Chapter 29

The Tsagaan Oloom Formation, southwestern Mongolia

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Abstract: The Tsagaan Oloom Formation (Fm.) in southwestern Mongolia contains two Neoproterozoic glacial deposits, with diamictite in the Maikhan Ul Member (Mb.) and in the Khongoryn Mb., which are separated by over 500 m of limestone. The Maikhan Ul Mb. ranges in thickness between 5 m and greater than 300 m, expanding in deeper-water sections towards the SW, where it is composed of two massive diamictites separated by over 100 m of sandstone, siltstone and shale. The basal 10 m of the overlying Tayshir Mb. of the Tsagaan Oloom Fm. consists of a fine-laminated, dark grey limestone. The Khongoryn Mb. is composed primarily of limestone clasts in a shale matrix, and is between 0 and 23 m thick. The overlying Ol Mb. contains sedimentary structures characteristic of basal Ediacaran cap carbonates including micropeloids, tubestone stromatolites, giant wave ripples and former aragonite crystal fans. U–Pb evaporation ages from zircons in the underlying Dzabkhan Volcanics constrain the Tsagaan Oloom Fm. to <773 Ma, and tuffs within the Maikhan Ul and Tayshir members testify to the potential for additional geochronology. The Cryogenian organic-rich limestone of the Tayshir Mb., which lies between the two glacial deposits, is ideally suited for geochemical studies and has been the subject of several carbon, strontium and rare earth element investigations. Limited palaeomagnetic studies suggest a mid- to low-latitude position of the Dzabkhan platform during deposition of the glaciogenic strata, and additional studies are in progress.

Neoproterozoic diamictites are present on the Dzabkhan platform (also referred to as the Zavkhan basin) of southwestern Mongolia, in a >100 km NW–SE trending belt, with additional discontinuous exposures further north. The most complete exposures of the Tsagaan Oloom Fm. are between the Khasagty-Nuru ridge and the Dzabkhan River (Fig. 29.1). The geology of the Dzabkhan platform was first described by Bezzibetsev (1986), who divided the stratigraphy into three formations (the Dzabkhan, Tsagaan Oloom and Bayan Gol). Subsequent work focused on the early Cambrian palaeontology of the Bayan Gol Fm., with an eye for correlation with Siberia; the results of these studies were published entirely in Russian (for a list of these references see Brasier *et al.* 1996*b*). The first descriptions in English came in 1996 with the publication of a *Geological Magazine* issue dedicated to the Neoproterozoic-Cambrian stratigraphy of southwestern Mongolia (Brasier *et al.* 1996*a*). The studies reported therein were the product of two international field excursions, one in 1991 as part of the 21st Joint Soviet–Mongolian Palaeontological Expedition (Zhegallo & Zhuravelev 1991), and a second in 1993 sponsored by IGCP Project 303 and the Mongolian Academy of Sciences (Dorjnamjaa *et al.* 1993). The results of these excursions included the translation of geological maps and measured sections into English (Khomentovsky & Gibsher 1996), a reconnaissance chemostratigraphic characterization of the Tsagaan Oloom and Bayan Gol formations (Brasier *et al.* 1996*b*), and a detailed stratigraphic study of the Maikhan Ul diamictite at Tsagaan Gol (Lindsay *et al.* 1996).

Recently, Macdonald *et al.* (2009) conducted detailed chemo- and litho-stratigraphic studies on previously unstudied sections and discovered an additional diamictite higher in the succession. This work supported the earlier conclusion of Brasier *et al.* (1996*b*) that the Maikhan Ul member is early Cryogenian in age and established that the Khongoryn diamictite is an end Cryogenian glacial deposit. With the new C-isotope chemostratigraphic correlations and the documentation of a low-angle unconformity, a >40 million year hiatus was identified within the Tsagaan Oloom Formation, above the Khongoryn diamictite but below the phosphorite horizon (Macdonald *et al.* 2009).

At Tsagaan Gol, the Maikhan Ul Mb. contains two diamictites separated by over 100 m of sandstone, siltstone and shale (Lindsay *et al.* 1996). This creates a bit of confusion in the literature, particularly with the discovery of an additional diamictite higher in the Tsagaan Oloom Fm., because the two diamictites within the Maikhan Ul Mb. have also been referred to as the upper and lower diamictites of the Tsagaan Oloom Fm. (Khomentovsky & Gibsher 1996; Lindsay *et al.* 1996). Macdonald *et al.* (2009) grouped the lower two diamictites and the intervening clastic units together in the Maikhan Ul Mb., while referring to the diamictite *c.* 500 m higher in the sequence as the Khongoryn member. Levashova *et al.* (2010) informally referred to the Maikhan Ul diamictite as the Tayshir Fm. Here, we do not follow this nomenclature because it creates unnecessary confusion, particularly as the overlying carbonates have been previously called the Tayshir Mb. (Macdonald *et al.* 2009).

