Chapter 30

The Khubsugul Group, Northern Mongolia

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Abstract: The Khubsugul Group of northern Mongolia contains diamictites in the Ongoluk and Khesen formations that are succeeded by a stratiform phosphorite deposit and >2 km of early Cambrian dolomite. The stratigraphy of the Khubsugul Group, including the two diamictites, can be correlated with that of the Dzabkhan platform in southern Mongolia. By correlation, the Ongoluk diamictite is an early Cryogenian glacial deposit. A glaciogenic origin is inferred from the presence of striated clasts and bed-penetrating dropstones. The younger Khesen diamictite consists predominantly of a massive carbonate-clast diamictite, but also contains bed-penetrating dropstones in rare stratified facies, and is inferred to be end Cryogenian in age. The two diamictites are separated by as much as 250 m of allodapic carbonate. The phosphorite in the upper Khesen Formation (Fm.) is likely latest Ediacaran to early Cambrian in age and is separated from the glacial deposits by a major hiatus. Consequently, no links can be made between the phosphogenesis and the glacial deposits. Only limited geochemical, geochronological and palaeomagnetic results from the Khubsugul basin have been reported to date, but work is ongoing and there is strong potential for future studies.

Diamictites in the Ongoluk and Khesen formations of the Khubsugul Group of northern Mongolia are exposed discontinuously in a *c.* 250 km north–south belt (Fig. 30.1). The most complete exposures of the two diamictites and the overlying carbonate and phosphorite occur along the Khesen and Ongoluk Gols (*tr.* Rivers), on the west side of Lake Khubsugul (Fig. 30.2; 50°42.5′N, 100°11′E and 50°44.3′N, 100°12.2′E).

Most of the studies in the Khubsugul basin have focused on the phosphorite deposits and the regional tectonics, with the diamictites mentioned only in passing (e.g. Ilyin 1990, 1998). Although much of this work is in the Russian literature, several key manuscripts from *Litologiya i Poleznye Iskopaemye* have been translated to English in *Lithology and Mineral Resources* (e.g. Osokin & Tyzhinov 1998; Ilyin 2004). Additionally, a Russian field guide of the Khubsugul Basin was produced for an IGCP excursion to the phosphorite localities (Ilyin & Byamba 1980). This field trip spawned the hypothesis that ice rings orbited Precambrian Earth, that the shadow of these rings initiated the Neoproterozoic glaciations, and that their collapse led to phosphogenesis and precipitated the Cambrian radiation (Sheldon 1984).

Geological work commenced in the Khubsugul basin in the mid-1960s with the discovery of ore-grade phosphorites (Donov *et al.* 1967). The Khubsugul Group was originally described in detail, including the identification of diamictites in the Ongoluk Fm., by Ilyin (1973). Osokin & Tyzhinov (1998) later differentiated a second diamictite in the basal Khesen Fm. and documented the presence of both diamictites throughout the Khubsugul basin.

The diamictites in the Khubsugul basin have not been formally named, and the formations within which they occur have been named differently in Mongolia and Siberia (see Chumakov 2011). The diamictite at the base of the Ongoluk Fm. in the Khubsugul basin is likely equivalent to the diamictite in the Khushatai Fm. of the Sarkhoi Group (Osokin & Tyzhinov 1998). Otherwise, the Khubsugul Group in Mongolia is largely correlative with the Boxon Group in Siberia, with the Khesen Fm. roughly equivalent to the Zabit Fm. Correlations of specific diamictites in the Khesen and Zabit formations are complicated by multiple conglomeratic horizons within both formations (Kheraskova & Samygin 1992; Osokin & Tyzhinov 1998).

Ilyin (1973, 2004) referred to the upper *c.* 50 m of the lower diamictite as the ‘perforated shales’ after the holes left behind from eroded carbonate clasts, and he defined the diamictite as the basal member of the Khubsugul Group; however, the diamictite is underlain by an additional several hundred metres of clastic rocks that he included with the underlying Arasan Fm. Following Osokin & Tyzhinov (1998), we include these clastic rocks with the Ongoluk Fm. of the Khubsugul Group, and refer to the diamictite in the Ongoluk Fm. as the Ongoluk diamictite. The upper diamictite is in the basal Khesen Fm. of the Khubsugul Group and is herein referred to as the Khesen diamictite. The two diamictites are separated by 100–250 m of carbonate of the upper Ongoluk Fm.

Structural framework

The Khubsugul terrane is a composite Precambrian terrane, hosting a heterogeneous Archaean and Proterozoic crystalline basement intruded by *c.* 800 Ma continental arc volcanism (Badarch *et al.* 2002). Based on similarities in Neoproterozoic stratigraphy, radiometric ages in the underlying basement (Badarch *et al.* 2002) and the continuity of aeromagnetic anomalies associated with fringing Neoproterozoic ophiolites (Buchan *et al.* 2002), the southwestern margin of the Dzabkhan platform can be traced to the western margin of the Khubsugul basin along the Tuva-Mongolia border (Fig. 30.1, Macdonald 2011). The eastern boundary of the Dzabkhan terrane is obscured by Palaeozoic intrusions (Badarch *et al.* 1998) and, consequently, pre-Ordovician connections with the Baidrag terrane remain ambiguous. Overlap assemblages indicate that the Dzabkhan, Khubsugul, Baidrag and Tarvagatay terranes had amalgamated into a single continental mass by the Devonian (Badarch *et al.* 2002).

On both the Khubsugul and Dzabkhan terranes, Palaeoproterozoic basement is overlain by thick volcanic–volcaniclastic successions (Badarch *et al.* 2002). On the Khubsugul terrane, the Sarkhoi volcanic rocks have been interpreted as having a continental arc affinity (Kuzmichev *et al.* 2001). These are unconformably overlain by the rift-related volcanic rocks and clastic sediments of the Dharkhat Group (Ilyin 1990). The Khubsugul terrane transformed from a continental arc to a thermally subsiding passive margin after the *c.* 800 Ma Shishkhid arc accreted to its western margin and prior to rifting along its eastern margin (Kuzmichev *et al.* 2005).

