of an ash layer within the upper of the two diamictites (Kachab dropstone unit) in the metamorphosed internal zone yielded an age of $635.5 \pm 1.2$ Ma (Hoffmann et al., 2004). Given that the Swakop Zone diamictites and the Otavi platform are both north of the rift between the Congo and Kalahari cratons, this is the most likely correlation. It is, however, unclear how distant the cratonal blocks may have drifted apart by the time of the Marianoan ice age since initial rifting around 750–800 Ma, nor the magnitude of compressional tectonism, shortening and thrusting that accompanied peak collision of the two cratons around 540 Ma (see Part 5).

The $\sim 635$ Ma Marianoan age constraint from the Kachab dropstone is compelling as it is an excellent match with the age determined for ash discovered within a cap carbonate lithofacies at the base of the Doushantu Formation in South China (Zhou et al., 2004a; Condon et al., 2005) supporting their equivalence. Of the sedimentologic characteristics assumed to be Marianoan based on the view from Namibia (Hoffman and Schrag, 2002), only sheet crack type cements and barite are known to occur in the basal Doushantuo cap carbonate, which is considerably more organic-rich than its potential Namibian counterpart.

11.1.2.3. Gaskiers

U-Pb zircon age constraints on volcanic rocks within the thick Conception Group (Gaskiers) diamictite in Newfoundland ($582 \pm 0.4$ Ma) extended the record of demonstrable Neoproterozoic ice ages into the Ediacaran Period (Knoll et al., 2004). This age determination pushes the temporal record of ice ages and the unique multicellular organisms that characterise this interval of Earth history much closer together than had been
previously believed. However, similar U-Pb ages for volcanic rocks on either side of the Gaskiers diamictite indicate that the duration of this particular ice age was less than one million years.

Radiometric constraints on a potential Gaskiers ice age diamictite in Namibia come from a 555±22 Ma double spike Pb-Pb age on the Bloeddrif cap carbonate (Holgat Group) atop the Numees diamictite (Fölling et al., 2000), which has otherwise been equated with the Marinoan ice age worldwide. Even with the large uncertainty, this age stands out as distinctly younger than that of the Gaskiers at ~582 Ma. A second potential Ediacaran diamictite in Namibia occurs in the Vingerbreek Formation of the Nama Group (Germs, 1983), which unconformably overlies the Holgat Group in southern Namibia. The Vingerbreek diamictite lies in U-shaped valley fill above an ash bed in the Zaris Formation dated by U-Pb zircon techniques at ~548 Ma (Grotzinger et al., 1995; Saylor et al., 1998). If these young ages apply to discrete glacial events, it would appear likely that all of Cryogenian through Ediacaran time was characterised by dramatic oscillations in climate.

11.1.3. Chemostratigraphic Records of Palaeoclimatic Events in Southwestern Gondwana

Insofar as the São Francisco Craton is considered to be conjugate to the Congo Craton in Neoproterozoic time (Porada, 1989; Dalziel, 1997; Trompette, 1997; Alkmim et al., 2001, 2006; Gray et al., 2008), glaciogenic successions in South America have been under intense stratigraphic and geochemical scrutiny since the Snowball Earth hypothesis resurfaced in Namibia. For this reason, the most straightforward stratigraphic test of palaeoclimate change observed in the Otavi Group comes from detailed comparisons of glacial deposits and isotope trends with those in the Bambuí Group and its equivalents in Brazil, which faced their Otavi Group equivalents across the widening Adamastor-Brazilide ocean (Dalziel, 1991; Hoffman, 1991; Pedroso-Soares et al., 1998). Bambuí carbonates are overwhelmingly composed of bituminous limestone and these are typically interleaved with organic-rich shale — in marked contrast to the organic-lean dolomites and oxidised shales that dominate Otavi Group strata. While rock exposure in Brazil lags far behind Namibia, the excellent preservation of outcrop samples and the general availability of exploration drill cores through many of the glaciogenic successions makes the Brazilian units excellent targets for isotopic and biomarker tests of the Snowball Earth hypothesis.

11.1.3.1. Carbon isotopes

Among the most powerful reflections of Neoproterozoic climatic and environmental change are the strong positive-to-negative trends in δ13C that occur across Sturtian and Marinoan glacial divides (Knoll et al., 1986; Kaufman et al., 1991, 1997; Narbonne et al., 1994; Hoffman et al., 1998; Halverson et al., 2002; Corsetti and Kaufman, 2003; Hoffman and Halverson, 2008). The likelihood of multiple discrete ice ages within each of the glacial epochs, however, limits the use of such oscillatory isotopic signals as temporal markers; characteristic carbon isotope trends likely reflect specific post-glacial conditions, but these may occur repeatedly throughout the Cryogenian interval. Nonetheless, the biogeochemical anomalies remain valuable as a predictive tool in carbonate-dominated successions lacking clear evidence for glacial diamictite, and they further provide a geochemical window to the deep oceans that gives us great insight to the Neoproterozoic carbon cycle.

Accepting that the carbon isotope variations reflect global changes in seawater composition through time, rather than depth-dependent controls on 13C abundance in seawater proxies (Swart, 2008), local facies controls in near-shore environments (Frimmel, 2009), or diagenetic artefacts in carbonate-poor systems (Bristow and Kennedy, 2008), high-resolution trends may be used to correlate distinct lithofacies during pre-glacial sea level fall and post-glacial transgression. In successions where the magnitude of sub-glacial erosion is minimal, pre-glacial negative excursions (known as the Trezona anomaly) of up to 15‰ have been recognised. In some cases these reflect progressive shallowing of lithofacies prior to the deposition of glacial diamictite (Narbonne et al., 1994; Corsetti and Kaufman, 2003), while in others the pre-glacial negative carbon isotope excursion appears to step smoothly across several parasequences (Hoffman et al., 1998; Halverson et al., 2002; Hoffman and Halverson, 2008). By subdividing high-resolution records of δ13C change in the post-glacial cap carbonates into distinct time segments Hoffman et al. (2007) illustrate the possible diachronity of cap carbonate accumulation across depositional platforms.

11.1.3.2. Strontium isotopes

Because of the long residence time of strontium in modern oceans and its high abundance in aragonite, strontium isotope variations in biogenic and inorganic carbonates have been used for decades as a chemostratigraphic tool allowing for the correlation between, and age estimates of, Cenozoic (DePaolo and Ingram, 1985) to Palaeozoic
Veizer et al. (1999) sediments. Strontium isotope studies of older Neoproterozoic carbonates also reveal strong secular variations in $^{87}\text{Sr}/^{86}\text{Sr}$ that have been interpreted in light of rifting (Veizer et al., 1983; Asmerom et al., 1991) and orogenesis (Derry et al., 1992a; Kaufman et al., 1993).

Subsequent stratigraphic studies of strontium isotope variations in well-preserved carbonates reveal long-term trends to progressively higher $^{87}\text{Sr}/^{86}\text{Sr}$ values (ranging from ca. 0.7055 to 0.7085) through the Neoproterozoic (Kaufman et al., 1993, 1997; Jacobsen and Kaufman, 1999; Halverson et al., 2007a). Notably, the lack of strontium isotope change in carbonates deposited across Otavi Group glacial divides was the first published evidence that openly questioned the validity of multi million year isolation of the oceans predicted by the end-member Snowball Earth hypothesis (Jacobsen and Kaufman, 1999).