Structural framework

The Dzabkhan terrane (also referred to as the Baydaric microcontinent when grouped with the Baidrag terrane, Fig. 29.1a) is a composite Precambrian terrane, hosting a heterogeneous Archaean and Proterozoic crystalline basement intruded by *c.* 805–770 Ma continental arc volcanism (Badarch *et al.* 2002; Zhao *et al.* 2006). Based on similarities in the Neoproterozoic stratigraphy, radiometric ages in the underlying basement (Badarch *et al.* 1998), and the continuity of aeromagnetic anomalies associated with the fringing Neoproterozoic ophiolites (Buchan *et al.* 2002), the southwestern margin of the Dzabkhan basin can be traced to the western margin of the Khubsugul basin along the Tuva-Mongolia border (Fig. 29.1a). The tectonic events that transformed the southwestern and western margins of the Dzabkhan and Khubsugul terranes from continental arcs to thermally subsiding passive margins remain unclear. On the southern margin of the Dzabkhan terrane, on the south side of the Khasagty-Nuru ridge, the Dzabkhan and the Tsagaan Oloom Formations are separated by as much as 2 km of canabalizing, rift-related sediments with inter-fingering basalt that are referred to as the Shargyngol complex (Ruzhentsev & Burashnikov 1996). Facies patterns and the orientation of cross-beds in the Tsagaan Oloom Fm. indicate deepening to the SW (Macdonald *et al.* 2009). In the latest Ediacaran to early Cambrian, the rifted passive margin began to subside again after a depositional hiatus of >40 Ma. It has been proposed that this accommodation space was created by flexure with the arrival of the Khantayshir-Dariv arc (Macdonald *et al.* 2009). With the early Cambrian arc–continent collision, the Neoproterozoic stratigraphy was shortened and repeated in thrust blocks with a basal detachment beneath the Dzabkhan Fm. The deformation is largely brittle and thin-skinned, without involvement of the basement. Early Palaeozoic granites and narrow NW-trending grabens

From: Arnaud, E., Halverson, G. P. & Shields-Zhou, G. (eds) *The Geological Record of Neoproterozoic Glaciations*. Geological Society, London, Memoirs, **36**, 331–337. 0435-4052/11/$15.00 © The Geological Society of London 2011. DOI: 10.1144/M36.29