Ilyin (2004) documented a deepening to the west in the phosphorite-bearing strata of the Khesen Fm. and the overlying

From: Arnaud, E., Halverson, G. P. & Shields-Zhou, G. (eds) *The Geological Record of Neoproterozoic Glaciations*. Geological Society, London, Memoirs, **36**, 339–345. 0435-4052/11/$15.00 DOI: 10.1144/M36.30

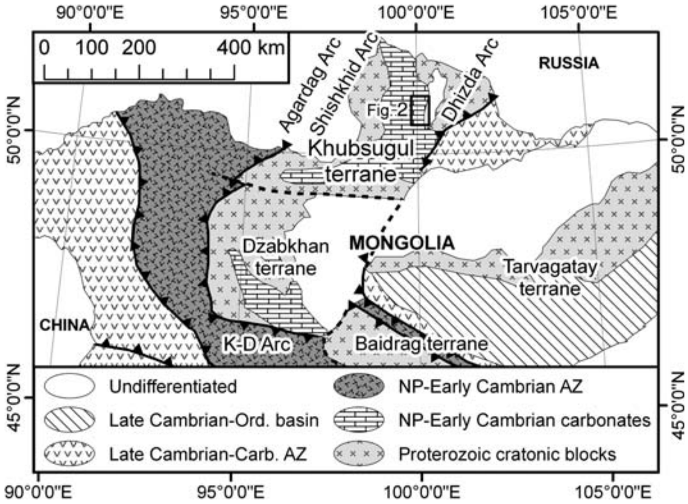

Fig. 30.1. Tectonic map of western Mongolia modified from Badarch *et al.* (2002) and Windley *et al.* (2007). Teeth on faults indicate the inferred dip of subduction zones. K-D Arc, Khantayshir-Dariv Arc; AZ, accretionary zone including arcs, metamorphic rocks and ophiolites; NP, Neoproterozoic; Ord, Ordovician; Carb, Carboniferous.

early Cambrian shelf carbonates, and suggested these were deposited in a rift graben. Macdonald *et al.* (2009) alternatively posited that most of the Neoproterozoic sediments on the Dzabkhan and Khubsugul terranes were deposited on a thermally subsiding rifted margin, but that the late Ediacaran to early Cambrian phosphorites and overlying early Cambrian deposits formed in a foredeep basin in response to the Salarian orogeny (Ruzhentsev & Burashnikov 1996).

Exposures of Cambrian carbonates on the west side of Lake Khubsugul are folded in tight, south-plunging synclines and are cut by Palaeozoic granites (Fig. 30.3), perhaps also related to an extension of the early Cambrian Salarian orogeny (Ruzhentsev & Burashnikov 1996) accompanying the collision between the Agradag arc and the Khubsugul terrane. Palaeozoic intrusions are particularly common in the south of the Khubsugul basin where they effectively obliterate the host stratigraphy (Badarch *et al.* 1998).

Lake Khubsugul and the Darkhat depression formed as a southern arm of the Neogene Baikal rifting episode. Neoproterozoic–Cambrian stratigraphy on the west side of Lake Khubsugul was uplifted and exposed along a rift shoulder. Rifts commonly followed Precambrian structures and were accompanied by voluminous basaltic volcanism (Logatchev 1984).

Stratigraphy

The Khubsugul basin sequence begins with rift-related volcanic and clastic rocks of the Darkhat Group that rest unconformably on Precambrian basement and meta-sediments (Ilyin 1973, 1990, 2004). These volcanic rocks are overlain with hundreds of metres of clastic and carbonate rocks that are variably preserved under the sub-Khubsugul Group unconformity (Osokin & Tyzhinov 1998). The Khubsugul Group begins with as much as 100 m of argillite, unsorted sandstone and minor limestone of the basal Ongoluk Fm. and grades upwards into the Ongoluk diamictite, with clasts becoming larger and more abundant upwards. The Ongoluk diamictite is overlain by 100–250 m of allodapic dolomite of the upper Ongoluk Fm. The Khesen Fm. begins with a second diamictite that is *c.* 50 m thick and carbonate clast-dominated (Osokin & Tyzhinov 1998). The Khesen diamictite is capped with a 3–5 m dolostone, the top of which hosts centimetre-scale barite fans. Stratiform and granular phosphorite rests above a major flooding surface, less than 50 m above the basal Khesen diamictite (Ilyin 2004). Poorly sorted, carbonate clast conglomerates and syn-sedimentary folding are also common in the uppermost Khesen formation. The upper *c.* 2 km of the Khubsugul Group consists of late Ediacaran and Cambrian platformal carbonates of the Erkhelnur Fm.

Glaciogenic deposits and associated strata

The Ongoluk diamictite

Near Lake Khubsugul, the Ongoluk diamictite is composed of a matrix-supported, stratified diamictite that ranges in thickness from *c.* 200 m to 415 m, thinning to the south and west. The thickest and most complete section of the Ongoluk Fm. is on the ridge north of Khesen Gol (Fig. 30.4). There, the basal contact of the diamictite is gradational with gravel-sized lonestones becoming more common upwards, both in an unsorted sandstone matrix and in a laminated argillite matrix, and, as such, the base is difficult to define. Sub-angular to sub-rounded gravel clasts of dolomite and quartzite are most common, with occasional cobbles of granite. Clasts become larger and more common in the upper *c.* 100 m of the diamictite (the 'perforated shale' member of Ilyin 1973, 2004), consisting predominantly of dolomite cobbles in an argillite or siltstone matrix.