However, the use of strontium isotope ratios as chemostratigraphic tools is limited by the paucity of limestone in many of the successions, and by the likelihood of alteration in sample with low strontium contents through the ingrowth of $^{87}\text{Sr}$ from the decay of $^{87}\text{Rb}$ in co-existing clay minerals. Geochemical screens ($^{87}\text{Rb}/^{86}\text{Sr}$, Mn/Sr and $\delta^{18}\text{O}$) have been developed to evaluate the degree of alteration of strontium isotopes (Veizer, 1983; Kaufman et al., 1992, 1993; Misi and Veizer, 1998; Jacobsen and Kaufman, 1999) and have been widely adopted.

Unfortunately, because of differences in the tectonic and diagenetic history of individual basins, the empirical limits delimiting altered and unaltered samples has varied — leading to some confusion in the literature.

For the purposes of this review of palaeoclimatic events in southwestern Gondwana and their correlation, we consider the analyses of only high Sr abundance limestone in cap carbonate lithofacies, especially those with ex-aragonite crystal fans, which have passed through the most stringent of the geochemical screens.

### 11.1.3.3. Isotopic observations of pre-Sturtian (?) ice ages in southwestern Gondwana

New radiometric constraints on glacial deposits in Australia, Oman and the United States (see above) suggest that the Sturtian glacial epoch comprised several discrete ice ages. If the Ghaub diamictite is Marinoan, then the Chuos diamictite (and its equivalents, potentially including the Kaigas in the coastal Gariep Group and Blaubeker in south-central Witvlei Group) remains the only Sturtian example in Namibia.

#### 11.1.3.3.1. Congo Craton

While no glacial diamictite is recognised in the pre-Chuos (> 746 Ma) Otavi Group or the rift-related siliciclastics of the underlying Nosib Group, sedimentologic evidence of shallowing and exposure of the lower Otavi carbonate platform accompanies a negative $\delta^{13}\text{C}$ excursion from values of +6 to near 0‰ in the O1 member of the Ombombo Subgroup (Figure 11.1.2). Based on previous observations it seems possible that this carbon isotope excursion represents a pre-glacial anomaly associated with an older Sturtian event (Jacobsen and Kaufman, 1999). Similar reasoning was used to interpret the origin of a negative $\delta^{13}\text{C}$ anomaly at the base of the Beck Springs Dolomite in Death Valley, USA (cf. Corsetti and Kaufman, 2003) as a cap carbonate equivalent to the Sturtian Rasthof Formation in Namibia. In this case the carbon isotope anomaly occurs in dark microbial carbonates with unusual roll up structures atop an unconformity. Since the iron-rich diamictites at the base of the overlying Kingston Peak Formation have traditionally been associated with Sturtian glaciation, the interpretation of second ice age lower in the succession supports the view of multiple discrete events during this glacial epoch.

Alternatively, either or both the Ombambo and lower Beck Springs $\delta^{13}\text{C}$ anomalies might be associated with profound environmental change during true polar wander completely unrelated to glaciation — as interpreted for a ca. 800 Ma negative isotope excursion in northeastern Svalbard (Halverson et al., 2007a).

#### 11.1.3.3.2. São Francisco Craton

Even older ice ages in southwestern Gondwana are predicted by the presence of glacial diamictite in the Macaúbas Group of Brazil, which lies unconformably beneath rocks of the Bambuí Group and overlies the Mesoproterozoic Espinhalço Supergroup in Minas Gerais and in central Bahia. Age constraints for this succession place the Macaúbas glaciation around the Mesoproterozoic-Neoproterozoic transition (ca. 1,000 Ma: D’Agrella Filho et al., 1990; Almeida-Abreu and Renger, 2002). A similar age (ca. 1,000–1,100 Ma) is estimated from a Re–Os study of organic-rich shale in the basal Lapa Formation (Vazante Group), Brazil (Azmy et al., 2007). The basal beds preserve a negative $\delta^{13}\text{C}$ excursion above a diamictite with ice-rafted debris and iron-formation lithofacies (Azmy et al., 2006). If these ages are substantiated it will be necessary to either revise our view of the duration of Cryogenian ice ages, or propose that these Brazilian deposits represent a separate late Mesoproterozoic glacial epoch (Geboy et al., 2006; Azmy et al., 2007).
Figure 11.1.2 Sequence and chemical stratigraphy of the Neoproterozoic Otavi Group, northeastern and northwestern Namibia. New data from the upper Elandshoek and Hüttenberg formations from core S86A from the Tsumeb Mine region in the Otavi Mountainland reveal a major positive carbon isotope excursion in organic-rich limestone and dolostone with sustained values $> +12\%$ (cf. Kaufman et al., 1991). Using a thermal subsidence model for the Otavi Group, the Hüttenberg biogeochemical anomaly is estimated to have lasted over 15 million years.
11.1.3.4. Lithologic and isotopic observations of Sturtian ice ages in southwestern Gondwana

11.1.3.4.1. Congo Craton

The Sturtian Chuos Formation in Namibia is typically developed above continental rift-related siliciclastic deposits of the Nosib Group or pre-Damaran basement and is present in the Central and Eastern Kaoko Zone, the Northern Platform as well as the Northern and southern Central Zone of the Damara Belt (see Part 5). It has not been found to date in the southern parts of the Damara Belt. The thickness is variable and in places, a fluvio-glacial origin is indicated. A characteristic feature of this formation is locally well-developed beds or lenses of iron-formation or iron-cemented diamictite with dropstones. Where present, the iron-formation is typically found in the lower parts of the unit, whereas Fe-enrichment at the top is related to secondary enrichment on palaeosurfaces. Thin intercalated beds of massive, white, very fine-grained dolomitic reflect breaks in glacial deposition. In the western part of the southern Central Zone of the Damara Belt, the Chuos Formation partly consists of graded mass-flow to turbiditic arenaceous beds with dropstones in the fine-grained tops. The formation oversteps the underlying Rössing Formation (see Part 5) in a southerly and easterly direction. From this onlap it is concluded that the northern rift shoulder of the southern rift graben in the Damara Belt was still exposed during Chuos times.

In northern Namibia glacial deposits of the Sturtian Chuos Formation are sandwiched by carbonates that preserve the noted positive-to-negative δ13C anomaly (Figure 11.1.2; Hoffman et al., 1998; Hoffman and Halverson, 2008). The post-glacial Rasthof cap carbonate is characterised by deep water rhythmites composed of authigenic limestone cements (with 87Sr/86Sr compositions as low as 0.7066) and allogenic grainstones overlain by a dark microbial reef with characteristic roll up structures. The Rasthof carbonates begin with δ13C values near −5% at the base and quickly rise through 0 to a plateau of +5% in as few as 15 m of section, associated with shallowing of the basin and deposition of microbial laminites and stromatolites facies. It is likely that the rise in δ13C compositions and wholesale precipitation of carbonate may be directly related to sea floor shallowing into the photic zone and the sudden bloom of photosynthetic mats. By rapidly drawing 12CO2 out of seawater and pumping reduced carbon into sediments, the activity of the bentic mats would have increased pH and supersaturated oceanic alkalinity. This allowed for carbonate precipitation from evolving seawater with progressively more enriched 13C compositions.

The Naos Formation in the Southern Marginal Zone (Hakos Terrain) of the Damara Belt, which is composed of metadiamicrite interbedded with micaschist, amphibolite and quartzite is currently regarded as correlative of the Ghaub Formation. Earlier lithostratigraphic correlations, however, equated this metadiamicite with supposedly younger diamictites of the Blässkranz Formation in the nearby Naukluft Nappe Complex (Hoffmann, 1989). To date isotopic studies of overlying carbonates in the overlying Melrose/Samara formations have not been conducted. Locally, volcano-exhalative siliceous iron formation occurs in proximity to some of the amphibolite bodies. The entire succession in the SMZ has been interpreted as incipient passive continental margin deposits laid down at the end of continental break-up in the Southern Zone (see Chapter 5.3).