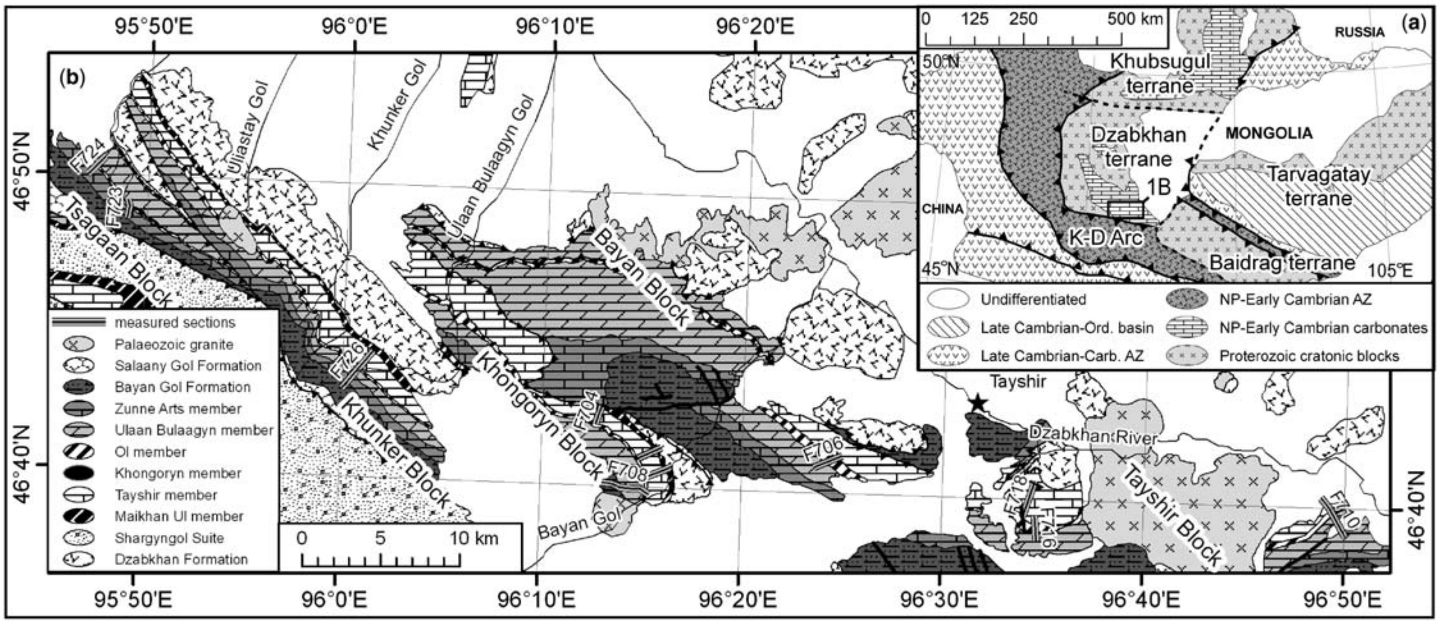

Fig. 29.1. (**a**) Tectonic map of western Mongolia modified from Badarch *et al.* (2002) and Windley *et al.* (2007). Teeth on faults indicate the inferred dip of subduction zones. Key: K-D Arc, Khantayshir-Dariv Arc; AZ, accretionary zone including the arc, metamorphic rocks and ophiolitic assemblages. (**b**) Geological map of the Tayshir region, highlighting the members of the Tsagaan Oloom Fm. and the position of measured sections.

cut the Cambrian NNE-vergent structures. On the outcrop scale, the diamictite and carbonate rocks of the Tsagaan Oloom Fm. are little deformed with no apparent strain. Sedimentary structures are typically preserved in limestone, but are often obfuscated by recrystallization in dolomite.

Stratigraphy

The stratigraphy of the Dzabkhan basin (Fig. 29.2) begins with >2 km of silicic to intermediate volcanic rocks of the Dzabkhan Fm. On the south side of the Khasagty-Nuru ridge, the Dzabkhan Fm. is succeeded by as much as 2 km of sandstone turbidites and conglomerate that are referred to as the Shargyngol complex (Ruzhentsev & Burashnikov 1996). North of the Khasagty-Nuru ridge, the Shargyngol complex is <100 m thick and often absent, with the Maikhan Ul Mb. of the Tsagaan Oloom Fm. nonconformably overlying the Dzabkhan Fm. The Maikhan Ul Mb. is composed of diamictite, sandstone and shale, and varies in thickness from 5 m to >275 m. The Maikhan Ul Mb. is overlain with a knife-sharp contact by the Tayshir Mb., which consists of *c.* 570 m of limestone that included three super-sequences (Macdonald *et al.* 2009).

The Tayshir Mb. is succeeded by the Khongoryn diamictite, which is composed of limestone cobble to boulder lonestones in a shale matrix and varies from 0 to 23 m in thickness. The Khongoryn diamictite is in turn overlain by micropeloidal dolostones of the Ol Mb. (Macdonald *et al.* 2009). In the subsequent transgression, formerly aragonite crystal fans are developed at the dolostone–limestone transition. Above the post-glacial transgression, the Ol Mb. shallows upwards from grey limestone rhythmite into *c.* 10 m of limestone grainstone. The overlying Ulaan Bulagyn Mb. is up to 500 m thick and is composed primarily of massive weathering dolomite; however, in more distal sections, the Ulaan Bulagyn Mb. thins to less than 100 m and is composed largely of limestone.

The Zunne Arts Mb. begins with distinct pink-coloured columnar stromatolites (*Boxonia grumulosa*) that overly a karstic surface with metre-scale relief (Macdonald *et al.* 2009). The *Boxonia* bioherms are overlain by 10–20 m of violet and green shale that are variably phosphatized and interbedded with lenses of dolomite and microcrystalline to nodular phosphorite. This phosphatic shale is overlain by more than 100 m of blue limestone rhythmite and ribbonite that include nodular black chert and bed parallel, meandering ichnogenera (Goldring & Jensen 1996). Above the Zunne Arts Mb. of the Tsagaan Oloom Fm., the early Cambrian Bayan Gol Fm. is composed of *c.* 1000 m of mixed carbonate and siltstone with a rich diversity of ichnogenera, small shelly fossils and calcimicrobial patch reefs (Kruse *et al.* 1996).

Glaciogenic deposits and associated strata

The Maikhan Ul Member

The Maikhan Ul Mb. progressively thickens to the SW (Fig. 29.3), but also displays considerable variability on individual thrust blocks. For example, at the easternmost exposures on the Tayshir Block (F718), the Maikhan Ul Mb. is only 6.7 m thick and is composed predominantly of a massive cobble–boulder clast diamictite, whereas just 1 km to the west (F713) it thickens to 81.6 m with multiple diamictite units separated by 57 m of massive, fine to coarse-grained sandstone. These sandstone bodies are composed of graded centimetre- to metre-thick beds and contain no evidence of tidal influence (Fig. 29.3).

Further south, in more distal sections, the Maikhan Ul Mb. continues to thicken. On the Khongoryn Block (F701), the Maikhan Ul Mb. fills palaeo-canyons and varies in thickness between 160 and 283 m. One palaeo-canyon, directly west of F701, is *c.* 125 m deep and 0.6 km wide. This palaeo-canyon has an erosive base that is mantled with a volcanic-clast, cobble conglomerate and is filled with stratified diamictite units with dropstones and striated clasts (Macdonald *et al.* 2009), thin-bedded sandstone beds and a *c.* 0.5-m-thick carbonate bed. Two massive to bedded diamictite units lie above the canyon fill, separated by 62 m of siltstone and sandstone with rare cobble lonestones and two additional *c.* 0.5-m-thick carbonate beds.

