ABSTRACT

The Khuvsgul Group (Khuvsgul Province, Mongolia) is a Late Neoproterozoic to Cambrian carbonate-dominated succession that includes minor glacial diamictite and one of the largest known ore-grade phosphate deposits in the world. These strata, which have experienced low-grade metamorphism, are exposed in the Khoridol-Saridag Range on the western margin of Lake Khuvsgul. Since 2017, new geologic mapping and field studies have been conducted in the Khuvsgul region. During the course of this work, it has become necessary to restructure the stratigraphic framework of the Khuvsgul Group in order to better facilitate geologic mapping, stratigraphic observations, and regional correlations. We have divided the lower Khuvsgul Group into four distinct formations spanning the Cryogenian and Ediacaran, each of which encompass strata associated with the Sturtian glaciation, Cryogenian non-glacial interlude, Marinoan glaciation, and basal Ediacaran transgression respectively. The phosphorites of the Khuvsgul Group are now included within a new distinct formation, while the overlying Cambrian carbonates and siliciclastic rocks have been further subdivided to streamline mapping and correlation efforts. The stratigraphic framework outlined below will simplify identification and differentiation of Khuvsgul Group rocks in the field and provide a foundation for the interpretation of Khuvsgul Group strata within the context of the changing climatic, tectonic, and paleoenvironmental conditions of the late Neoproterozoic and early Cambrian.

Keywords: sedimentology, phosphorite, Cryogenian, Ediacaran, Cambrian, CAOB.

INTRODUCTION

Located on the northern Tuva-Mongolia terranes (Ilyin, 1971; Kuzmichev, 2015; Bold et al., 2019), and exposed in a north-south belt along the ridgelines above the west shores of Lake Khuvsgul (Figs 1 and 2), the Khuvsgul Basin hosts the late Neoproterozoic to Cambrian Khuvsgul Group (Ilyin and Ratnikova, 1981; Macdonald and Jones, 2011). The Khuvsgul Group is a ~3 km-thick succession composed predominantly of limestone and dolomite, with minor diamictite, phosphorite, and siliciclastic rocks. Early geological investigation of the Khuvsgul Group centered around the ore-grade Khuvsgul phosphorite (Ilyin, 1973; Ilyin and Ratnikova, 1981). More recent work has focused...
on Cryogenian Snowball Earth glaciations recorded by the diamictite units (Macdonald and Jones, 2011) and the late Ediacaran to Cambrian Doushantuo-Pertatanka-type microfossil assemblage within the phosphatic strata (Anderson et al., 2017; 2019). Over the past half-century, workers have developed a variety of stratigraphic schemes for the Khuvsgul Group, with correlations to putatively equivalent units on the Siberian side of the Russian-Mongolian border (Osokin and Tyzhinov, 1998; Kuzmichev et al., 2001; Vishnevskaya and Letnikova, 2013), or the southwest margin of the Zavkhan terrane (Macdonald and Jones, 2011, Smith et al., 2016, Bold et al., 2016a,b). Stratigraphic frameworks proposed by previous workers are summarized in Fig. 3. Here we propose an updated stratigraphic framework based on new geological mapping, lithostratigraphic observations, and biostratigraphic constraints (see Figs 2, 3, 4, and 5).

Based on the regional basinal stratigraphic divisions outlined by Macdonald and Jones (2011), our new stratigraphy further divides map units on the basis of discrete lithostratigraphic trends observed throughout the Khuvsgul paleobasin. First, we propose that the Ongolog Formation, which includes diamictite and carbonate, be separated into the Ongolog Formation (glacial facies) and Bakh Formation (non-glacial facies). The Bakh Formation is further subdivided, based on basinically-consistent lithological changes, into the Khurts, Bumbulug, and Salkhitai members. Next, strata formerly incorporated into the Kheseen Formation (Macdonald and Jones, 2011) are subdivided: the newly defined Shar Formation includes a diamictite and breccia sequence, while a cap carbonate and overlying