Other likely Sturtian diamictites on the Congo Craton include the Grand Conglomerat of the Nguba Group (Lufilian Arc in the Democratic Republic of Congo and Zambia), which is overlain by the Calcaires du Kokontwe limestone. The diamictite consists of fine-grained argillitic matrix, with scattered quartz and lithic clasts, including carbonate, biotite, clay and black shale. A U-Pb SHRIMP zircon age of zircons in Ngumba Group volcanic unit indicates that the Grand Conglomerat is younger than 760 ± 5 Ma (Key et al., 2001). Carbonate of the Calcaires du Kokontwe above the diamictite in two cores show upsection depletions in 13C ranging from −2.4 to −4.7% and −3.6 to −6.2%, respectively (Bodiselitsch et al., 2005; Bodiselitsch, personal communication, 2007). The lowest 87Sr/86Sr isotopic ratios of equivalent post-glacial (Bas Congo mixtite inférieure) limestone from the ‘Haut Shiloango’ Subgroup in the West Congo foreland are ~0.7068 (Frimmel et al., 2006; Poidevin, 2007), which match well with those in the Rasthof Formation of northern Namibia.

11.1.3.4.2. Kalahari Craton

The Blaubeker Formation in the Southern Foreland of the Damara Belt on the shores of the Kalahari Craton may similarly be a correlative of the Chuos Formation but it lacks iron-formation. A dark finely laminated dolomitic near the base of the Court Formation and above the diamictite preserves moderately negative δ13C compositions (Kaufman et al., 1991; Saylor et al., 1998); it is considered a likely cap carbonate lithofacies.

In the Gariep Belt, the older diamictite is known as the Kaigas Formation, which takes a similar stratigraphic position as the Chuos Formation. Lithologically the Kaigas Formation differs from the Chuos by lacking iron-formation and carbonate intercalations. Most of the formation is not a typical tillite but a poorly sorted conglomerate, in places with upwards fining graded bedding and has a fluvio-glacial signature. Whether the Kaigas deposits reflect a further, older, global glacial event, remains uncertain. As the Kaigas Formation diamictite is not developed in open-marine palaeoenvironments but only locally, at near-shore river mouths and/or entry points of land-based glaciers, it is possible that this formation was formed as consequence of only regional glaciation. Carbon
isotope analyses of the thin (≈2 m) dark-blue to grey, finely laminated dolomictic of the Pickelhaube cap carbonate, as well as minor limestone and dolomite intercalated with arenite and shale, reveal continuously negative δ13C values for ≈100 m above the glacial contact (Fölling and Frimmel, 2002). The lowest 87Sr/86Sr values recorded in two sections of the Pickelhaube Formation are ≈0.7071 and ≈0.7073.

11.1.3.4.3. São Francisco Craton

On the opposite shore of the Adamastor Ocean, Sturtian equivalent diamictites — variably known as the Bebedouro, Jequitai, Carandai or Carrancas formations (Karfunke and Hoppe, 1988; Martins-Neto et al., 2001) – floor the flat-lying Bambuí and Una groups on the São Francisco Craton in Brazil. In the Irecê Basin, the iron-rich Bebedouro diamictite (Figure 11.1.3A) is overlain by a thinly laminated reddish dolomictic at the base of the Salitre Formation, an equivalent of the Sete Lagoas Formation in the Bambuí Basin to the south. It is likely that the very first isotopic analysis of post-glacial cap carbonate anywhere came from the study of this deposit (Torquanto and Misi, 1977), although these authors then interpreted the −5‰ carbon isotope values as reflecting a lacustrine environment of deposition. Above the basal cap level, δ13C values of carbonates in the Salitre and the equivalent organic-rich Sete Lagoas Formation rise sharply to near +8‰ in organic-rich microbialaminites (Figure 11.1.3B; Iyer et al., 1995; Misi and Veizer, 1998; Santos et al., 2000).

11.1.3.5. Lithologic and isotopic observations of Marinoan ice ages in southwestern Gondwana

11.1.3.5.1. São Francisco Craton

Lithologic and geochemical evidence for a second Bambuí Group ice age is found stratigraphically higher near the top of the Sete Lagoas Formation. Associated with this ice age is a fall in δ13C of marine limestones by as much as 15‰ to values as low as −5‰ in the Pedro Leopoldo facies (cf. Peryt et al., 1990; Iyer et al., 1995; Babinski et al., 2007; Misi et al., 2007), a remarkable outcrop of neomorphosed aragonitic seafloor cements (akin to those in the Keilberg Member of the Mieberg Formation: Figure 11.1.3C) and limestone rhythmites (Figure 11.1.3D). In the type locality at Samba Quarry the Pedro Leopoldo facies sits on a basement high, but in nearby Inhuama a basement clast dominated diamictite was recently discovered beneath a thick clay interval and a thinly laminated pink cap dolostone. This post-glacial carbonate contains precipitate fabrics and an upward trend to more negative δ13C values as low as 5‰ as reflecting a lacustrine environment of deposition. Above the basal cap level, δ13C values of carbonates in the Salitre and the equivalent organic-rich Sete Lagoas Formation rise sharply to near +8‰ in organic-rich microbialaminites (Figure 11.1.3B; Iyer et al., 1995; Misi and Veizer, 1998; Santos et al., 2000).

A notable negative carbon isotope excursion is also recognised in the correlative Salitre Formation associated with the informal B1 member (Misi and Veizer, 1998) and the deposition of phosphate-rich stromatolites described as Jurusania krilov (Figure 11.1.3E; Misi and Kyle, 1994). Biostromes of similar but somewhat larger plumb stromatolites are preserved as organic-rich limestone (Figure 11.1.3F) in the overlying Serra de Santa Helena Formation. These structures are indistinguishable from those near the base of the Maieberg Formation cap carbonate, but have δ13C values near +10‰. Analyses of well-preserved high Sr samples show 87Sr/86Sr values tightly bunched around 0.7072–0.7074 in the ex-aragonite seafloor precipitates at Samba Quarry and in the equivalent horizon in Irecê.

Based on remarkable textural similarities (i.e. seafloor aragonite precipitates) and an exact match of Sr isotopes (≈0.7073) in the high Sr precipitate fabrics, the pink cap carbonates at Inhuama above the diamictite and the crystal fans at Samba Quarry are most likely to be a direct equivalent to the Maieberg Formation. The Pb-Pb age constraint (740 ± 22 Ma: Babinski et al., 2007) for the aragonite fans at Samba Quarry, however, would place the two units convincingly in the Sturtian epoch, and not the Marinoan (cf. Hoffman and Schrag, 2002). While this eleven point Pb-Pb isochron with notably low MSWD is compelling, the age should be considered tentative at present given the lack of complementary U–Pb analyses on the same samples.

11.1.3.5.2. Congo Craton

In Namibia, one of the most precisely dated examples of Marinoan glacial deposits occurs in the southern Central Zone of the Damara Belt. Hoffmann et al. (2004) obtained a precise U–Pb zircon age of 635.5 ± 1 Ma for a thin ash bed near the top of a metadiamicite unit that these authors correlate with the well-developed glaciomarine Ghaub Formation that occurs all along the Northern Platform, including the Eastern Kaoko Zone, Northern Marginal Zone, Northern Zone and Central Zone of the Damara Belt (see Chapter 5.3). Based on this correlation the above age is typically referred to as the most precise constraint on the age of the Ghaub Formation in southwestern Africa.