At Tsagaan Gol, where the member measures 304 m, again, two diamictite units are separated by a thick sequence of flat-bedded shale, siltstone and sandstone (Lindsay *et al.* 1996). Cobble lonestones are present in both the basal and upper metre of this clastic succession, between the two massive diamictites. Khomentovsky & Gibsher (1996) also reported a measured section from Urtor Tsakhir Mountain, *c.* 120 km west of Tayshir, where the Maikhan Ul Mb. is even thicker but still preserves this general stratigraphic pattern of two diamictite units separated by sandstone and siltstone. In this area, mudcracks are also well developed near the top of these intervening clastic units.

In both the upper and lower diamictite units of the Maikhan Ul Mb., the most common lithology comprises a matrix-dominated diamictite with shale and sandstone encasing sub-rounded cobble derived from the underlying Dzabkhan Formation; granite, metamorphic and carbonate clasts of unknown origin are also present. Also, near the base of the Maikhan Ul Mb. at Tsagaan Gol, clasts of deformed soft sediment have been reported (Lindsay *et al.* 1996). Clast size varies from grit to blocks >2 m across.

The Khongoryn Member

The Khongoryn Mb. is thickest one gully east of Tsagaan Gol (F723); however, like the Maikhan Ul Mb., there are significant facies changes both from north to south and from east to west (Fig. 29.4). East of Tsagaan Gol, the diamictite is 23 m thick and composed of pebble- to boulder-sized clasts of blue-grey limestone from the underlying Tayshir member in a dark grey shale matrix that becomes more marly and lighter coloured up-section. Striated clasts and limestone clasts with soft sedimentary deformation are also present. Just 6 km west, near Tsagaan Gol, the diamictite is nearly absent and only 2 m of recessive shale are preserved. The Khongoryn Mb. is also well developed on the Khongoryn block, south of Bayan Gol (F708), where it consists of 14.7 m of sub-rounded limestone pebbles, cobbles and boulders in a grey shale matrix. Both laterally and up-section, clasts are irregularly distributed, varying from clast-poor facies to boulder nests. To the NE of the Khongoryn block, the Khongoryn Mb. is either thin or absent.

Associated carbonate rocks

The basal 10 m of the Tayshir Mb., which overlies the Maikhan Ul Mb., is composed of a dark grey, millimetre-laminated limestone. Overall, the Tayshir Mb. consists of <650 m of limestone that record three regionally extensive sequences. The base of the first sequence is defined by a *c.* 10-m-thick, dark grey (weathering to tan), millimetre laminated limestone that is succeeded by *c.* 100 m of limestone marl and rhythmite, shoaling up-section to *c.* 20 m of grainstone. The second sequence begins with *c.* 10 m of limestone marl and rhythmite followed by *c.* 200 m of massively bedded, blue grainstone and microbialaminite. The third sequence begins with *c.* 50 m of limestone rhythmite and debris flows with numerous black chert beds and nodules, and then shallows up-section to *c.* 210 m of dark, fetid limestone microbialaminite and minor grainstone with giant ooids (>0.5 cm diameter).

The Ol Mb., which overlies the Khongoryn diamictite, begins with 7–40 m of buff to pink coloured, largely recrystallized, micropeloidal dolostone. Low-angle cross-stratification (Aitken 1991), tubestone stromatolites (Corsetti & Grotzinger 2005), and giant wave ripples (Allen & Hoffman 2005) are also present in the Ol Mb. dolomite (Fig. 29.4). The Ol Mb. transgresses upwards into limestone ribbonite and then rhythmite with