![Fig. 1. Location and geologic context of northern Mongolia. A: Geopolitical map of northern Mongolia. B: Tectonic map of the northern Mongolian portion of the Central Asian Orogenic Belt, modified from Bold et al. (2016b, 2019) and Kuzmichev (2015). C: Generalized geologic map of the Kholidol-Saridag Range and Darkhat Valley. A detailed geologic map of the area outlined in red is shown in Fig. 2.](image-url)
Fig. 2. Geologic map of the eastern and central Khoridol-Saridag Range, Khuvsgul Aimag, Mongolia. Locations of measured stratigraphic sections are depicted with lavender lines. Only type-locality measured sections are labeled, as are river drainages or gorges ("gols") relevant to locations discussed in this work. Note that the Shar Formation and Khirvesteg Formation are depicted in this figure as a single unit, as the Khirvisteg Formation is generally too thin to be clearly discernible at the map scale presented here.
Fig. 3. Compilation of previous stratigraphic frameworks, including nomenclature, cartoon representations, and approximate thicknesses. A schematic representation of the new framework outlined in this study is shown in the column at right.
transgressive sequence form the Khirvesteg Formation. The newly-defined Kheseen Formation (spelling adapted to conform to Mongolian anglicized spelling standardization) includes the Khuvsgul phosphorite and overlying carbonate grainstones and mass-flow deposits. We then define Lower, Middle, and Upper members of the Erkhelnuur Formation based on regional lithostratigraphic trends in order to streamline mapping, field identification, and structural relationships. Finally, varied siliciclastic rocks overlying the Erkhelnuur Formation are incorporated into the Ukhaatolgoi Formation.

**METHODS**

During the course of a geological mapping campaign spanning three field seasons (summers of 2017-2019), we measured more than 8,000 m of stratigraphic section at sub-meter resolution through Khuvsgul Group exposures in the Khoridol Saridag Range and Darkhat Valley. Section locations are depicted in Fig. 2, while representative stratotype sections are plotted in Fig. 5. By combining our lithostratigraphic and facies observations (both from measured sections and from outcrop encountered during the course of geologic mapping) with structural relationships from our mapping efforts, we discretized constituent formations of the Khuvsgul Group into a stratigraphic framework that will streamline future work in the region. Formalized unit names, type section locations, thicknesses, age constraints, and correlations are summarized in Table 1.

**Stratigraphy**

**Ongolog Formation**

Composed of poorly sorted sandstone, siltstone, conglomerate, and diamicite, the Ongolog Formation is 250-650 m thick, with changes in both thickness and facies observed in north-south along-strike exposures west of Lake Khuvsgul. The Ongolog Formation is well exposed on the northern slopes of Ongolog Gorge (Fig. 2), with recessive, poorly outcropping clast-free sequences of fine to medium-grained lithic arenites giving way up-section to more resistant matrix-supported stratified diamicite, with the matrix composed of the same material that makes up the clast-free interval below. On a ridge north of Kheseen Gorge (Fig. 2), a continuous section preserves the gradual transition from clast-free siliciclastic material to massive diamicite (see sections M613 and M614 in Macdonald and Jones, 2011). At both localities, the formation culminates in massive, dark-colored, argillite matrix diamictite with clasts of carbonate, sandstone, and crystalline basement (“perforated shales” of Ilyin, 1973), depicted in in Fig. 4A.

**Bakh Formation**

Named for its type locality on a ridgeline above Bakh Gorge (EA1701 and EA1702, Fig. 5), the Bakh (бах; tr. “toad”) Formation is composed of platformal and upper slope carbonate sequences that are subdivided into three distinct members.

**Khurts Member**: Dolomite wackestone and fine-laminated grainstone of the lowermost Khurts (хурц; tr. “sharp”) Member of the Bakh Formation directly overly the Ongolog Formation, with a sharp, conformable or paraconformable contact. Although most Khurts Member exposures are heavily recrystallized, a generally shallowing-upward trend is suggested by the increase of coarse grainstone and grainflow deposits containing ooids and microbial mat rip-up clasts towards the top of the member. The Khurts Member is 20-120 m thick, and thickens to the southwest.