The Ghaub glaciation led to a major drop in sea level, estimated to be as much as 400 m, which resulted in exposure and widespread karsting of the Northern Platform. Consequently, the Ghaub Formation diamictite is not
developed everywhere but is either very thin or missing over large areas. As the Ghaub glaciation took place during a
tectonically less active period compared to the Chuos glaciation, the Ghaub Formation is lithologically not as variable
(Hoffman and Halverson, 2008) being composed primarily of carbonate clasts. Iron enrichment is notable only in the
dropstone-laden rhythmite immediately beneath the Maieberg cap, which is distinctly pale cream to pink, lean in
organic carbon, and has characteristic sheet crack cements, graded laminations of clastic carbonate, plumb
stromatolites, megaripples (Allen and Hoffman, 2005), barite and ex-aragonite seafloor precipitates.

The negative biogeochemical anomaly in the Maieberg cap carbonate contrasts with the Rasthof anomaly in
both its trend and apparent duration. Basal Maieberg dolomicrites begin at $-3\%$ and then fall to $-5\%$ in overlying
limestone rhythmites before rising over hundreds of metres upsection to near 0\%, as the shelf shallowed and

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**Figure 11.1.3** Photographs from the Neoproterozoic Bambuí Group and equivalents, Brazil. A: Iron cemented diamicrite
of the Bebedouro Formation; B: organic-rich microbialaminite limestone of the Sete Lagoas Formation with synaeeresis (?)
cracks; C: tufted ex-aragonite precipitates and draping micrite from the Pedro Leopoldo facies at Samba Quarry;
D: limestone rhythmite from the uppermost Sete Lagoas Formation at Paraíso Quarry; E: phosphate-rich stromatolites classified
as _Junussania krilov_ from the B1 member of the Salitre Formation, Una Group (Misi and Kyle, 1994); F: limestone tubestone
stromatolites from the Serra de Santa Helena Formation.
was finally exposed (Hoffman et al., 1998; Hoffman and Schrag, 2002). Strontium isotope compositions of ex-aragonite limestone and rhythmite from deep water Maieberg lithofacies yield values of ca. 0.7073 (Kaufman et al., 1997; Halverson et al., 2007a), which are an exact match with the identical facies of the Sete Lagoas Formation at Sambra Quarry (and the high Sr limestones from the Pickelhaube cap carbonate in southern Namibia) supporting their direct equivalence.

Finally, the Petit Conglomerat of the Kundelunga Group in the northeastern Congo Craton and its equivalents in the Democratic Republic of Congo and Zambia is considered a Marinoan glacial diamictite (Bodiselitisch et al., 2005). The Petit Conglomerat overlies the Nguba Group with an erosional unconformity (Wendorff, 2003) and contains abundant faceted and striated clasts of both intrabasinal and extrabasinal origin. The diamictite is overlain by a 10 m thick fine-grained cap dolostone known as the Calcaire Rose. Carbon isotopes in this cap progressive decrease upsection from ca. −1.8 to −4.1‰ (Bodiselitisch et al., 2005; personal communication, 2007), but in the West Congo Belt the equivalent carbonates of the Schisto-Calcaire Subgroup reveal extremely variable δ¹³C ratios ranging between −3 and +9‰ and a lowest ⁸⁷Sr/⁸⁶Sr value from Sr-rich limestone of ∼0.7074 (Frimmel et al., 2006; Poidevin, 2007).

11.1.3.5.3. Kalahari Craton
Other potential Marinoan diamictites in Namibia include the Bläskranz Formation preserved in the Naukluft Nappe Complex on the Kalahari Craton. In the Naukluft the diamictite is overlain by the Tsabis cap carbonate, which is a dark rhythmic limestone with negative δ¹³C compositions and lowest ⁸⁷Sr/⁸⁶Sr values of ∼0.7081. This value is identical to those in high Sr precipitate fabrics from the correlated LaFraque Member of the Buschmannsklippe Formation in the nearby Witvlei Group (Hegenberger, 1993; Saylor et al., 1998). It is also an exact match for high Sr rhythms in transgressive limestone above the basal Doushantuo cap dolostone (Jiang et al., 2007). Analogous to stratigraphic relations seen in the Maieberg cap carbonate, plumb stromatolites in the Bildah Member underly ex-aragonite crystal fans of the LaFraque Member. Notably, the negative δ¹³C values continue for a considerable stratigraphic throw (also like the Maieberg) continuing throughout the Buschmannsklippe Formation and stepping over a significant unconformity into the fossiliferous Nama Group (Kaufman et al., 1991; Saylor et al., 1998).

11.1.3.5.4. Amazon Craton
On the Amazon Craton in the northern Paraguay Belt of Brazil, glacial diamictite of the Puga Formation is generally believed to be Marinoan in age, which is consistent with a new Pb-Pb carbonate age of 633 ± 25 Ma for the Mirassol d’Oeste cap (see Chapter 2). The glacial deposit comprises thick sheets of pebbly siltstone and diamictite that accumulated in a glaciomarine setting (Alvarenga and Trompette, 1992). The Puga is overlain by transgressive carbonates of the Araras Group (Nogueira et al., 2003, 2007b; Riccomini et al., 2007). The contact between the Puga and overlying Mirassol d’Oeste cap carbonate is highly irregular (Figure 11.1.4A), in contrast to the knife-sharp surface recognised across glacial terminations elsewhere, suggesting that at the time of emplacement of the cap the underlying diamictite was still soft (Nogueira et al., 2003). This observation supports the view of a rapid icehouse to greenhouse transition, and has similarly been noted at the contact between the Jequitaiá diamictite and basal Sete Lagoas cap carbonate near Belo Horizonte in south central Brazil on the São Francisco Craton (Figure 11.1.4B).

The Mirassol d’Oeste cap dolostone and lowermost Guia Formation limestone atop the Puga diamictite contains many of the same suite of lithologic and textural features found in the Maieberg (sheet crack cements, plumb stromatolites and megaripples in the dolostone, and seafloor crystal fans in the organic-rich limestone facies) (Nogueira et al., 2003; Trinidad et al., 2003); barite was recently discovered in a horizon between the stromatolites and fans as predicted by their position relative to these features in similar cap lithofacies in Namibia and arctic Canada interpreted to be characteristic of Marinoan (∼635 Ma) glaciation (Hoffman and Schrag, 2002).

A high-resolution carbon isotope study of the Mirassol d’Oeste cap dolostone reveals highly negative δ¹³C values at the base of the unit (ca. −9‰) that rises to a plateau of −4 to −5‰ in the plumb stromatolite dominated interval (Font et al., 2006). Similar values characterise the precipitate interval at the base of the Guia Formation. The lowest ⁸⁷Sr/⁸⁶Sr value recorded in high Sr precipitate limestone from this unit is 0.7074 (Nogueira et al., 2003; Trinidad et al., 2003) supporting its equivalence with similar precipitates in the Sete Lagoas and Maieberg cap carbonates on the São Francisco and Congo cratons, respectively.