At Ongoluk Gol, the base of the Ongoluk diamictite is not exposed, but *c.* 130 m of clast poor siltstone and very coarse sandstone are present that are very similar to the lower *c.* 300 m at Khesen Gol. The 'perforated shale' member is *c.* 50 m thick at Ongoluk Gol, beginning with a 5-m-thick, massive, clast-supported dolomite diamictite, and continuing upwards with a dark, laminated argillite matrix with sub-rounded to angular, boulder-sized clasts of granite, quartzite, volcanic and metamorphic rocks, and gravel to boulder-sized clasts of dolomite. Quartzite and volcanic clasts are commonly faceted and striated (Osokin & Tyzhinov 1998).

The Khesen diamictite

The Khesen diamictite tends to be thinner than the Ongoluk diamictite, and is composed of a massive, carbonate clast-dominated diamictite. The thickness of the Khesen diamictite ranges from 10 to 65 m, with no systematic geographical trend. The thickest measured section of the Khesen diamictite in the Lake Khubsugul area is exposed on the ridge north of Ongoluk Gol (Figs 30.3 & 30.5) and consists predominately of a massive, carbonate-clast diamictite. Clasts are composed of angular to sub-rounded dolomite and limestone (including giant ooid and stromatolite clasts) that are commonly imbricated, with sizes ranging from pebble to boulders. The Khesen diamictite has a yellow-weathering dolomite matrix, with the massive, unbedded deposits broken only by thin, lenticular, rhythmically bedded marls. At Khesen Gol, quartzite and volcanic pebbles are also present, and the massive diamictite is interrupted with multiple fine-laminated beds that are penetrated by outsized clasts.

Boundary relations with overlying and underlying non-glacial units

Near Lake Khubsugul the Ongoluk diamictite has a gradational basal contact with clast-size and abundance decreasing gradually down-section until completely disappearing from the siltstone and sandstone (Osokin & Tyzhinov 1998). At Khesen Gol, the underlying clastic units consist of nearly 100 m of millimetre-laminated argillite and siltstone, with 0.5 m interbeds of unsorted very coarse sandstone and gravel conglomerate, and at least two beds of texture-less limestone. These units rest unconformably

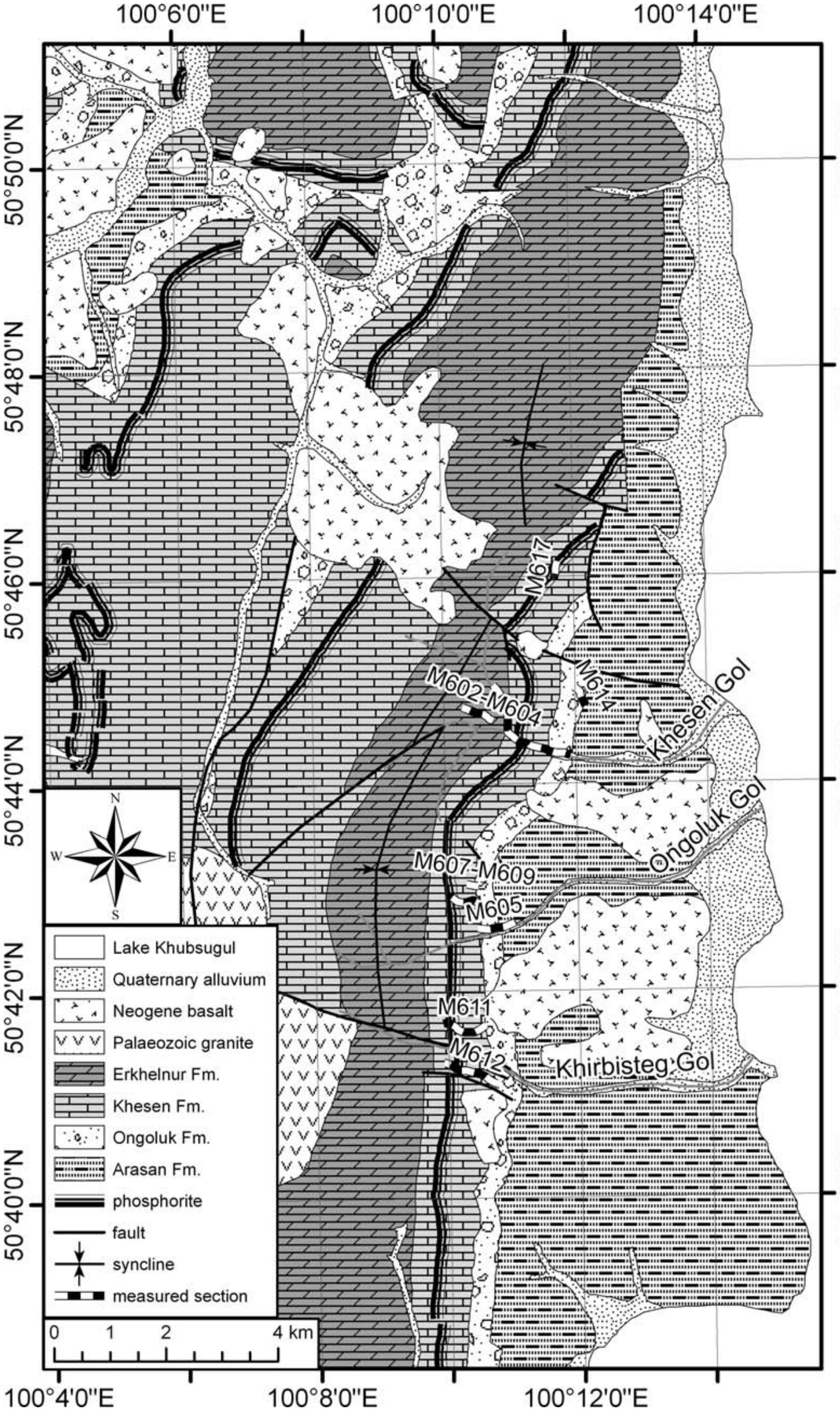

Fig. 30.2. Geology of the western shores of Lake Khubsugul, showing the positions of measured sections.

on dolostone of the Arasan Group. The Ongoluk diamictite is separated from overlying dolomite by a sharp contact, although regionally, deposition appears to be uninterrupted.