**Bumbulug Member**: A conformable transition to repeating shallowing-upward parasequences of limestone mudstone, marl (mixed carbonate and fine-graded siliciclastic rocks), and rhythmite (graded calcisiltite to micrite) interbeds marks the beginning of the Bumbulug (бөмбөлөг; tr. “bubbly”) Member. Vitreous black-grey ellipsoidal chert nodules from 1-3 cm are distributed throughout thicker, tawny-brown mudstone beds, giving outcrops a bubbly, almost sponge-like appearance. Thinner laminated mudstone, marl, and rhythmite are more frequent up-section, with mm- to cm-scale bedded chert interspersed throughout; the Bumbulug Member is 50-150 m thick.
Table 1. Formalization of newly defined stratigraphic units of the Khuvsgul Group

| Name                                      | Mongolian Geoscientist 26 (52) 2-15 |
|-------------------------------------------|-------------------------------------|
| **Table 1. Formalization of newly defined stratigraphic units of the Khuvsgul Group** |                                      |
| **Name**                                  | **Ongol Formation**                 |
| **Name Derivation**                       | Good, albeit incomplete, exposures in and around Ongol Gorge, Khuvsgul Aimag, Mongolia, previously used as the name for a broader formation that included the now-differentiated Ongol and Balh Formation. |
| **Category and Rank**                     | Lithostratigraphic Formation        |
| **Type Area**                             | South-facing slopes north of Khuvsgul Gorge, Khuvsgul Aimag, Mongolia |
| **Unit Type Section**                     | Composite section M613 and M604 (Macdonald and Jones, 2011, Fig. 2, this paper). South-facing slope near top of ridge/drainline north of Khuvsgul Gorge, near northeasternmost exploratory trench visible on satellite imagery. Gradational basal contact begins just west of section start (50.74B67N, 100.19523E), ends just below first exposure of alluvial deposits of unnamed stream. |
| **Unit Description**                      | Poorly sorted litharenites, silt, and gritty-lake deposits are exposed. Beige-green to purple weathering, matrix-supported, friable, tuffaceous clays or claystones (dominantly carbonates, with minor quartz and granitic clasts) ranging from pebbles to boulders. Rounded and faceted clasts (Ooskn and Typhemia, 1999) suggest a glaciogenic origin. Massive and stratified tuffaceous clays are present in varying abundance throughout the section, with rapid facies and thickness variability apparent between along-strike exposures at 500 m length scales. Uppermost strata of the Ongol Formation include massive tuff with sub-angular to blocky angular carbonate, granite, and quartz clasts supported by a dark grey argillitic matrix. |
| **Unit Reference Sections**               | 1. M605 (50.71066N, 100.17850E) and M607 (50.71060N, 100.18107E) (Macdonald and Jones, 2011), located in Ongol Gorge, and on ridge north of Ongol Gorge, respectively. |
| **Dimensions**                            | ~430m in composite type section, estimated thicknesses from ~250m in Ongol Gorge to ~650m in north. |
| **Geologic Age**                          | Earliest Cryogenian (~710Ma) to end-Sturtian (~660Ma) via correlation with globally distributed Sturtian glacial facies. |
| **Regional Correlation**                  | Møsthul-Öl沁, Zavtshah Terrane, Mongolia (Macdonald and Jones, 2011; Bold et al., 2016a) |
| **Name**                                  | **Balh Formation (Khüree, Bombolob, and Salkhit Member)** |
| **Name Derivation**                       | Type section located on ridge west of Balh Gorge, Khuvsgul Aimag, Mongolia, with best access by foot up Balh Gorge. Khats (epa; n=sharp). Member consists of dark gray, well-laminated, and immature clasts are present in the lower part of the section. |
| **Category and Rank**                     | Lithostratigraphic formation composed of 3 component members. |
| **Type Area**                             | Ridge on the westernmost rim of the upper northern drainage area of Balh Gorge, Khuvsgul Aimag, Mongolia. |