11.1.3.5.5. Rio de la Plata Craton
In the southern Paraguay fold belt of Brazil (state of Mato Grosso do Sul) on what some interpret to be the northern margin of the Rio de la Plata Craton (Gaucher et al., 2003, 2008b) the Puga diamictite in its type section and a thin cap dolostone are overlain by siliciclastics and carbonates of the Corumbá Group. Other researchers
believe that this glacial unit lies on the Amazon Craton, and still others as a microcontinent unrelated to either craton. The cap carbonate above the basal Corumbá diamictite has \( \delta^{13}C \) ranging between -5 and -6‰ and a lowest \(^{87}\text{Sr}/^{86}\text{Sr}\) value of 0.7077. This value is just slightly more radiogenic than the Mirassol d’Oeste cap carbonate on the Amazon Craton thus supporting the equivalence of the two Puga units.

However, recent studies have suggested that the Araras Group is older than the Corumbá Group. The equivalence of the two Puga units is controversial because the late Ediacaran Period biomineralising fossil Cloudina and an ash bed dated at ca. 545 ± 6 Ma are found in the Tamengo Formation (Nogueira et al., 2003, 2007b; Riccomini et al., 2007), which is ~100 m above the base of the Corumbá Group — neither of which have been found in the Araras Group. A minor negative \( \delta^{13}C \) excursion and low \(^{87}\text{Sr}/^{86}\text{Sr}\) of ~0.7085 (Sial et al., 2008) at the base of the Tamengo has been used to suggest that the Tamengo is equivalent to the Shuram (Sial et al., 2008), but the magnitude of the two biogeochemical anomalies are considerably different. The stratigraphic puzzle is complex, but might be explained by either a hiatus in the Corumbá section above the cap carbonate on the Rio de la Plata Craton, or by missing chronostratigraphic markers (i.e. Cloudina and the ash bed) above the cap carbonate on the Amazon Craton. Depending on which correlation is correct, both of these diamictites may be Marinoan in age, or alternatively one may be Marinoan and the other Gaskiers.

Along the southern margin of the craton, the Las Ventanas and Playa Hermosa formations (Uruguay) also contain glacial diamictites that may correlate with each other (being proximal and distal equivalents, respectively) and with the Puga to the north. The diamictites in Uruguay are constrained by K-Ar and U-Pb zircon dates to be younger than 600 Ma (see Chapter 4.5) so these most likely represent a Gaskiers ice age.
11.1.3.6. Lithologic and isotopic observations of Gaskiers ice ages in southwestern Gondwana

The U-Pb zircon age constraints on the timing and duration of the Gaskiers diamictite in Newfoundland (Bowring et al., 2003b) pose problems for the definition of the Ediacaran Period and end-member views on the Snowball Earth hypothesis. These results clearly push an ice age far into Ediacaran time in close temporal proximity to the organisms that give the newly ratified period (Knoll et al., 2004) its name. Furthermore, they show that the Gaskiers ice age was less than one million years in length, and may be related to the most profound negative $\delta^{13}$C excursion recorded in Earth history (Xiao et al., 2004a; Fike et al., 2006; Kaufman et al., 2007; McFadden et al., 2008).

Equivalents include successions in South Australia (Calver, 2000) and Oman (Burns and Matter, 1993; An throat et al., 2003) where the carbon isotope excursion was first recognised. In these well-studied successions, however, there are no known glacial diamictites associated with the negative $\delta^{13}$C anomaly, which document smooth stratigraphic trends across facies. However, since the sedimentary rocks from which the anomalies are recorded are poor in carbonate, the depletion in $^{13}$C may be interpreted as a diagenetic artefact (Bristow and Kennedy, 2008). In the western United States and Siberia, however, the ‘Shuram’ anomaly is reproduced with high fidelity in clearly open marine oolitic carbonates and deeper water ex-aragonite crystal fans (Corsetti and Kaufman, 2003; Kaufman et al., 2007; Sovetov and Komlev, 2005) supporting the primary interpretation of this excursion. In Death Valley, the biogeochemical anomaly lies immediately above an unconformity that cuts out $> 50 \text{ m}$ of underlying sediment potentially related to eustatic sea level fall associated with Gaskiers glaciation (Kaufman et al., 2007).

Models suggest that this biogeochemical anomaly is the result of stepwise oxidation of an Ediacaran world ocean (Fike et al., 2006; Canfield et al., 2007; Kaufman et al., 2007; McFadden et al., 2008) where the carbon cycle was buffered by a large oceanic dissolved organic carbon (DOC) pool (Rothman et al., 2003; Peltier et al., 2007). This Ediacaran scenario is in strong contrast to today where seawater is dominated by dissolved inorganic carbon (DIC) and DOC is relatively minor. The biogeochemical anomaly accompanies a rise in oceanic sulphate abundance and fall of $\delta^{34}$S in carbonate-associated sulphate and sulphides (Fike et al., 2006; Kaufman et al., 2007; McFadden et al., 2008). These studies suggest that the excess $^{13}$C-rich alkalinity delivered to the surface oceans was probably associated with a dramatic rise in atmospheric $\text{O}_2$, resulting in DOC oxidation as well as the oxidation of the atmosphere and of fossil organic matter in exposed continental shelf sediments. Surface oxidation may have driven climate change through the breakdown of methane (and the proportional cooling of the planet surface) if this gas dominated over $\text{CO}_2$ in the early Ediacaran atmosphere (cf. Bekker and Kaufman, 2007).

11.1.3.6.1. Kalahari Craton

Glacial phenomena have been recognised for some time from the Ediacaran Nama Group on the Kalahari Craton of southern Namibia. There erosional palaeovalleys that begin at or near the base of the Schwarzrand Subgroup cut extensive grooved glacial pavements into underlying Kuibis Subgroup quartzites (Germs, 1972b). U-Pb zircon ages from ash beds above and below the sub-glacial unconformity (which may be correlative with the unconformity at the base of the Groenefontein Formation of the Cango Caves Group) constrain the age of the Vingerbreek event to between 549 and 545 Ma (Grotzinger et al., 1995). A minor negative $\delta^{13}$C excursion characterises this potential glacial interval (Saylor et al., 1998), but to date there is no isotopic evidence of a Shuram magnitude event in the Nama Group. Deeply incised palaeovalleys, in places filled with diamictite, also occur at the base of the Early Cambrian Nomtas Formation above the Nama Group sediments. A glacial origin has been suggested for the unconformity and the diamictite, which is constrained by U-Pb zircon analyses at $\sim 539 \text{ Ma}$ (Germs, 1972b; Grotzinger et al., 1995). Evidence for both of these glacial intervals remains controversial, and more systematic research on these is warranted.

While the Numees diamictite was previously assigned to the Marinoan glaciation (Frimmel et al., 2002), a Pb-Pb double spike carbonate age of $555 \pm 28 \text{ Ma}$ for the Bloeddriif cap carbonate suggests a younger, potentially syn-Gaskiers age for this formation (Fölling et al., 2000; Frimmel and Fölling, 2004). If correct, the Gariep Basin would have been exposed in Marinoan time as there are no other syn-Marinoan deposits known from the Gariep Belt. A major hiatus in sedimentation exists at the base of the largely siliciclastic Wallekraal Formation within the Port Nolloth Zone (external Gariep Belt). In many places, large parts of the older Gariepian stratigraphy have been eroded along that palaeosurface, in places down to the pre-Gariep basement. No potential tectonic cause is evident for this erosion surface and it is suggested that this palaeorelief at the base of the Wallekraal Formation was carved out by ice during a sea level low stand. Considering the global extent of the ice age, it is speculated that Gariep Belt palaeorelief formed during Marinoan times.

