The crustal assembly of southern Mongolia: New structural, lithological and geochronological data from the Nemegt and Altan ranges

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ABSTRACT

The Gobi Altai region is an ideal setting for studying processes of continental growth and subsequent intracontinental and intraplate deformation, including terrane accretion and dispersal, ophiolite obduction, crustal reactivation and intraplate mountain building. To assess the diverse tectonic evolutionary models of the Gobi Altai and the wider region, more field data and geochronological data are required to constrain the tectonic evolution of individual terranes, and the relationship of adjacent crustal domains to each other throughout time. In this paper, we present new lithological, structural and 40Ar/39Ar age data, which constrain the crustal evolution across a previously unreported late Paleozoic terrane boundary in the Gobi-Altai. Nemegt and Altan Nuruu are topographically linked mountain ranges that were formed by Miocene-recent uplift at a right-stepping restraining bend along the left-lateral Gobi–Tien Shan Fault System in southern Mongolia. Ordovician–Carboniferous arc rocks and an ophiolite are exposed in the mountain ranges and form a small part of the east–west arcuate Trans-Altai Zone. Field observations of rock types and structures, combined with petrographic data are used to distinguish metamorphosed volcano-sedimentary arc rocks in Altan Nuruu and western Nemegt Nuruu from arc rocks in central and eastern Nemegt Nuruu. These distinct sequences are correlated with the Dzolen and Edrengin terranes in the Trans-Altai Zone along strike to the west. Integration of field data, 40Ar/39Ar age data and published studies are used to describe a polyphase deformation history that includes late Carboniferous ophiolite obduction, mid-Permain to late Triassic shortening and lateral terrane redistribution, Cretaceous rifting and late Cenozoic intraplate mountain building.

1. Introduction

The Central Asian Orogenic Belt (CAOB) is the location of the most extensive Phanerozoic continental growth on Earth and consists of a complex collage of Neoproterozoic to Paleozoic terranes covering an area greater than 4.5 million km² (Xiao et al., 2009a; Rojas-Agramonte et al., 2011). The Gobi Altai Mountains, in southern Mongolia, occupy a core position within the CAOB, sandwiched between the Precambrian blocks underlying the Hangay Dome to the north, and the Composite Tarim–North China craton to the south (Fig. 1, inset). The Gobi Altai region is an intracontinental and intraplate orogen that formed in the Late Miocene–Recent as a distant response to the Indo-Eurasia collision 2500 km to the south (Tapponnier and Molnar, 1979). Geologically youth, long and narrow mountain ranges expose older basement rocks, which record a polydeformational history starting with Paleozoic terrane accretion and culminating in modern mountain building. The mountains are separated by broad basins, giving the region a basin and range physiography. The arid conditions and sparse vegetation mean that there is excellent rock exposure. This makes the Gobi Altai region an ideal setting for studying rocks and geological structures formed by processes of continental growth and subsequent intracontinental deformation, including terrane accretion and dispersal, ophiolite obduction, crustal reactivation and intraplate mountain building (Lamb and Badarch, 2001; Badarch et al., 2002; Windley et al., 2007; Cunningham, 2010; Glorie et al., 2011).

In order to document the complicated spatial and temporal evolution of the CAOB, it is important to determine the lithotectonic evolution of all its major terranes, the structural nature of terrane boundaries, and timing of major accretion and amalgamation events. However, in large parts of the CAOB, compared to, for example, the North American terrane collage (e.g. Coney, 1989), there are few studies of the terrane amalgamation history, and large regions are frontier areas that remain virtually unstudied. In this study, we present new lithological, structural and 40Ar/39Ar data for Nemegt and Altan Nuruu, a pair of topographically linked late Cenozoic uplifted mountain ranges in the southern Gobi Altai (Figs. 1, 2). Nemegt and Altan Nuruu represent a structural and metamorphic culmination in the southern Gobi Altai region and contain an important mid-late...
Paleozoic arc–arc terrane boundary and ophiolitic suture. Late Cenozoic mountain building in Nemegt and Altan Nuruu is only the latest event in a polyphase history that includes Silurian–Devonian arc volcanism, late Carboniferous arc accretion and ophiolite obduction, Permian to Triassic shortening and oroclinal bending, and mid-Cretaceous rifting (Cunningham et al., 1996; Owen et al., 1999; Rippington, 2008;...
Rippington et al., 2008; Cunningham, 2009, 2010). The data presented here lead to a new interpretation of the crustal growth of the southern Gobi Altai region with implications for the tectonic processes that led to terrane assembly and crustal consolidation. It also provides insights into the crustal conditions that existed prior to Mesozoic and late Cenozoic regional crustal reactivation.