| **Unit Type Section**                     | EA1701-2 (Figures 2 and 5, this paper). Lower boundary: lowest continuous exposure of Khuts Member (50.8797N, 100.1784E) above nearly Ongol Formation outcrop. Section follows exposures along the northern and eastern edges of ridge crests. Upper boundary, contact with overlying yellow carbonate diamictite of Khuvsgul Formation (50.875802N, 100.17934E). |
| **Unit Description**                      | Khuts Member: dolomite wackestones and laminated grains, often heavily recrystallized to the point of destroying primary sedimentary textures. Generally appears to shallower upper section: ooids and microbial textures are more frequent towards top of member. |
| **Unit Reference Sections**               | 1. ~40m to EA1814 (50.85331N, 100.08885E), Arran Gorge (Figures 2 and 5, this paper), partial exposures in Khaksan and Ongol Gorges (Fig. 2, this paper). Section is conformable with the lower part of the Ongol Formation. |
| **Dimensions**                            | At the type section, the Khuts Member is at least 20m thick, the Bombolob Member is ~120m thick, and the Salkhit Member is ~175m thick. Elsewhere in the basin, the Khuts, Bombolob, and Salkhit Members have been estimated to be of maximum thickness at 120m, 150m, and 175m, respectively. |
| **Geologic Age**                          | Cryogenian non-glacial interval; ~660Ma to likely younger than ~657Ma (Rooney et al., 2020). |
| **Regional Correlation**                  | Tsuishin Fm, Zavtshah Terrane, Mongolia (Macdonald and Jones, 2011; Bold et al., 2016a) |
| **Name**                                  | **Khvsgul Formation (Khüree, Bombolob, and Salkhit Member)** |
| **Name Derivation**                       | Good exposure in outcrop on the south-facing slopes west of Khvsgul Gorge, Khuvsgul Aimag, Mongolia |
| **Category and Rank**                     | Lithostratigraphic Formation        |
| **Type Area**                             | Ridge on the westernmost rim of the upper northern drainage area of Khvsgul Gorge, Mongolia. ~300m to EA1701-2 (50.87548N, 100.17971E), Balh Gorge ridgeline (Figures 2 and 5, this paper). Lower boundary: locally conformable contact with underlying dolomite grains of Salkhit Member, Balh Formation (50.875802N, 100.1784E). Section continues through overlying outcrop exposure on northern edge of ridgeline. Upper boundary, unconformity surface at contact with Khutsan Formation (50.875516N, 100.17965E). |
| **Unit Type Section**                     | Yelow-weathering, massive matrix-supported diamictite, containing angular to sub-angular carbonate clasts in a dolomitic matrix. Often interbedded with angular dolomite breccia units, which are typically small (<1m thick) and are composed of single or multiple dolomitic breccia packages (20-40m thick). The massif is predominantly carbonate and is a subrounded to angular carbonate clasts supported by a dark grey argillitic matrix. Above the cap carbonate, a transgressive sequence of muds, siltstones, and fluvial carbonates are exposed, ranging in color from white to brown on weathered surfaces, is found at most exposures. |
| **Unit Reference Sections**               | 1. M611 (50.69284N, 100.17212E), Khvsgul Gorge, (Macdonald and Jones, 2011). 2. M607-M609 composite section (50.691538N, 100.17412E), northern Ongol Gorge. 3. ~200m to EA1814 (50.85310N, 100.06520E), Arran Gorge (Figures 2 and 5, this paper). |
| **Dimensions**                            | At the type section, the dolomite breccia units are ~15m thick, the Khutsan member is ~3m thick, and the overlying Ediacaran strata are ~20m thick. Diamictites at Arran Section 3 are ~5m thick, with a 2m-thick cap carbonate sequence and nearly 50m of overlying Ediacaran strata. Around the basin, thicknesses range from ~0.5 to ~7m for the Khvsgul diamictite, 1-3m for the Khutsan carbonate package, and 0 to 50m for the Ediacaran strata. |
| **Geologic Age**                          | Oostracite Glacial (younger than ~657Ma; Rooney et al., 2020) to early Ediacaran (younger than ~635Ma). |
| **Regional Correlation**                  | Khööbar Formation and over Ol Formation, Zavtshah Terrane, Mongolia (Macdonald and Jones, 2011; Bold et al., 2016a). |
### Table 1. Formalization of newly defined stratigraphic units of the Khuvsgul Group (continue)