The Numees Formation in the Gariep Belt consists of a several hundred metres of massive, laterally continuous, glaciomarine diamictite with interbedded thin laminated iron-formation near the base with dropstones. The lithology of ice-rafter debris reflects the entire pre-Numees stratigraphy including basement rocks. A marked depletion in $^{13}$C characterises the carbonates immediately below and above the Numees
Formation (Fölling and Frimmel, 2002), including the Bloeddrif cap carbonate, which has predominantly negative δ¹³C values (Frimmel and Fölling, 2004) although there is some facies-dependent variability. The lowest ⁸⁷Sr/⁸⁶Sr value recorded in high Sr limestone rhythmite from the Bloeddrif is ca. 0.7082.

A likely equivalent of the Numees Formation exists in the Chameis Subterrane of the largely oceanic Marmora Terrane (western Gariep Belt). There, exotic dropstones occur in a diamictite matrix that consists of volcanic and volcaniclastic rocks of distal oceanic provenance (Frimmel and Jiang, 2001). The surrounding rocks lack any continental component and reflect an open-marine environment with oceanic islands and atolls. This is significant as it represents one of only very few Neoproterozoic examples of glacial influence away from a continental margin. Seafloor metamorphism has been dated by Ar-Ar hornblende data at approximately 610 Ma (Frimmel and Frank, 1998).

By analogy, the diamictite in the Bloupoort Formation of the Gilberg Group in the Vredendal Inlier further south, is considered a correlative of the Numees Formation (Frimmel, 2008). No direct evidence of a Numees-equivalent diamictite unit exists in the Saldania Belt. However, a negative δ¹³C excursion at the base of the Kombuis Member, Matjies River Formation (Cango Caves Group) coupled with its Pb-Pb age (553±30 Ma) and micropalaeontological characteristics (Fölling and Fölling, 2002; Gaucher and Germs, 2006) suggest that this unit is part of a cap carbonate lithofacies equivalent to the Bloeddrif Member, although the lowest ⁸⁷Sr/⁸⁶Sr in the Kombuis carbonates is ca. 0.7085. An unconformity at the base of the Kombuis Member probably reflects a hiatus during that glacial period.

11.1.3.6.2. Rio de la Plata Craton

Similar to examples from South Australia, Oman and Death Valley, USA, circumstantial evidence for Gaskiers glaciation also comes from the preservation of a long-lived negative δ¹³C anomaly in carbonates from the late Ediacaran Polanco Formation (Arroyo del Soldado Group) of Uruguay (570–540 Ma; Gaucher et al., 2004c, 2007c). In this case, the onset of the positive-to-negative isotope excursion (from +5 to −4%) accompanies a relative shallowing of seawater (as revealed from sedimentary facies variations) and an upsection drop in ⁸⁷Sr/⁸⁶Sr from 0.7085 (an expected value for this time interval) down to 0.7078. To date this detail of Ediacaran Period strontium isotope change has not been seen in other broadly equivalent sections, so its interpretation at present warrants caution. Gaucher et al. (2004c) interpret the fall in sea level as well as carbon and strontium isotope excursions to glacial eustacy (cf. Kaufman et al., 2007).

The Polanco negative δ¹³C excursion stretches over some 200 m of examined section similar to examples of the Shuram event in Oman and South Australia. Notably, the Polanco carbonate hosts the late Ediacaran index fossil Cloudina riemkeae (Gaucher et al., 2008a; see Chapter 4.3). These observations are consistent with the age of basement granite beneath the Yerbal and Polanco formations, which make these units younger than 582 Ma (Gaucher et al., 2008b).

Stratigraphically upwards, the Barriga Negra Formation records renewed sea-level drop and shelf exposure (Gaucher, 2000) this time accompanying a minor negative δ¹³C excursion to values as low as −2% at the Polanco—Barriga Negra transition (Gaucher et al., 2004c). At the same stratigraphic level, sea-level drop, palaeostratification and platform exposure is recorded in the Sierras Bayas Group (Tandilia) 300 km to the south (Barrio et al., 1991).

11.1.3.6.3. Amazon Craton

Back on the Amazon Craton, a late Ediacaran glacial diamictite and cap carbonate have recently been reported from limited outcrops of the Serra Azul Formation in the northern Paraguay belt (Alvarenga et al., 2007; Figueiredo and Babinski, 2007). This glacial couplet lies stratigraphically above the Puga/Mirassol d’Oeste pair and is thus likely to be of Gaskiers age although there are no significant radiometric constraints in either region. Carbon isotope compositions of the Serra Azul limestones range down to −8‰, which match those from the thin cap above the Gaskiers diamictite in Newfoundland (Myrow and Kaufman, 1999), and have ⁸⁷Sr/⁸⁶Sr compositions near 0.7085, an expected value for the late Ediacaran time frame (e.g. Kaufman et al., 1993; Jacobsen and Kaufman, 1999).

11.1.3.7. Palaeoclimatic change at the Ediacaran-Cambrian boundary and beyond

The end of the Ediacaran Period is defined — by international agreement — at the first appearance in a succession of alternating siliciclastics facies of the trace fossil known as Treptichnus pedum (Narbonne et al., 1987). While this biological first appearance follows the typical search engine for Phanerozoic boundaries, the Precambrian-Cambrian transition is more readily characterised by a profound negative δ¹³C anomaly, which has been recorded in carbonate-dominated successions worldwide (Brasier et al., 1990; Kirschvink et al., 1991; Narbonne et al.,...
1994; Knoll et al., 1995; Kaufman et al., 1996; Pelechaty et al., 1996; Bartley et al., 1998; Shen and Schidlowski, 2000; Kimura and Watanabe, 2001; Corsetti and Hagadorn, 2003). The magnitude of this biogeochemical anomaly (down to −10% in many key sections) rivals that of the Shuram δ13C excursion — notably this defines the interval of most Ediacaran fossils, although Lazarus specimens of Swartpuntia may also appear in Lower Cambrian strata of the Death Valley region (Hagadorn et al., 2000). Between these isotope extrema lies a unique window to climatic and environmental change during the nexus of Ediacaran organismal diversification.

In Namibia, the boundary δ13C anomaly is not recorded in 543 Ma carbonates of the Nama Group (Spitzkopf Member), which notably also contain Swartpuntia (Grotzinger et al., 1995; Narbonne, 1998). This member, however, is truncated by U-shaped valleys, which are filled with coarse clastic debris of the Nommats Formation dated around 539 Ma. Insofar as these have been interpreted as glacial in origin (Germn, 1972b), the biogeochemical anomaly at the boundary might have been cut out in southern Namibia (Saylor et al., 1998), as was the Hüttenberg in northwestern Namibia earlier in Neoproterozoic time.

Studies worldwide have shown that the succeeding Cambrian Period is characterised by a series of large-scale δ13C excursions, some of which are associated with faunal turnover and extinction. Ten of these excursions have been defined (Alvaro et al., 2008) from the BACE (Basal Cambrian Isotope Excursion: noted above) to the TOCE (Top of Cambrian Excursion: Ripperdan, 2002; Sial et al., 2008; Figure 11.1.5). None of these biogeochemical events, however, have been directly related to glaciation; some have been associated with falls in sea level that may be eustatic in origin (Ripperdan, 2002; Sial et al., 2008). It seems additionally likely that these are related to faunal turnover and diversification, as well as the progressive increase in bioturbation and ventilation of organic-rich sediments through Cambrian time (Droser and Bottjer, 1988).