2. Regional tectonic setting and previous work

2.1. Amalgamation of the Central Asian Orogenic Belt

The origin of the CAOB can be traced back to the breakup of the Rodinia supercontinent and subsequent closure of various seaways between older Precambrian cratonic blocks (Cocks and Torsvik, 2007, 2005; Windley et al., 2007; Rojas-Agramonte et al., 2011). Paleomagnetic reconstructions (Pisarevsky et al., 2003) and rift-related dyke swarms with isotopic ages of 974–900 Ma (Dobretsev et al., 2003) indicate that Rodinia began to break up in the Neoproterozoic. Rift-separation of Baltica, the Angaran craton (Siberia) and the North China craton led to the creation of several small gneissic micro-continents situated adjacent to the Angaran craton (Kravchinsky et al., 2001). A belt of Neoproterozoic ophiolites obducted around the Angaran craton indicates that a series of island arc terranes, seamounts and oceanic crust, that formed between and around these micro-continents, were reattached by subduction-accretion between 500 and 544 Ma (Khain et al., 2003; Windley et al., 2007). Subsequently, throughout most of the Paleozoic, the Palaeasian Ocean, which separated the older cratons and accreted Neoproterozoic terranes, was episodically closed through successive collision events. However, models differ on the palaeogeographical context and processes involved during ocean closure.

Sengör et al. (1993) postulated the formation, successive bending and strike-slip duplication of a single large magmatic arc system, the Kipchak arc, which was situated between Baltica and the Angaran craton, and adjacent to the pre-Uralide and Baikalie orogens. A three-arc modification and extension of this model into the Mongolian part of the CAOB was proposed by Yakubchuk et al. (2001). The most important initial constraint on the Kipchak arc models is that Baltica and the Angaran craton were attached in Neoproterozoic to Cambrian time, allowing the Kipchak arc to form along their unified margins in the early Cambrian (Sengör and Natal'in, 1996). However, early Cambrian fossils found in strata deposited around Baltica and the Angaran craton (McKerrow et al., 1992), and paleomagnetic data (Hartz and Torsvik, 2002; Meert and Lieberman, 2004; Murphy et al., 2004, Cocks and Torsvik, 2005; Popov et al., 2005) indicate that the cratons were separated by a wide ocean in the early Cambrian. Therefore, the Kipchak arc could not have existed along a continuous continental margin in the earliest Cambrian (Windley et al., 2007).

Zonenshain et al. (1990) suggested an alternative model which draws comparison between the amalgamation of the CAOB and the tectonic evolution of the modern southwestern Pacific (e.g. Hall, 2009); a theme which has been developed in a number of subsequent studies (Ruzhentsov and Pospelov, 1992; Dorjnamjaa et al., 1993; Buslov et al., 2001; Badarch et al., 2002; Laurent-Charvet et al., 2002; Xiao et al., 2003, 2012; Windley et al., 2007; Wilhelm et al., 2012). These models all propose that rift-separation of the Angaran and North China cratons was succeeded by the development of the Palaeo-Asian Ocean, which contained micro-continental fragments and several intra-oceanic subduction zones with juvenile arcs systems. Accretion of these arc elements began in the north of the CAOB in the early Paleozoic, and progressed southwards over dominantly north-dipping subduction zones to produce progressively younger arc rocks and ophiolite belts in southern Mongolia and bordering regions of China (Badarch et al., 2002). However, paleomagnetic reconstructions indicate that the Tuva-Mongol and Dzabkar-Baydrag microcontinents, which have an approximately northwest–southeast orientation today, were oriented north–south in the Permian (Fig. 3; Zorin et al., 1993; Xiao et al., 2009b; Lehmann et al., 2010). This assumption requires that Paleozoic terrane accretion occurred from west to east, above a westward-dipping subduction zone. The entire terrane collage must have been subsequently rotated and redistributed to form their present day east–west arcuate trend. On the basis of detailed structural observations in southwest Mongolia, Lehmann et al. (2010) postulated that this redistribution of terranes occurred by shortening, oroclinal bending, anti-clockwise rotation and lateral displacement of terranes along paleo-transform faults, caused by north–south convergence in response to the northward movement of the North China craton in the Permo-Triassic.