Along the Bokson River in Siberia, rocks that are equivalent to the Ongoluk diamictite rest unconformably on the Darkhat volcanics with a 15-m-thick weathering crust at the base (Kuzmichev 2001). A similar, though thinner breccia has been documented in the Darkhat region of Mongolia and along the Sarkhoi River (Osokin & Tyzhinov 1998).

The yellow-weathering Khesen diamictite rests disconformably on a sharp contact with the underlying light blue dolomites. The upper contact, however, is commonly broken with a couple of metres of dolomite breccia between the massive diamictite and the thin dolomite overlying the Khesen diamictite. The dolomite

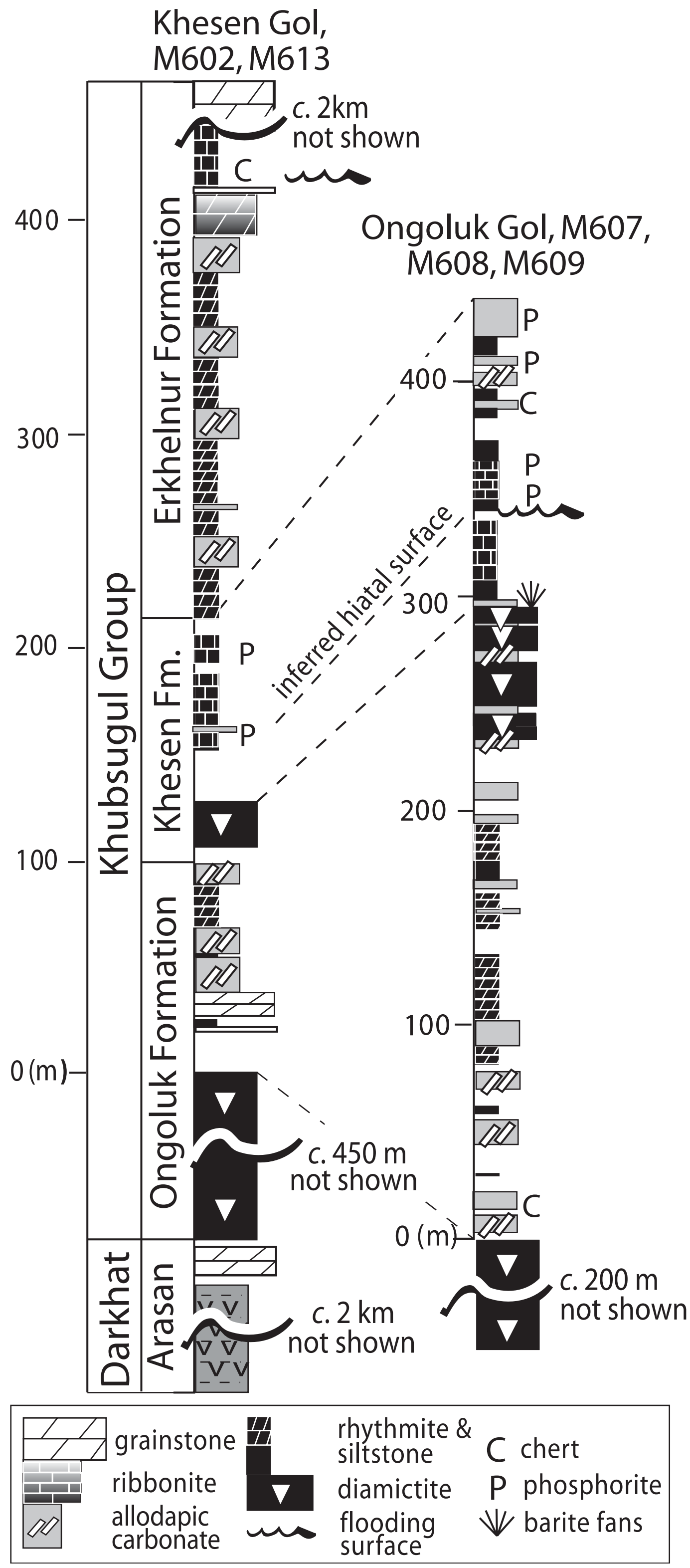

Fig. 30.3. Stratigraphy of the Khubsugul Group along the Khesen and Ongoluk Gols. The locations of measured sections are shown in Figure 30.2.

is only *c.* 1 m thick at Ongoluk Gol with centimetre-scale bladed barite fans at the upper dolomite–limestone transition. Approximately 20 km north, the overlying white dolomite reaches a maximum thickness of 6 m, and is interspersed with bed-parallel cements (Fig. 30.5). A transgression continues above the dolomite into as much as 100 m of dark grey limestone rhythmite. The phosphorite-bearing strata is composed largely of dolomite with common olistostromes and mass flow deposits, and comes in above a disconformable flooding surface (Ilyin 2004) that cuts down into the underlying units (Fig. 30.5).

Chemostratigraphy

Chemostratigraphic studies have not been reported for the carbonate units bounding the two diamictites, although work is in progress. Carbon-isotope values through the phosphatic interval of the Khesen Fm. at Ongoluk Gol range from −7% to +5% (Ilyin & Kiperman 2000; Ilyin 2004); however, as these data have not yet been reproduced, their utility for correlation is questionable. Strontium-isotope values of *c.* 0.7080 have also been reported from carbonate interbedded with the Khubsuglul phosphorite deposit (Shields *et al.* 2000).