### 11.1.4. A SYNTHESIS OF THE PALAEOCLIMATIC PUZZLE FROM SOUTHWESTERN GONDWANA

To know the tempo of Neoproterozoic palaeoclimatic change, Cryogenian diamictites and post-glacial cap carbonates must be accurately correlated and constrained in time. For successions in southwestern Gondwana these correlations are complicated by Damaran era rifting (Hoffman, 1991) and orogeny throughout southwestern Gondwana. The geologic jigsaw puzzle left behind in Namibia is particularly complicated and diamictites of different Neoproterozoic age are scattered about the country. Isotope chemostratigraphy was first applied here, in fact, to piece together a history of glaciation and the evolution of Ediacaran organisms (Kaufman et al., 1991, 1993).

#### 11.1.4.1. The Hüttenberg positive carbon isotope anomaly

Those early studies revealed strong negative δ13C anomalies in the post-glacial cap carbonates, especially notable and long-lived in the Maieberg Formation, which was followed by a profound positive δ13C excursion up to extremes > +12‰ (Kaufman et al., 1991; Frimmel et al., 1996c). In a later study high-resolution sampling and analysis of an unmineralised 900 m core from the Tsumeb mine through the thick Elandshoek and organic-rich Hüttenberg formation carbonates revealed a remarkably sustained and highly positive carbon isotope excursion in post-Maieberg strata (Figure 11.1.2). The positive biogeochemical anomaly is preserved in cherty rhythmite, ribbon and grainstone lithofacies reflecting a broad range of sea levels and environmental conditions. Evidence of shallow marine conditions comes from an abundance of fenestral textures and parasequence surfaces marked by enrichments in iron as well as intraformational chert and carbonate breccia. Interbedded dolostone and limestone reveal similar levels of δ13C enrichment. The plateau of values ranging from +8 to +12‰ is distinctly more 13C enriched and considerably longer (> 500 m) than in any Neoproterozoic interval before or after the Hüttenberg and its equivalents. It includes dark microbialites, ribbons of limestone or dolomite in discrete intervals and black organic-rich shale.

Structural repetition in the strata around Tsumeb mine is considerable (and fortunate insofar as faults were certainly the conduits for ore-bearing fluids) and thickening of the unit is likely. This may partially explain the chattering of the isotopic signal in the middle T7 interval. At the top of the succession δ13C values fall sharply to near 0‰, a trend very similar to the pre-Ghaub negative excursion in the uppermost parasequences of the Ombaatjie Formation (Hoffman et al., 1998; Halverson et al., 2002). The negative δ13C excursion at the top of the Hüttenberg was interpreted as the isotopic signal of impending glaciation (cf. Knoll et al., 1986; Kaufman et al., 1991).

Above the Maieberg Formation in northwestern Namibia the Otavi succession includes shallow water dolomites of the Elandshoek Formation, which rise to values only as high as +8‰ (Halverson et al., 2005a; Hoffman and Halverson, 2008). The Tsumeb Subgroup above the Elandshoek, however, is truncated by molasse of the Mulden Group in this part of Namibia, so the compiled chemical stratigraphy for the Otavi Group...
presented by Halverson et al. (2005a) and reproduced in many subsequent publications appears incomplete (Figure 11.1.2). The remarkable positive $\delta^{13}C$ anomaly is clearly reproduced in the organic-rich limestones of the upper Bambuí Group on the São Francisco Craton (Misi et al., 2007). Above the Sete Lagoas Formation, siliciclastic and carbonate strata of the Bambuí Group become increasingly enriched in organic matter, and $\delta^{13}C$ values of samples (including rhythmite, microbialite, stromatolite and oolite facies) rise to positive Neoproterozoic extremes of ca. +14% (Figure 11.1.6; Iyer et al., 1995; Misi and Veizer, 1998; Misi et al., 2007). Molasse of the Três Marais Formation then truncates the Brazilian succession in the same fashion as the Mulden Group molasse atop the Otavi Group in Namibia. The sustained positive biogeochemical anomaly is also recorded near the top of the Akademikerbreen Group in Svalbard and its equivalents in East Greenland (Knoll et al., 1986; Halverson et al.,...
The recent discovery of a diamictite at Inhuma near Samba Quarry supports previous chemostratigraphic data (Misi et al., 2007; Babinski et al., 2007) that supported this unusual deposit of ex-aragonite crystal fans as a cap carbonate lithofacies. Tubestone stromatolites lay stratigraphically higher in the Santa Helena Formation, which is also characterised by high δ^{13}C values near +10‰. Carbon isotope compositions of overlying bituminous carbonates of the Lagoa do Jacaré Formation and their equivalents in the Una Basin and Serra do Ramalho region (Misi et al., 2007) rise to as high as +14‰.
2004), which precede two widely distributed glacial diamictites generally associated with Marinoan events (but see Halverson et al., 2005a who assign these units to the Marinoan and Gaskiers glacial epochs, respectively). In Svalbard and East Greenland a pre-glacial drop in δ13C was also recorded.

Insofar as the magnitude of the Hüttenberg biogeochemical anomaly is significantly larger than in any other time in the Neoproterozoic Era, it has been considered as a chemical divide between Sturtian and Marinoan ice ages (Smith et al., 1994; Kaufman and Knoll, 1995; Kaufman et al., 1997; Figure 11.1.7). This reasoning placed the Ghaub diamictite and Maieberg cap carbonate into the Sturtian era glaciations (Kaufman et al., 1997; Hoffman et al., 1998), but this view was later changed after comparison with suspected Marinoan units in arctic Canada that preserved matching features (Hoffman and Schrag, 2002). In our view, failure to recognise this important divide has profound consequences for correlation of the Cryogenian diamictites and of geochemical trends across the Neoproterozoic Era.

11.1.4.2. Strontium isotope correlations of cap carbonates in southwestern Gondwana

In order to test the temporal placement of the Maieberg Formation into the Marinoan or Sturtian epochs relative to the Hüttenberg anomaly, we have compiled an independent record of strontium isotopes in well-preserved post-glacial limestones from southwestern Gondwana (Figure 11.1.7). These are compared with key sections also believed to be Marinoan in age elsewhere, to evaluate whether there is temporal significance to the unusual textural features and carbon isotope trends in the Cryogenian cap carbonates (Hoffman and Schrag, 2002).

Strontium isotope data from high Sr limestones in cap lithofacies across southwestern Gondwana fall consistently into three modes with values near 0.7066, 0.7073 and 0.7081. These are represented by the Rasthof, Maieberg and Bildah caps in Namibia, respectively, and their temporal equivalents (Figure 11.1.7).

For example, based on $^{87}\text{Sr}/^{86}\text{Sr}$ alone one would predict that the Calcaires du Kokontwe above the Grand Conglomerat in the Lufilian Arc is a Rasthof equivalent cap carbonate. Although Sr isotopes have not been measured from the dolomitic caps atop the iron-rich Jequitaí and Bebeduoro diamictites these are also considered in this compilation to be equivalents to the Chuos diamictite beneath the Rasthof. Outside of southwestern Gondwana $^{87}\text{Sr}/^{86}\text{Sr}$ values of $\sim 0.7066$ are found in limestone rhythmites above the Rapitan equivalent diamictite in the Mackenzie Mountains of arctic Canada, which is widely accepted as a Sturtian archetype (Kaufman et al., 1997).