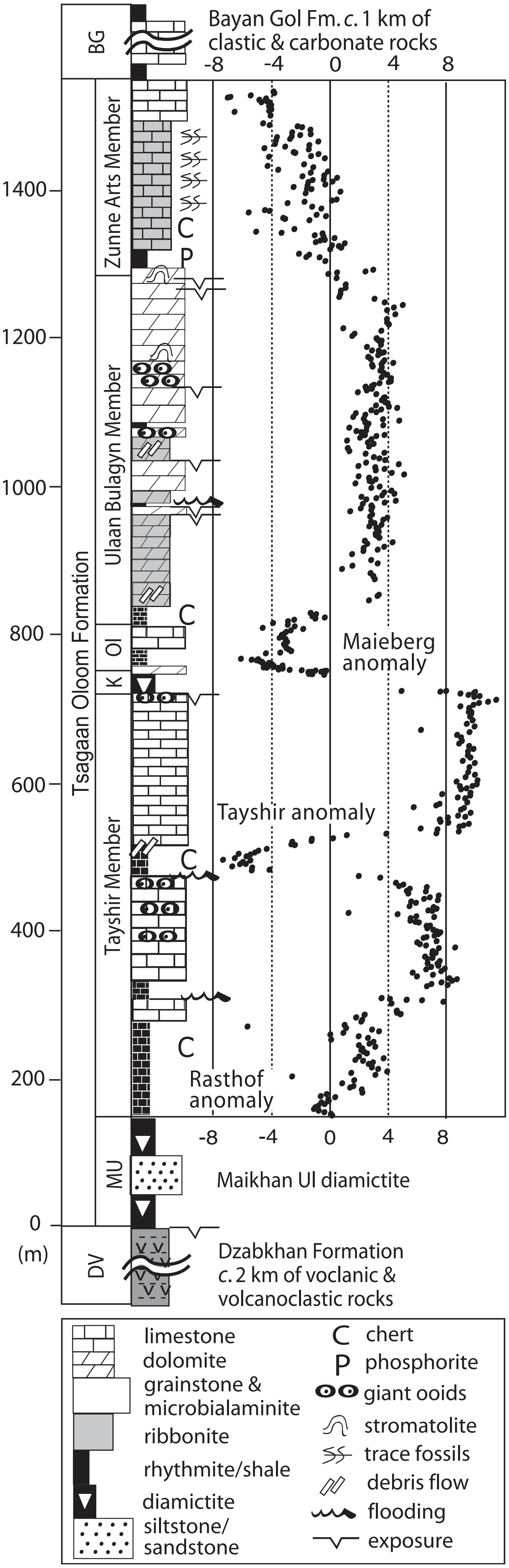

Fig. 29.2. Composite carbon chemo- and lithostratigraphy of the Dzabkhan basin, modified from Macdonald *et al.* (2009). K, Khongoryn diamictite. The Rasthof anomaly was first well-documented in Namibia (Yoshioka *et al.* 2003) and, like the Maieberg anomaly (Halverson *et al.* 2005), has now been reported globally. The Tayshir anomaly was first documented in Mongolia (Macdonald *et al.* 2009) and a potentially correlative mid-Cryogenian anomaly is also present in the Bonahaven Fm. of the Dalradian Supergroup in Scotland and Ireland (Prave *et al.* 2009).

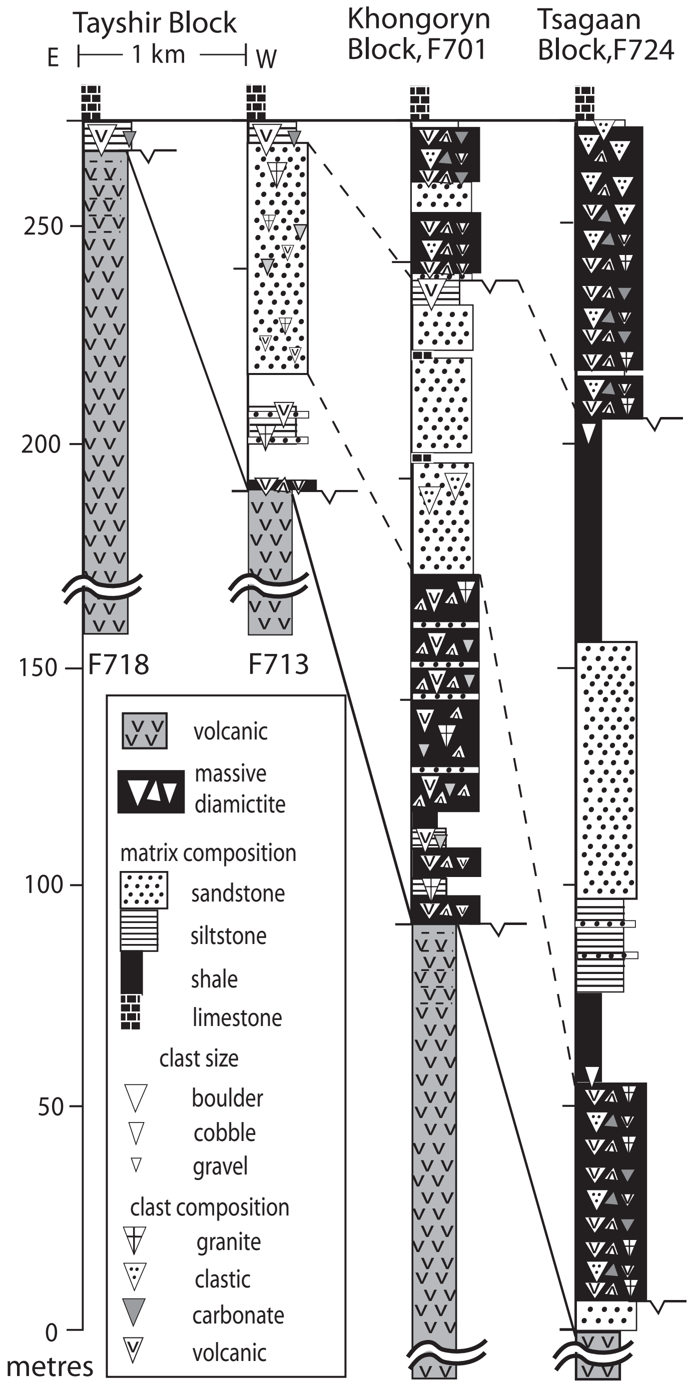

Fig. 29.3. Stratigraphy of the Maikhan Ul Mb. Locations of sections are shown in Figure 29.1b. Section F724 is modified from Lindsay *et al.* (1996). Symbols used that are not in the legend are in Figure 29.2.

c. 5-cm-tall former aragonite crystal fans present at the limestone–dolostone transition. Crystal fans are present both as individual blades growing upwards into the sediment, and as crystal fan shrubs that are over 10 cm across.