Palaeolatitude and palaeogeography

Cocks & Torsvik (2007) provide a review of the palaeomagnetic and Palaeozoic fauna affinity studies of Siberia and the peri-Siberian terranes. However, there are very few reliable palaeomagnetic data on the Khubsugul terrane, particularly in the Neoproterozoic, so the palaeolatitudes presented are highly speculative.

From palaeomagnetic studies on peri-Siberian terranes, 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).

Along with other peri-Siberian terranes, it has been suggested that the Khubsugul 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, 2005). Sengor & Natal'in (1996) further posit that throughout the late Neoproterozoic and early Palaeozoic, these terranes were attached to the Central Mongolian Block, which along with other terranes, stretched to the present day Sea of Okhotsk. However, this reconstruction is inconsistent with the presence of Ordovician accretionary zones on the NW margins of the Baidrag and Dzabkhan terranes and a Late Cambrian Dhizda arc on the west margin of the Khubsugul terrane (Badarch *et al.* 2002). The Khubsugul and Tavargatay terranes host Cambrian trilobites endemic to Siberia (Astashkin *et al.* 1995) and Silurian brachiopods characteristic of the peri-Siberian realm (Hou & Boucot 1990). Thus, although there is a paucity of reliable palaeomagnetic constraints on the Khubsugul terranes, several lines of evidence indicate that they were adjacent to Siberia in the Neoproterozoic and early Palaeozoic. Pisarevsky *et al.* (2000) present a strong *c.* 615 Ma pole on red beds along the Lena River, pinning Siberia at equatorial latitudes in the Neoproterozoic. Further palaeomagnetic studies on the Khubsugul terrane are necessary, and are in progress (J. Meert pers. comm.).

Geochronological constraints

Although the diamictites of the Khubsugul Group have not been directly dated, there are at least two radiometric constraints on the maximum age of the deposits. In Siberia, the Bokson Group overlies the Shishkhid arc, which contains magmatic zircons from rhyolites with a concordant U–Pb SHRIMP age of 800 ± 2 Ma (Kuzmichev *et al.* 2005). The Bokson Group also overlies the Sorkhoi Group, which contains volcanic rocks that have been dated with whole-rock Rb–Sr at 718 ± 30 Ma (Buyakaite *et al.* 1989). In Mongolia, the volcanic rocks of the Sorkhoi Group are stratigraphically equivalent to the Darkhat and Dzabkhan volcanics (Macdonald 2011), which have been dated at 850 ± 2 and 750 ± 3 Ma (Pb/Pb zircon, Burashnikov 1990), and more recently, at 777 ± 6 Ma (U–Pb SHRIMP zircon, Zhao

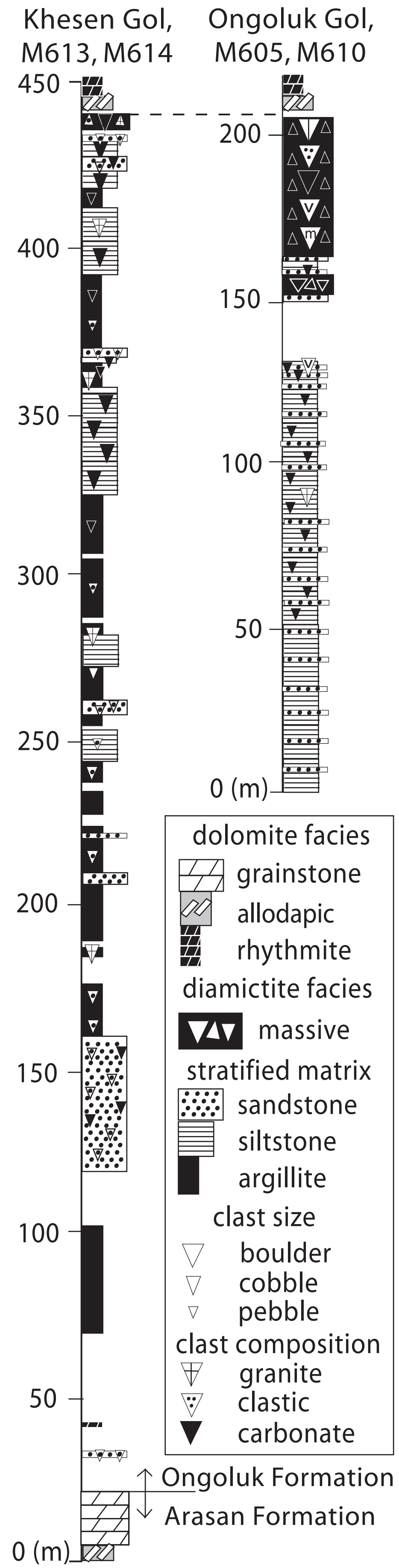

Fig. 30.4. Detailed stratigraphy of the Ongoluk diamictite along the Khesen and Ongoluk Gols. The locations of measured sections are shown in Figure 30.2. m, metamorphic clasts; v, volcanic clasts.