| Name                     | Kheseen Formation                                                                 |
|--------------------------|-----------------------------------------------------------------------------------|
| Name Derivation          | Good exposure in and around Kheseen Gorge, Khuvsgul Aimag, Mongolia; previously used as the name for a broader formation (frequently spelled "Kheizen") containing the now-differentiated Khiurvesteg Formation and the new Kheseen Formation |
| Category and Rank        | Lithostratigraphic Formation                                                      |
| Type Area                | Ridge on the westernmost rim of the upper northern drainage area of Bath Gorge     |
| Unit Type Section        | ~345m into EA1701-2 (50.875516N, 100.179958E) Bath Gol Ridge (Figures 2 and 5, this paper). Lower Boundary: carbonates directly above unconformity surface at contact with Kheseen Formation (50.875516N, 100.179958E). Section continues along fall-line exposure directly up ridge to east. Upper Boundary: end of continuous exposure before contact with overlying Erkhermel Formation. Thin, interbedded limestone and dolomite mudstones, solid marls, and phosphatic and silicified hardgrounds form discontinuous beds frequently truncated by co-scale channelization and autochthonous debris flows. These lower Kheseen Formation strata contain abundant primary phosphate precipitates, and, in addition to hosting a DPT-type microfossil assemblage (Anderson et al., 2017, 2019), also contain stromatolitic and microbial mat textures. Thin interbeds of the lower Kheseen Formation are usually overlain by a marker bed of amorphous chert, which is subsequently overlain by allogenic carbonate grainstones bearing phosphatic and siliceous algal assemblages. While exposure at the type section locality ends within the allogenic carbonate sequence, exposures at Reference Section 1 reveal an expanded carbonate grainstone sequence in which phosphatic and silicified grainstones become sparse upsection before the occurrence of a second thick bed of amorphous chert. At Reference Section 2, the uppermost allogenic carbonates begin to exhibit a strong siliciclastic allochemical component, eventually giving way to graded lithic conglomerates and larger debris flows with up to bedder-sized clasts. Here, the contact with the overlying Erkhermel Formation is a microcrystalline disconformable exposure surface. |
| Unit Reference Sections  | 1. ~230m into EA1814 (50.855144N, 100.065212E), Arsal Gorge (Figures 2 and 5, this paper); 2. EA1905 (50.855144N, 100.184000E), Kheseen Gorge (Figures 2 and 5, this paper) |
| Dimensions              | At least 130m thick at the type locality, at least 50m thick at Reference Section 1, and between 120 and 400m at other exposures around the basin |
| Geologic Age             | Latest Ediacaran to earliest Cambrian via correlation with Zavkhan equivalents (Macdonald et al., 2009; Macdonald and Jones, 2011) |
| Regional Correlations    | Zutan Arts Formation, Zavkhan Terrane, Mongolia (Macdonald and Jones, 2011; Smith et al., 2016) |
| Name                     | Lower, Middle and Upper Members of the Erkhermel Formation                          |
| Name Derivation          | Relative stratigraphic heights of differentiable units of the Erkhermel Formation   |
| Category and Rank        | 3 constituent Members of a Lithostratigraphic Formation                            |
| Type Area                | Lower Member: ridges west of Khuvsgul Gorge; Middle Member: ridges west of Khuvsgul and Ongolog Gorges. Upper Member: ridges west of Ongolog and Kheseen Gorges, as well as in several locations in the upper Arsal Gorge drainage |
| Unit Type Section        | Lower Member: EA1901-2 (50.706571N, 100.12742E), ridge west of Khuvsgul Gorge (Figures 2 and 5, this paper). Lower Boundary: base of EA1801-2, located ~20m above contact with Kheseen Formation, which is covered by vegetation. Section follows ridgecrest to North. Upper Boundary: ~580m into EA1801-2 |
| Unit Reference Sections  | Middle Member: begins at upper boundary of Lower Member. Section continues north, following ridge crest, before turning east at (50.723044N, 100.136873E) and continuing along the ridgeline to the east, into EA1825, which follows the same ridge. Upper Boundary: ~660m into EA1825 (50.724445N, 100.1366252E), ridge west of Ongolog and Kheseen Gorges (Figures 2 and 5, this paper). |
| Dimensions              | Upper Member: begins at upper boundary of Middle Member. Exposure continues until EA1825 ends at core of syncline. Uppermost Upper Member is exposed in EA1920 (50.766544N, 100.03005E), Upper Arsal Gorge drainage (Figures 2 and 5, this paper). Section continues up gully until conformable contact with overlying Udhalotrol Formation |
| Geologic Age             | Lower Member: bounded below by a disconformable exposure surface at the top of the Kheseen Formation, the Lower Member of the Erkhermel Formation is composed of dolomite and dolomitic limestone shallow-water parasequences (typically laminated mudstones and grainstones, coarser grainstones with infrequent stromatolitic horizons, and allogenic packstones and coarse grainstones containing ooids and oncoids. Occasional silicified surfaces) |
| Regional Correlations    | Middle Member: abrupt transition to parasequences dominated by dark-grey weathering limestone grainstone beds; this gray band is easy to identify on satellite or aerial imagery. Idiomorphic fossils begin to appear, with abundant bioturbation increasing up section, eventually obliterating all primary sedimentary structures and bedding features. Archelonoidid reefs and sharks appear ~500m above the base of the Middle Member |
| Name                     | Upper Member: base is demarcated by an abrupt transition to white-cream dolomitic grainstone beds. Heavy recrystallization throughout, with occasionally discernible laminated grainstones and rhytmites. White dolomites are also visible in satellite and aerial imagery, and serve as a valuable market bed. The uppersmost portion of the Upper Member begins to incorporate lithic grains and fragments in grainstone beds, with the frequency of lithics increasing upsection until carbonate deposition is overwhelmed at the conformable contact with the overlying Udhalotrol Formation |
| Name Derivation          | ~300m into EA1005 (50.741915N, 100.183101E), Kheseen Gol (Figures 2 and 5, this paper), which includes the disconformable contact at the base of the Lower Member of the Erkhermel Formation |
| Category and Rank        | Lower Member: ~300m thick; Middle Member: ~600-800m thick; Upper Member: ~500-600m thick |
| Type Area                | Moscovian and Tatarian Stages (~525-515Ma) |
| Unit Reference Sections  | Archelonoidid appearances continue the Middle Member to within the Moscovian and Tatarian Stages (~525-515Ma) |
| Dimensions              | Moscovian and Tatarian Stages (~525-515Ma) |
| Geologic Age             | Putative correlation with Bayangol Formation, Zavkhan Terrane, Mongolia (Smith et al., 2016) |
Salkhitai Member: The uppermost portion of the Bakh Formation, the Salkhitai (салхитай; tr. “windy”) Member, conformably overlies the Bumbulug Member and contains coarse limestone grainstone-dominated parasequences that transition into a coarsening-upward stack of dolomitized grainstone, grainflow deposits, and intraclast breccia with a minor siliciclastic granular component. The top of the Salkhitai Member is marked by a coarse, carbonate-cemented sandstone with carbonate granules that is overlain by a massive unit of dolomite grainstone. The Salkhitai Member ranges between 100 m and 150 m in thickness.