Boundary relations with overlying and underlying non-glacial units

The Maikhan Ul Mb. rests with an erosive base on the Shargyngol suite and the Dzabkhan Formation (Khomentovsky & Gibsher 1996), and fills palaeo-topography with conglomerates lining palaeo-valleys (Fig. 29.3). According to Lindsay *et al.* (1996), at Tsagaan Gol, soft-sedimentary deformation is present in sandstone below the Maikhan Ul Mb., indicating only a limited hiatus. However, it is not clear if this sandstone is part of the Shargyngol suite or should be included within the Maikhan Ul Mb. South of Tsagaan Gol, the clastic units between the Dzabkhan Fm. and the lower Maikhan Ul diamictite unit thicken to over 100 m and lack any evidence of glacial influence on sedimentation. Conversely, to the east and north of Tayshir, both the Maikhan Ul Mb. and the Dzabkhan Fm. thin, with the diamictites of the Maikhan Ul resting on an erosional contact with the Dzabkhan Fm. or the basement rock.

Contact between the Maikhan Ul Mb. and the overlying Tayshir Mb. is very sharp. The Tayshir Mb. rests conformably on a laterally persistant, *c.* 10-cm-thick layer of red clay that marks the top of the Maikhan Ul Mb.

The Khongoryn diamictite typically lies above blue-grey, giant ooid grainstones of the lower limestone of the Tsaagan Oloom Fm.; however, on the Khongoryn Block (F708), there is an additional 7.7 m of black shale and rhythmite preserved above the ooids. The erosion of this shale likely provides the detrital matrix for the Khongoryn diamictite. The Khongoryn diamictite is overlain with a sharp yet conformable contact by dolostone and limestone of the Ol Mb.

Chemostratigraphy

Strontium isotope values rise from 0.7067 to 0.7073 in the limestones of the Tayshir Mb. In the Ulaan Bulagyn Mb. $^{87}Sr/^{86}Sr$ values rise from 0.7073 to 0.7077, and then in the Zunne Arts Mb. from 0.7078 to over 0.7080 (Brasier *et al.* 1996*b*; Shields *et al.* 2002).

Carbonate $\delta^{13}C$ values in the dark-grey laminated limestone above the Maikhan Ul Fm. are moderately negative with values increasing upwards through the overlying pink marls to +8‰ (Fig. 29.2). Values plummet abruptly at the flooding surface in the middle of the Tayshir Mb., reaching a low of −7.5‰. Macdonald *et al.* (2009) refer to this sudden drop in $\delta^{13}C$ values as the Tayshir anomaly. From this nadir, $\delta^{13}C$ values increase smoothly to +9‰ for the upper Tayshir Mb., with values reported as high as +11‰ (Brasier *et al.* 1996*b*). Shields *et al.* (2002) also measured $\delta^{13}C$ of organic matter in the Tayshir Mb. of the Tsagaan Oloom Fm. and found that trends roughly followed those exhibited by the $\delta^{13}C$ in carbonate.

Overlying the upper diamictite, $\delta^{13}C$ values in the Ol Mb. begin around −1‰ and follow a sigmoidal profile (Fig. 29.2). Values return to *c.* −1‰ at the top of the dolostone, and then decrease again at the limestone–dolomite transition, reaching a nadir of −6‰. Above the Ol Mb., $\delta^{13}C$ values oscillate around +3‰ for most of the Ulaan Bulagyn Mb., returning to 0‰ below the sub-Zunne Arts Mb. karstic surface.

Sheilds *et al.* (1997, 2002) reported a Ce anomaly in the Tayshir Mb. from samples collected at Tsagaan Gol. In this section, the recessive strata bearing the C-isotope anomaly are not exposed, and thus, they did not document the transgressive sequence or the negative C-isotope values.