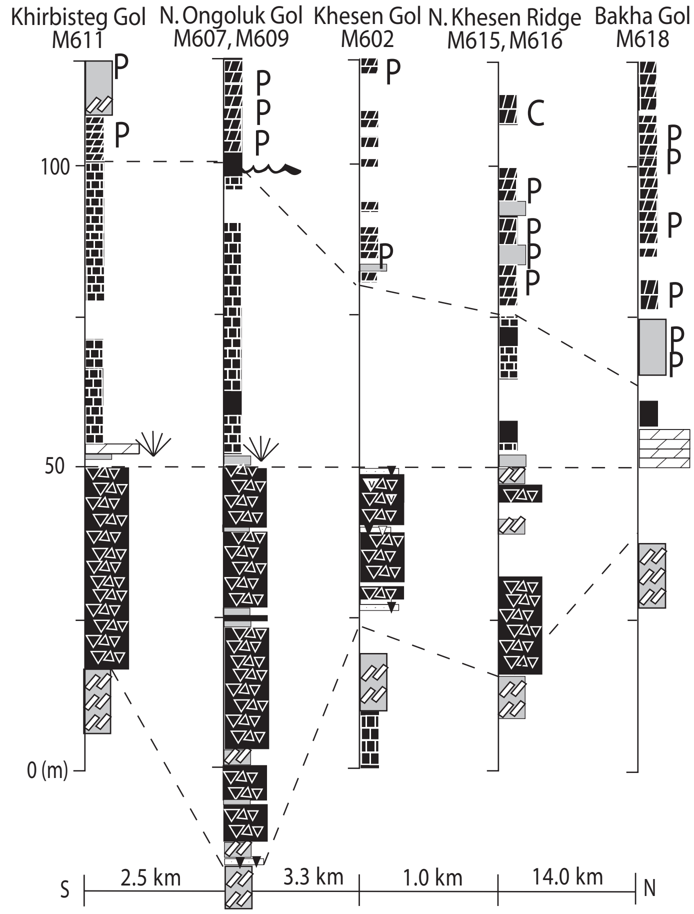

Fig. 30.5. Detailed stratigraphy of the Khesen diamictite and overlying basal Khesen Fm. on the western shores of Lake Khubsugul. Positions of measured sections are in Figure 30.2. For legend see Figures 30.3 and 30.4.

et al. 2006), and 803.4 ± 8.0 and 773.5 ± 3.6 Ma (laser evaporation zircon, Levashova *et al.* 2010). The uppermost Khesen Formation is thought to be latest Ediacaran in age by correlation with the Zabit Fm. in Siberia, which contains *Cloudina* and *Renalsis* (Kheraskova & Samygin 1992). The Khesen Fm. is overlain by the early Cambrian, *Archaeocyathid*-bearing Erkhelnur Fm. (Ilyin & Zhuraveleva 1968), providing a robust minimum age on the diamictites.

Discussion

Although the Dzabkhan platform of southern Mongolia may have been geographically separated from the Khubsugul basin, many units in the Tsagaan Oloom Fm. (Macdonald 2011) can be correlated with the Khubsugul Group. Both successions are underlain by riftogenic volcanic rocks and begin with interbedded clastic rocks and diamictites. The Maikhan Ul diamictite is an early Cryogenian glacial deposit (Brasier *et al.* 1996), and like the basal Ongoluk diamictite in the Khubsugul Group, it is commonly over 100 m thick and dominated by siltstone and coarse sand (Lindsay *et al.* 1996). The upper Ongoluk Fm. can be correlated with the Tayshir member of the Tsagaan Oloom Fm., and the carbonate-rich basal Khesen diamictite can be correlated with the Khongoryn diamictite (Macdonald *et al.* 2009). Chemostratigraphy indicates that the phosphorites on both the Khubsugul and Dzabkhan terranes were deposited in the latest Ediacaran to early Cambrian above a major Ediacaran hiatus (Shields *et al.* 2000; Macdonald *et al.* 2009).

Unconformities in the Ongoluk Fm. developed near basement highs on rift shoulders that were active at least until the onset of deposition of the Ongoluk diamictite (Osokin & Tyzhinov 1998). While the Khubsugul basin was undergoing extension a large thickness of diamictite accumulated near the present Lake Khubsugul. Evidence for a glaciogenic origin of the Ongoluk diamictite includes exotic clasts with a mixed lithology, bed-truncating lonestones, and faceted and striated clasts (Osokin & Tyzhinov 1998). The contact with the overlying light-blue allodapic dolostone is sharp, and as they appear regionally conformable, a rift–drift transition is inferred within the Ongoluk diamictite.

Although striated clasts have not been observed in the younger carbonate-rich Khesen diamictite, and exotic clasts are rare, a glacial origin of the massive deposit is inferred from the presence of bed-penetrating lonestones exposed along Khesen Gol, the geochemistry signature in associated carbonates (unpublished data) and the presence of overlying barite fans, which are present above basal Ediacaran cap dolostones in Australia (Kennedy 1996), Mauritania (Deynoux & Trompette 1976), NW Canada (Hoffman & Schrag 2002) and south China (Jiang *et al.* 2003). A basal Ediacaran age of the carbonate immediately overlying the Khesen diamictite is inferred from stratigraphic correlation with the Dzabkhan platform (Macdonald *et al.* 2009), and from the occurrence of the barite fans.

Kheraskova & Samygin (1992) rejected a glaciomarine origin of diamictites in the Zabit Formation exposed on the Siberian side of the border, arguing that these deposits represent rift-related submarine slumps and debris flows. They further suggested that the diamictites in the Zabit Fm. (and correlative Khesen Fm.) are latest Ediacaran to early Cambrian in age, citing the presence of *Cloudina* and *Renalsis* in the Zabit Fm. On the Mongolian side of the border, there is no evidence of a glacial origin for the diamictite at the base of the Khesen Fm., or the carbonate and carbonate clasts conglomerate associated with the phosphorite in the uppermost Khesen Fm., which were interpreted as olistostromes and slumps. It is possible that, like the Dzabkhan platform to the south (Macdonald *et al.* 2009), there is a major hiatus in the Ediacaran and that Kheraskova & Samygin (1992) are miscorrelating mass flows in the latest Ediacaran to early Cambrian upper Khesen Fm. with the end Cryogenian Khesen diamictite described here from the base of the Khesen Fm. Dobretsov (1985) considered the Siberian diamictites to be 'nappe thrust olistostromes' related to the Salarian orogeny, which has been stratigraphically constrained to the early Cambrian on the Dzabkhan terrane (Ruzhentsev & Burashnikov 1996). Again, it seems likely that there is a conflation between the Khesen diamictite in the lower Khesen Fm., which is interpreted here as glaciogenic, and the conglomerates interpreted as olistostromes and allodapic deposits in the upper Khesen Fm.