Shar Formation
The Shar (шар; tr. “yellow”) Formation is composed of a massive matrix-supported...
diamictite with a distinctive yellow-ochre dolomite matrix (Fig. 4B), often closely associated with coarse, gray-weathering angular dolomite breccia. Around the basin, thickness of diamictite-breccia packages ranges from 0.5-70 m. The base of the member is defined as the transition from dolomite grainstone of the uppermost Bakh Formation to diamictite or dolomite breccia. At the stratotype locality above Bakh Gorge, the Shar Formation is approximately 20 m thick, with nearly ten meters of angular dolomite breccia overlain by the eponymous yellow diamictite (EA1701-2, Fig. 5).

Khirvesteg Formation
Conformably above the diamictite and breccia, the base of the Khirvesteg Formation is defined by a 1-3 m thick dolomite grainstone containing barite fans and sheetcrack cements (Hoffman et al., 2011). The cap carbonate is overlain by thin dolomitic marl, mudstone, and carbonaceous shale. Although exposures to the south are locally only 2-3 m thick, 25 m of marl, shale, and dolomite mudstone are found in the stratotype section on the ridge above Bakh Gorge (EA1701-2, Fig. 5). Note that in Fig. 2, the Shar and Khirvesteg Formations are shown as a single map unit for visual clarity at the presented map scale.

Kheseen Formation
Ranging from 160-500 m in thickness, the Kheseen Formation is separated from the Khirvesteg Formation by a prominent erosional unconformity. Above this surface, the basal Kheseen Formation is composed of interbedded black micritic limestone and dolomite mudstone, foetid marl and shale, and phosphatic and silicified hardgrounds (Fig. 4C). Bedding is largely discontinuous along strike, and is often truncated by channelization or autoclastic debris flows, while thicker carbonate beds contain stromatolitic and thrombolitic textures. Phosphatic hardgrounds and phosphatic grainflows in these strata contain a Doushantuo-Pertatanka-Type microfossil assemblage, described by Anderson et al. (2017; 2019). This sequence, referred to in previous works as the lower phosphate unit (Ilyin and Ratnikova, 1981; Ilyin, 1998), is 10-60 m thick, and contains the most concentrated phosphate ore (average of 22% and up to 34% $P_2O_5$; Dorjnamjaa and Altanshagai, 2015) in the region. This phosphatic unit is capped by 1-5 m of massive amorphous black chert. Above this, granular phosphorite is present in graded allogapic limestone and dolomite grainstone (Fig. 4D). This facies forms the majority of phosphorite exposure in the Khuvsgul Basin. In the Western Khoridol Saridag Range (KSR), the Kheseen Formation is capped by a second chert bed, whereas in the easternmost KSR it is composed of grainstone and coarse conglomerate with a large siliciclastic component not observed elsewhere in the basin. The stratotype section for the Upper Kheseen Formation is on the ridge above Bakh Gorge (EA1701-2) with reference sections in Arsai Gorge (EA1814), which includes an expanded upper phosphorite sequence, and in Ongolog Gorge (EA1905), which contains conglomerate with abundant lithic clasts at the top of the formation. All sections are depicted in Fig 5.