Palaeolatitude and palaeogeography

Recent palaeomagnetic studies on the 805–770 Ma Dzabkhan Fm. indicate that the Dzabkhan terrane was located at a latitude of $47^\circ + 16^\circ/-12^\circ$ (Levashova *et al.* 2010). From palaeomagnetic studies on peri-Siberian terranes, including the early Cambrian Salaany Gol Fm. on the Dzabkhan terrane, Kravchinsky *et al.* (2001) concluded that the Tuva-Mongolia belt was at low latitude, adjacent to Siberia throughout the Ediacaran and Cambrian. However, this study lacked a robust confidence test (i.e. only a reversal test with few samples and low resolution). Moreover, an earlier study on the Salaany Gol Fm. gave entirely different

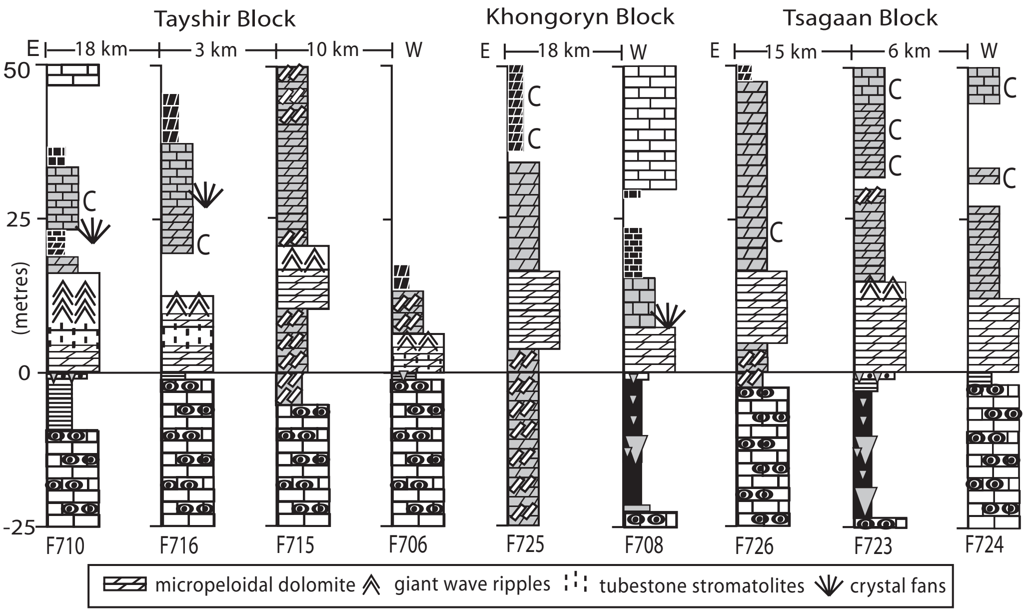

Fig. 29.4. Stratigraphy of the Khongoryn diamictite and overlying Ol Mb. Positions of measured sections are in Figure 29.1b. Symbols used that are not in the legend are in Figures 29.2 and 29.3.

results (Evans *et al.* 1996), but it was also compromised by uncertainty in the relative ages of the folds used in the fold test and possible magnetic overprints. Further palaeomagnetic studies on the Dzabkhan terrane are necessary, and are in progress (Gregory *et al.* 2007). Nonetheless, as non-skeletal carbonate is preferentially produced in the warmest parts of the surface ocean (Broecker & Peng 1982), and the Tsaagan Oloom Fm. is dominated by shallow-water carbonates, it is likely that the Dzabkhan terrane was situated at low latitudes (less than 30°) throughout the Cryogenian and Ediacaran.

Along with other peri-Siberian terranes, it has been suggested that the Dzabkhan terrane occupied a Precambrian position between Siberia and Laurentia (Gladkochub *et al.* 2006), and rifted away from Siberia in the late Neoproterozoic (Sengor & Natal'in 1996; Kuzmichev *et al.* 2001; Kuzmichev *et al.* 2005). Sengor & Natal'in (1996) further posit that throughout the late Neoproterozoic and early Palaeozoic, the Dzabkhan terrane was attached to the Central Mongolian Block, which along with other terranes, stretched to the present day Sea of Okhotsk. Both the Tuva-Mongolia (including the Dzabkhan terrane) and Central Mongolian Blocks host Cambrian trilobites endemic to Siberia (Astashkin *et al.* 1995) and Silurian brachiopods characteristic of the peri-Siberian realm (Hou & Boucot 1990). Alternatively, citing similarities in SHRIMP ages on zircons, Zhao *et al.* (2006) and Demoux *et al.* (2009) have suggested that the Baydrag and Dzabkhan terranes originated from the northern margin of Gondwana. This reconstruction is supported by the palaeomagnetic results of Levashova *et al.* (2010), which point to Neoproterozoic connections with India, South China, Tarim or Australia.

Geochronological constraints

Although the diamictites of the Dzabkhan basin have not been directly dated radiometrically, maximum age constraints on the glacial deposits are provided by zircons from rhyolites within the Dzabkhan Formation of 777 ± 6 Ma (Zhao *et al.* 2006), 803.4 ± 8.0 and 773.5 ± 3.6 Ma (U–Pb laser evaporation, Levashova *et al.* 2010).