Sheldon (1984), Osokin & Tyzhinov (1998) and Ilyin (2004) have suggested a genetic relationship between the diamictite and phosphorite. However, Ilyin (2004) documented a disconformity at the base of the phosphorite (Fig. 30.5). Chemo- and lithostratigraphic studies in the correlative Dzabkhan platform (Macdonald *et al.* 2009; Macdonald 2011) suggest a major hiatus and flooding surface between the Khesen diamictite and the phosphorite series, casting doubt on any genetic relationship.

Further chemo- and lithostratigraphic studies are needed to better constrain the basin dynamics and depositional setting of Neoproterozoic strata in Mongolia. The palaeogeography of the peri-Siberian terranes also remains speculative. It is clear, however, that island arcs surrounded the Khubsugul terrane for much of the Neoproterozoic and early Cambrian, and thus, there is excellent potential for geochronology in the Khubsugul basin.

We thank our field assistants U. Bold, J. Otgonhuu and Eerie. We also thank A. Bayasgalan and the Mongolian University of Science and Technology for making our fieldwork possible, D. Schrag for use of the Harvard University Laboratory for Geochemical Oceanography, and G. Eischeid for help in the laboratory. We thank the National Science Foundation for funding, and P. Hoffman for inspiration and support. This represents a contribution of the IUGS- and UNESCO-funded IGCP (International Geoscience Programme) project #512.

References

Astashkin, V. A., Pegel, T. V. *et al.* 1995. *The Cambrian System of the Foldbelts of Russia and Mongolia*. International Union of Geological Sciences, London.

Badarch, G., Byamba, J. *et al.* 1998. *Geological Map of Mongolia*. Mineral Resources Authority of Mongolia, Ulaan Baator.

Badarch, G., Cunningham, W. D. & Windley, B. 2002. A new terrane subdivision for Mongolia: implications for the Phanerozoic crustal growth of Central Asia. *Journal of Asian Earth Sciences*, **21**, 87–110.

Brasier, M. D., Shields, G., Kuleshov, V. N. & Zhegallo, E. A. 1996. Integrated chemo- and biostratigraphic calibration of early animal evolution: Neoproterozoic–early Cambrian of southwest Mongolia. *Geological Magazine*, **133**, 445–485.

Buchan, C., Pfander, J. *et al.* 2002. Timing of accretion and collisional deformation in the Central Asian Orogenic Belt: implications of granite geochronology in the Bayankhongor Ophiolite Zone. *Chemical Geology*, **192**, 23–45.

Burashnikov, V. V. 1990. *Tectonics of the Urgamal Zone, Early Calidonides of Western Mongolia*. Russian Academy of Sciences, Moscow.

Buyakaite, M. I., Kuzmichev, A. B. & Sokolov, D. D. 1989. 718 Ma Rb–Sr errorchron of the Sorkhoi Group in the East Sayan. *Doklady Akademii Nauk SSSR*, **309**, 150–154.

Chumakov, N. M. 2011. Glacial deposits of Bokson Group, East Sayan Mountains, Buryatian Republic, Russian Federation. *In*: Arnaud, E., Halverson, G. P. & Shields-Zhou, G. (eds) *The Geological Record of Neoproterozoic Glaciations*. Geological Society, London, Memoirs, **36**, 285–288.

Cocks, L. & Torsvik, T. H. 2007. Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic. *Earth Science Reviews*, **82**, 29–74.

Deynoux, M. & Trompette, R. 1976. Late Precambrian mixtite: glacial and/or non-glacial? Dealing especially with the mixtite of West Africa. *American Journal of Science*, **276**, 117–125.

Dobretsov, N. L. 1985. Overthrust tectonics of the East Sayans. *Geotectonics*, **19**, 26–34.

Donov, N. A., Edemsky, H. B. & Ilyin, A. V. 1967. Cambrian phosphorites of Mongolia Popular Republic. *Sovetskaya Geologia*, **3**, 55–60.

Gladkochub, D. P., Wingate, M. T. D., Pisarevsky, S. A., Donskaya, T. V., Mazukabzov, A. M., Ponomarchuk, V. A. & Stanevich, A. M. 2006. Mafic intrusions in southwestern Siberia and implications for a Neoproterozoic connection with Laurentia. *Precambrian Research*, **147**, 260–278.

Hoffman, P. F. & Schrag, D. P. 2002. The snowball Earth hypothesis; testing the limits of global change. *Terra Nova*, **14**, 129–155.

Hou, H. F. & Boucot, A. J. 1990. *The Balkhash-Mongolia-Okhotsk Region of the Old World Realm*. Geological Society, London, Memoir, **12**, 297–303.

Ilyin, A. V. 1973. *Khubsugul Phosphorite-Bearing Basin*. Geologicheskiy Institut, Akademiya Nauk SSSR, Moscow.

Ilyin, A. V. 1990. Proterozoic supercontinent, its latest Precambrian rifting, breakup, dispersal into smaller continents, and subsidence of their margins: Evidence from Asia. *Geology*, **18**, 1231–1234.

Ilyin, A. V. 1998. Rare-earth geochemistry of 'old' phosphorites and probability of syngenetic precipitation and accumulation of phosphate. *Chemical Geology*, **144**, 243–256.

Ilyin, A. V. 2004. The Khubsugul phosphate-bearing basin: new data and concepts. *Lithology and Mineral Resources*, **39**, 454–467.