Erkhelnuur Formation
The Erkhelnuur Formation (Zhegallo, 2000) is a 2 km thick carbonate sequence separated from the Kheseen Formation by a hiatal surface, observed in the Eastern KSR (EA1905) as a disconformable exposure surface, with the base of the Erkhelnuur Formation defined as the carbonate grainstones overlying this surface. In order to simplify structural interpretation and lithological differentiation of Erkhelnuur Formation carbonates in the field, we propose the subdivision of the formation into Lower, Middle, and Upper Members, which are summarized below.

Lower Member: The Lower Member includes repetitive dolomite and dolomitized limestone parasequences, composed of laminated mudstone and grainstone interbeds, dolomitized grainstone beds containing domal stromatolites, and allogapic packstone and coarse grainstone containing ooids and oncoids. Parasequences are commonly capped by horizons of lenticular grey-black chert. The Lower Member is 250-300 m
Fig. 5. Measured stratigraphic sections from Khuvsgul Group type-localities. All section locations are depicted in Fig. 2, while coordinate locations shown above are from the stratigraphic base of each section.
thick, with a stratotype exposure on a ridge above Khirvesteg Gorge (EA1801-2, Fig. 5).

**Middle Member:** The base of the Middle Member of the Erkhelnuur Formation is defined by an abrupt transition to parasequences dominated by dark grey limestone grainstone beds. While the parasequences include stromatolitic mudstone and dolomicrosparite, this transition is visible both in the field and on satellite imagery, where limestone-dominated parasequences appear as a dark blue-gray band. In most sections, bed-penetrating ichnofossils appear 20-50 m above the base of the Middle Member, consisting of irregular 1-2 cm diameter tubes. The density of bioturbation increases up-section to the point of obfuscating primary bedding features (Fig. 4E). Approximately 300 m above the base of the Middle Member, archaeocyathid reefs and hash can be observed in bioturbation-free zones (Fig. 4F), constraining the strata to a window of the early Cambrian between the Tommotian and Toyonian Stages (~525-511 Ma, or mid-Terreneuvian Age 2 and Cambrian Series 2, Age 4; Peng et al., 2020). The Middle Member of the Erkhelnuur Formation ranges from 600-800 m thick, and is best exposed in sections EA1801-1802 (see Fig. 5) on the ridges above Khirvesteg Gorge.

**Upper Member:** The base of the Upper Member of the Erkhelnuur Formation is demarcated by a sequence of >50 m thick white- to cream-colored dolomite grainstone beds. Although the white beds locally preserve laminated grainstone and rhythmite, in most exposures, primary bedding features are obliterated by recrystallization. Like the dark beds at the base of the Middle Member, the white dolomite forms a reliable marker bed that is easily visible in the field and satellite imagery. Above the white dolomite, grey dolomite and limestone laminites-grainstone-grainflow parasequences continue, with ichnofossils present in fine grainstone beds. Up-section, coarser-grained grainstone and grainflows incorporate terrigenous lithic fragments, which increase in frequency and size toward the uppermost grainflows are prominently exposed in section EA1820 (Fig. 5).

**Ukhaatolgoi Formation**

The >350 m thick Ukhaatolgoi Formation conformably overlies the Erkhelnuur Formation and is composed of siliciclastic rocks dominated by greywacke with minor siltstone, sandstone, and conglomerate. Carbonate parasequences of the uppermost Erkhelnuur Formation contain allochems that are gradationally succeeded by greywacke of the basal Ukhaatolgoi Formation. Previoulsy referred to as the Ukhtutologoy Formation (Zhegallo et al., 2000; Demidenko et al., 2003) and excluded from the Khuvsgul Group, the Ukhaatolgoi Formation is dominated by green greywacke, with rare granule to pebble lithic clasts, angular quartz and plagioclase grains, and carbonate fragments in a green siltstone matrix. The base of the formation is best documented in section EA1820, and the formation is best exposed at the cores of synclines in upper Arsai Gorge. Note that we do not include the formalization of this Formation in Table 1, as this nomenclature has been applied to these rocks by previous workers (Dorjnamjaa et al., 2015).