Using Sr isotopes as a chronostratigraphic tool, the Maieberg Formation equivalent in the Lufilian Arc would be the Calcaire Rose above the Petit Conglomerat. Other Sr isotope matches with the Maieberg in southwestern Gondwana are found in the Picklehaube cap atop the Kaigas diamictite in the Port Nolloth Zone on the Kalahari Craton, the Pedro Leopoldo and B1 member cap lithofacies on the São Francisco Craton and the Mirassol d’Oeste and Puga cap carbonates on the Amazon and Rio de la Plata cratons, respectively. Insofar as the Nantuo diamictite is considered a Marinoan archetype, it is noteworthy that lowest $^{87}\text{Sr}/^{86}\text{Sr}$ values in limestone rhythmites from the 635 Ma basal Doushantuo Formation (ca. 0.7081) do not match those of the Maieberg and its equivalents, but notably do match those of the Bildah and its equivalents on the Kalahari Craton. Furthermore, the Doushantuo cap does not contain tubestone stromatolites, crystal fans or a long-lived negative δ13C excursion (Jiang et al., 2007; McFadden et al., 2008). These clear lithologic and geochemical contrasts support the view that the Maieberg is not a Marinoan cap carbonate. If correct, it seems possible that the 635 Ma radiometric constraint on the ‘Ghaub’ diamictite in the Swakop Zone (Hoffman et al., 2004) alternatively applies to the upper of the two diamictites on the Kalahari Craton (Bläskranz), which in our compilation lies stratigraphically above the Hüttenberg positive carbon isotope anomaly.

Based on this analysis, we contend that peculiar textural features and carbon isotope trends in Cryogenian cap carbonates reflect the repeated occurrence of specific environmental conditions in the depositional basin during post-glacial transgression — rather than chronostratigraphic markers. The interpretation of multiple Sturtian epoch ice ages, including the Ghaub diamictite, from our combined carbon and strontium isotope analysis is supported by a growing number of radiometric constraints on Sturtian diamictites elsewhere. These include the Pb-Pb carbonate ages in the Sr isotope equivalent Picklehaube (728 ± 32 Ma) and Pedro Leopoldo (740 ± 22 Ma) cap carbonates on the Kalahari and São Francisco cratons, respectively.

Our isotopically driven correlations across southwestern Gondwana should be considered as one of several potential equivalent schemes, but these are consistent with emerging radiometric constraints based on Re-Os and U-Pb zircon analyses (with the exception of the problematic Swakop Zone ‘Ghaub’ equivalence noted above). Our reliance on Pb-Pb carbonate ages for the Sturtian cap carbonates may be questioned on diagenetic grounds, but these yield broadly consistent results from two separate cratons. On the other hand, a new Pb-Pb carbonate age (633 ± 30 Ma) for the Sr isotope equivalent Mirassol d’Oeste cap carbonate on the Amazon Craton may support a younger Marinoan age for this unit and its equivalents (Chapter 2) — although given the large uncertainty the age of this cap carbonate may be as old as 663 Ma. In the same vein, the Pb-Pb carbonate age of
Figure 11.1.7  Correlation of Cryogenian and Ediacaran glaciogenic successions in southwestern Gondwana based on strontium and carbon isotope comparisons as well as available radiometric age constraints. Units discussed in this review focus on platform environments the Congo, Kalahari, São Francisco, Amazon and Rio de la Plata cratons and their intervening mobile belts. Details on each of the reported units are found in the text. Where available, the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ composition of high Sr limestone samples from the cap carbonate lithofacies are reported, along with Pb-Pb ages. ΔΔΔ, diamictite.
the Bloeddrif cap carbonate atop the Numees diamictite on the Kalahari Craton is too young to conform with possible Marinoan equivalents — including the basal Doushantuo Formation in South China, which is constrained to be 635 Ma (Zhou et al., 2004a; Condon et al., 2005) and has identical low $^{87}$Sr/$^{86}$Sr of ca. 0.7081 in limestone rhythms (Jiang et al., 2007). The Kombuis Member of the Congo Caves Group in the Saldania Belt also has Pb-Pb carbonate age (553 ± 30 Ma; Fölling et al., 2000) very near to that of the Bloeddrif, but has a lowest $^{87}$Sr/$^{86}$Sr value of 0.7085, which is expected for a younger Shuram level event, but may reflect some diagenetic resetting of its original Sr isotope composition (Figure 11.1.7). Similarly, the downward $^{87}$Sr/$^{86}$Sr trend from 0.7085 to 0.7078 that accompanies sea level fall in the Ediacaran Period Polanco Formation, was unexpected, and highlights our need to better refine our understanding of temporal trends in $^{87}$Sr/$^{86}$Sr throughout the Neoproterozoic. Given the importance of accurately telling Neoproterozoic time in sedimentary successions, more research on the Re-Os shale and Pb-Pb carbonate systems is warranted, including the determination of Pb-Pb ages for the crystal fans in the Maieberg itself.

### 11.1.5. Conclusions

Lacking direct age constraints, the stratigraphic correlation of the discontinuous Ghaub diamictite in northern Namibia, which has served as a type section for Snowball Earth models, with glacial deposits on other Neoproterozoic cratons remains as equivocal today as it has for decades. Carbon isotope trends hold great promise for identifying ice ages in the absence of diamictites, but these oscillatory signals lose their temporal significance if there are multiple discrete events in Cryogenian time (Kaufman et al., 1997; Frimmel and Fölling, 2004; Frimmel, 2009) as indicated by emerging radiometric constraints.

Furthermore, new ages for glacial deposits in southwestern Gondwana appear to push widespread glaciation back into the Mesoproterozoic and forward towards the Precambrian-Cambrian boundary. These observations blur the once clear temporal boundaries of the proposed Cryogenian Period, although current thinking is likely to constrain this interval between ca. 750 and 635 Ma encompassing the known records of Sturtian and Marinoan ice ages.

Strontium isotope ratios in particular hold promise as chronostratigraphic tools if well-preserved samples can be identified, and if long-term trends through the Neoproterozoic show a regular progression to more radiogenic values (Kaufman et al., 1997; Jacobsen and Kaufman, 1999; Halverson et al., 2007a). However, given the scarcity of well-preserved limestone throughout this long interval of Earth history, it is likely that we do not have all the details of secular change in hand. Nonetheless, based only on a subset of repetitive $^{87}$Sr/$^{86}$Sr values in high Sr limestone samples from cap carbonate lithofacies, we recognise four discrete glacial events in southwestern Gondwana, including two Sturtian, one Marinoan and one Gaskiers ice age. Notably, the Namibian Maieberg cap carbonate — considered by many to be a Marinoan archetype — sits stratigraphically below a profound positive carbon isotope excursion (called the Huttenberg anomaly) and is correlated using Sr isotope ratios with identical post-glacial caps in southern Namibia on the Kalahari Craton and in Brazil on the São Francisco Craton dated by Pb-Pb carbonate techniques at ca. 740 Ma. If correct, the Pb-Pb carbonate age constraint places the Ghaub ice age and its equivalents into the Sturtian epoch.

Given the U-Pb age of ca. 635 Ma for a ‘Ghaub’ equivalent in the Swakop Zone of the Damara Orogen, however, we acknowledge the possibility that the Pb-Pb ages from southern Namibia and Brazil may have been reset — even if the cap carbonates are demonstrably equivalent. Lead loss, however, would more likely result in younger, not older ages using this technique. On the other hand, given the tectonic traffic created by Damara rifting and orogeny, and lacking an independent means of correlation of diamictites between the mobile zones and platform successions on both the Congo and Kalahari cratons each of which preserves two levels of glacial strata, the alternative view cannot be falsified at present.

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