Ilyin, A. V. & Byamba, J. 1980. *Handbook for the Excursion 'Phosphorites of the Khubsugul Basin in the Mongolian Peoples's Republic'*. Geologicheskiy Institut, Akademiya Nauk SSSR, Moscow.

Ilyin, A. V. & Kiperman, Y. A. 2000. Mass accumulation of biogenic rocks at the Vendian/Cambrian boundary and carbon isotopic anomalies. *Soveremenny voprosy geologii (Modern Problems of Geology)*. Nauchnyi Mir, Moscow.

Ilyin, A. V. & Zhuraveleva, I. T. 1968. On the boundary between the Cambrian and the Precambrian at Prikhusugulie (Mongolian PR). *Doklady Akademii Nauk SSSR*, **182**, 1164–1166.

Jiang, G., Kennedy, M. J. & Christie-Blick, N. 2003. Stable isotopic evidence for methane seeps in Neoproterozoic postglacial cap carbonates. *Nature*, **426**, 822–826.

Kennedy, M. J. 1996. Stratigraphy, sedimentology, and isotope geochemistry of Australian Neoproterozoic postglacial cap dolostones: deglaciation, $\delta^{13}C$ excursions, and carbonate precipitation. *Journal of Sedimentary Research*, **66**, 1050–1064.

Kherzaskova, T. N. & Samygin, S. G. 1992. Tectonic conditions in the East Sayan Vendian–Middle Cambrian terrigenous carbonate association. *Geotectonics*, **26**, 445–458.

Kravchinsky, V. A., Konstantinov, K. M. & Cogne, J.-P. 2001. Palaeomagnetic study of Vendian and Early Cambrian of South Siberia and Central Mongolia: was the Siberian platform assembled at this time? *Precambrian Research*, **110**, 61–92.

Kuzmichev, A. 2001. Early Baikalian tectonic events in the Tuva-Mongolia Massif: arc-microcontinent collision. *Geotectonics*, **35**, 185–198.

Kuzmichev, A., Bibikova, E. V. & Zhuravlev, D. Z. 2001. Neoproterozoic (~800 Ma) orogeny in the Tuva-Mongolia Massif (Siberia): island arc-continent collision at the northeast Rodinia margin. *Precambrian Research*, **110**, 109–126.

Kuzmichev, A., Kroener, A., Hegner, E., Dunyi, L. & &Yusheng, W. 2005. The Shishkhid ophiolite, nothern Mongolia: a key to the reconstruction of a Neoproterozoic island-arc system in central Asia. *Precambrian Research*, **138**, 125–150.

Levashova, N. M., Kalugin, V. M., Gibsher, A. S., Yff, J., Ryabinin, A. B., Meert, J. & Malone, S. J. 2010. The origin of the Baydaric microcontinent, Mongolia: constraints from palaeomagnetism and geochronology. *Tectonophysics*, **485**, 306–320.

Lindsay, J. F., Brasier, M., Shields, G., Khomentovsky, V. V. & Bat-Ireedui, Y. A. 1996. Glacial facies associations in a Neoproterozoic back-arc setting, Zavkhan Basin, western Mongolia. *Geological Magazine*, **133**, 391–402.

Logatchev, N. A. 1984. The Baikal rift system. *Episodes*, **7**, 38–42.

Macdonald, F. A. 2011. The Tsagaan Oloom Formation, southwestern Mongolia. *In*: Arnaud, E., Halverson, G. P. & Shields-Zhou, G. (eds) *The Geological Record of Neoproterozoic Glaciations*. Geological Society, London, Memoirs, **36**, 331–337.

Macdonald, F. A., Jones, D. S. & Schrag, D. P. 2009. Stratigraphic and tectonic implications of a new glacial diamictite-cap carbonate couplet in southwestern Mongolia. *Geology*, **37**, 123–126.

Osokin, P. V. & Tyzhinov, A. V. 1998. Precambrian Tilloids of the Oka-Khubsugul phosphorite-bearing basin (Eastern Sayan, Northwestern Mongolia). *Lithology and Mineral Resources*, **33**, 142–154.

Pisarevsky, S. A., Komissarova, R. A. & Khramov, A. N. 2000. New palaeomagnetic result from Vendian red sediments in Cisbaikalia and the problem of the relationsip of Siberia and Laurentia in the Vendian. *Geophysics Journal International*, **140**, 598–610.

Ruzhentsev, S. V. & Burashnikov, V. V. 1996. Tectonics of the western Mongolian Salairides. *Geotectonics*, **29**, 379–394.

Sengor, A. C. & Natal'in, B. A. 1996. Palaeotectonics of Asia: fragments of synthesis. *In*: Yin, A. & Harrison, M. (eds) *The Tectonic Evolution of Asia*. Cambridge University Press, Cambridge, 486–640.

Sheldon, R. P. 1984. Ice-ring origin of the Earth's atmosphere and hydrosphere and late Proterozoic–Cambrian phosphogenesis, *Phosphorite, Geological Survey of India Special Publication*, **17**, Udaipur, Rajasthan, India.

Shields, G., Stille, P. & Brasier, M. 2000. Isotopic records across two phosphorite giant episodes compared: the Precambrian–Cambrian and the Late Cretaceous–recent. *SEPM Special Publications*, **66**, 102–115.

Windley, B. F., Alexeiev, D., Xiao, W., Kroener, A. & Badarch, G. 2007. Tectonic models for accretion of the Central Asian Orogenic Belt. *Journal of the Geological Society of London*, **164**, 31–47.

Zhao, Y., Song, B. & Zhang, S. H. 2006. The Central Mongolian microcontinent: its Yangtze affinity and tectonic implications. *In*: Jahn, B. M. & Chung, L. (eds) *Symposium on Continental Growth and Orogeny in Asia*. Taipei, Taiwan, 135–136.