**DISCUSSION**

While the stratigraphic divisions outlined above are largely based on lithological characteristics that can be easily differentiated in the field by future workers, our stratigraphic framework is also reflective of significant changes in paleoenvironment and paleoclimate that occurred during the deposition of the Khuvsgul Group. For example, the Ongolog, Bakh, Shar, and Khirvesteg formations can be correlated with the Sturtian glaciation, Cryogenian nonglacial interlude, Marinoan Glaciation, and basal Ediacaran transgression respectively, with diamictites associated with both glaciations separated by a platformal carbonate sequence (Macdonald and Jones, 2011). A glaciogenic origin for the Ongolog Formation is established via the observation of exotic clasts in matrix-supported diamictite, as well as striated and faceted clasts (Osokin and Tyzhinov, 1998).
Typically exhibiting sheetcrack cements and crystal fans, the basal carbonate of the Khirvesteg Formation is interpreted as a cap carbonate sequence (Hoffman et al., 2011), coupled with the underlying diamictite of the Shar Formation. Additionally, these units can be correlated with Cryogenian and Ediacaran successions on the Zavkhan Terrane in southwest Mongolia (Macdonald and Jones, 2011; Bold et al., 2016b). Bound above and below by unconformities, the newly-defined Kheseen Formation records a depositional environment that resulted in the precipitation and eventual reworking of the Kheseen phosphorites, which may be condensed equivalents of the phosphatic shales of the Zuun Arts Formation on the Zavkhan Terrane (Macdonald and Jones, 2011). The lower units of the Kheseen Formation record precipitation of primary phosphatic material in a very shallow, energetic depozone, whereas phosphatic material in the upper parts of the formation has been redeposited in carbonate grainstones (Fig. 5). Importantly, the newly defined lower bound of the Kheseen Formation isolates the phosphatic strata from the underlying Khirvesteg and Shar formations, highlighting the lack of a previously-postulated genetic relationship between the Marinoan glaciation and phosphogenesis (Osokin and Tyzhinov, 1998). Furthermore, the disconformable exposure surface at the top of the formation separates the Kheseen Formation in time from the nearly 2 km of overlying Erkhelnuur Formation carbonates, introducing the possibility that the Kheseen and Erkhelnuur formations were accommodated by distinct basin-forming events. Additional petrographic, geochronological and chemostratigraphic data are necessary to better constrain the ages and depositional environments of the Kheseen phosphorites and Khuvsgul Group strata as a whole. The stratigraphic framework presented here provides a necessary foundation for future work in the Khuvsgul region.

**CONCLUSIONS**

A new stratigraphic framework for the Khuvsgul Group divides strata spanning nearly 200 My of Earth history into seven formations.

Cryogenian strata are divided into the Ongolog, Bakh, Shar, and Khirvesteg formations, discretizing units associated with the Sturtian glaciation, Cryogenian non-glacial interlude, Marinoan Glaciation, and basal Ediacaran transgression respectively. Phosphatic strata, bounded above and below by depositional hiatuses, are included in the newly defined Kheseen Formation. In order to streamline mapping and correlation, the Erkhelnuur Formation is divided into Lower, Middle, and Upper Members, while the overlying siliciclastic sequences are discretized as the Ukhaatolgoi Formation.

**ACKNOWLEDGEMENTS**

Thanks to Erdene Bayarsaikhan, Ekv Erdene, Sam Lobianco, Peter Otness, and Judy Pu for assistance, companionship, and camaraderie in the field, to M. Munkhbaatar, Batsukh Erdene, and Set for transportation and friendship, to Ariunsanaa Dorj and the Earth Science Center of Mongolia for logistic help, and to the Ministry of Environment of Mongolia and the rangers and staff of the Khuvsgul Nuur National Park and Khoridol Saridag Protected Zone for access. This work was funded by grant funds from Nasa Astrobiology: Exobiology and Evolutionary Biology, NNH10ZDA001N-EXO and the NSF-GRFP.

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