Discussion

A glacial origin of the Maikhan Ul diamictite units is indicated by the presence of faceted and striated clasts, and bullet-shaped dropstones that penetrate laminated beds. At Tsagaan Gol, cobble dropstones are also present in both the basal and upper metre of the clastic succession, between the two massive diamictite units. Moreover, in more proximal settings, such as on the Khongoryn and Tayshir blocks, rare lonestones are present within the sandstone beds. These observations indicate that the deposition of the clastic units was influenced, at least in part, by glaciation. Macdonald (2009) inferred a pro-glacial environment, including emergent conditions and proglacial lakes, for both the diamictite and the clastic units of the Maikhan Ul Mb. from the presence of mud cracks and 0.5-m-thick carbonate beds. A pro-glacial environment is further supported by high lateral facies variability. Within this context, the intervening clastic units can be interpreted as a step-back of the ice-line, and the upper diamictite as an ice-advance.

The rise in $^{87}Sr/^{86}Sr$ from 0.7067 to 0.7073 in the limestone of the Tayshir Mb. is mirrored in the Rasthof Fm. in Namibia and the Keele Fm. in NW Canada, suggesting that the underlying Maikhan Ul diamictites are early Cryogenian glacial deposits (Halverson *et al.* 2007). The black laminated cap carbonate above the Maikhan Ul diamictites also contains a modest negative C-isotope anomaly similar to the Rasthof Fm. (Yoshioka *et al.* 2003); the extremely enriched values of the Tayshir Mb. are also consistent with a Cryogenian age (Hoffman & Schrag 2002; Halverson *et al.* 2005). The Tayshir anomaly (Macdonald *et al.* 2009) can be correlated to the moderately negative $^{13}\delta C$ values obtained from the exposure-surface riddled Gruis Fm. of northern Namibia (Halverson *et al.* 2005) and the Cryogenian Bonahaven Dolomite of the British-Irish Caledonides (McCay *et al.* 2006), *or* to the Trezona anomaly in Australia (McKirdy *et al.* 2001) and Namibia (Halverson *et al.* 2005).

A glacial origin of the Khongoryn diamictite is indicated by the presence of striated clasts and dropstones that penetrate laminated beds. The Khongoryn diamictite is thin or absent on the most proximal sections to the NE of the map area (Fig. 29.1). In more distal sections to the SW, the diamictite is composed of cobble to boulder clasts of the underlying limestone within a weakly bedded shale to marl matrix. This shale matrix was likely derived via erosion of the shale unit in the upper portion of the Tayshir Mb., which is only present on the Khongoryn and Tsagaan blocks. The lack of stratigraphic architecture within the deposit, the irregular distribution of ice-rafted debris, such as boulder nests, and the conformable overlying contact with the Ol Mb. indicate that this deposit formed as a single rainout during the terminal deglaciation.

The overlying basal dolostone of the Ol Mb. is composed of fine-laminated micropeloids and contains tubestone stromatolites, giant wave ripples and pseudomorphosed crystal fans. These peculiar sedimentary structures, their specific order, and the distinct, sigmoidal C-isotope profile are characteristic of basal Ediacaran cap carbonates globally (Hoffman *et al.* 2007). This suggests that the underlying Khongoryn diamictite is an end-Cryogenian glacial deposit (Macdonald *et al.* 2009), with the termination bracketed elsewhere by U–Pb ages of 635.51 ± 0.54 Ma and 635.23 ± 0.57 Ma (Condon *et al.* 2005). The phosphorites in the Zunne Arts Mb. rest above a low-angle unconformity. Ediacaran chemostratigraphic correlations indicate that this surface represents a >40 Ma depositional hiatus, and as such is unrelated to the glacial deposits in the Khongoryn member (Macdonald *et al.* 2009).

Further sedimentological studies on the Maikhan Ul Mb. are needed to understand the significance of the interbedded sandstone and siltstone, and to determine if the Maikhan Ul diamictites represent a single episode of deglaciation or multiple ice advances and retreats. Stratigraphic studies are also needed to better understand the basin dynamics of the Neoproterozoic–Cambrian margins of the Dzabkhan terrane, and the relationships with other Mongolian terranes. The palaeogeography of the Peri-Siberian terranes also remains speculative. It is clear, however, that island arcs surrounded the Dzabkhan terrane for much of the Neoproterozoic and Cambrian, and therefore there is excellent potential for U–Pb zircon geochronology studies in the Dzabkhan basin. Furthermore, the low-grade and high organic content of the limestone in the Tayshir Mb. is ideally suited for multi-proxy studies to better constrain the geochemical evolution of Cryogenian oceans.

I thank field assistants B. Boldoo, E. Oyun, T. Adiya, J. Otgonhuu and U. Bold. I also thank Bayassa and A. Amaglaan for help with logistics. I thank D. Jones and P. Hoffman for comments and help in the field. I am grateful to P. Hoffman and NSF grant EAR-0417422 (to PFH) for support of this work. This represents a contribution of the IUGS- and UNESCO-funded IGCP (International Geoscience Programme) project #512.

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