The existence of diverse tectonic models for the amalgamation of the CAOB highlights the large degree of interpretive freedom afforded by a paucity of structural and geochronological data from southern Mongolia. In order to document the spatial and temporal evolution of this complex terrane mosaic, it is essential to understand the tectonic evolution and relationship between adjacent terranes. This requires more detailed field data, backed up by geochronological data, to constrain the timing of terrane accretion and deformation.

2.2. The Trans-Altai Zone, southern Mongolia

Nemegt and Altan Nuruu are situated in the east–west trending Trans-Altai Zone, which constitutes the region south of the Trans-Altai Fault and north of the Gobi–Tien Shan Fault Zone (Fig. 3). The Trans-Altai Zone has been divided into three subzones, or terranes, on the basis of lithological and structural descriptions of an area 100–300 km west of Nemegt and Altan Nuruu (Ruzhentsev et al., 1985; Kröner et al., 2010; Lehmann et al., 2010). From north to south, these are the Khuvinkharin terrane, the Edrengin terrane and the Dzolen terrane (Fig. 3).

The Khuvinkharin terrane consists of a sequence of Devonian conglomerates, which contain boulders of granite, quartz-porphory, micaceous quartzite, gritstone and marble which pass upwards into intercalated clay-rich siliceous shales, serpentine, jasper and basalt lavas. The sequence culminates in a 2000 m thick shale succession of middle to late Devonian age and mafic–volcanic rocks of intermediate composition, interpreted to have formed in a rift-setting (Ruzhentsov and Pospelov, 1992; Lehmann et al., 2010).

The Edrengin terrane is dominated by a volcano-sedimentary sequence, consisting of tuff and volcaniclastic sandstone. Lower Devonian brachiopods occur in lenses of limestone in the lower part of the sequence (Ruzhentsov and Pospelov, 1992). The upper part of the sequence consists of massive dacite, andesite and basaltic pillow lava, sometimes with tuff, interpreted as the products of island-arc volcanism (Ruzhentsov and Pospelov, 1992; Lamb and Badarch, 2001; Lehmann et al., 2010).

The Dzolen terrane (equivalent to the Zoolen terrane of Badarch et al., 2002) contains numerous strongly serpentinitized peridotite fragments, accompanied by gabbro, pillow lava and basaltic tuff. The terrane also contains Silurian–Devonian radiolarian jaspilite and quartz–hematite rocks (Zonenshain et al., 1975; Ruzhentsev et al., 1985; Lehmann et al., 2010). The Devonian sequence was originally interpreted as fragments of oceanic crust, but the volcanic rocks from the Dzolen range are of intermediate, calc-alkaline composition, consistent with formation in a juvenile intra-oceanic arc setting (Helo et al., 2006; Lehmann et al., 2010). The Devonian sequence is unconformably overlain by early Carboniferous basalt, andesitic basalt and andesite, and associated tuff, volcaniclastic sandstone, siltstone and conglomerate.

Deformation in the Trans-Altai Zone is characterised by tectonic imbrication of Devonian and Carboniferous rocks. Northwest to southeast and west–northwest to east–southeast cleavage orientations, folds and thrust faults dominate (Lehmann et al., 2010). Strain is most intense along the boundaries of the Khuvinkharin, Edrengin...
and Dzolen terranes, which have been interpreted as Permo-Triassic sinistral shear zones. Late Triassic sinistral shear zones are also interpreted to the east of Nemegt Nuruu, where the age of deformation is constrained by 40Ar/39Ar white mica ages (Webb et al., 2010). Permian to late Triassic and Jurassic 40Ar/39Ar ages are interpreted to constrain cooling following contractional deformation in the Gobi-Altai Zone to the north and west of Nemegt Nuruu (Lamb et al., 2008; Lehmann et al., 2010).

Following terrane amalgamation in southern Mongolia, the region underwent Jurassic–Cretaceous extension (Meng 2003). In the late Cenozoic, the Gobi Altai became part of an east–west trending corridor of left-lateral transpressional deformation, extending from the Chinese Tien Shan in the west to the Gurvan Sayhan ranges in the southeastern Gobi Altai (Fig. 1), in response to the ongoing India–Eurasia collision 2500 km to the south (Tapponnier and Molnar, 1979). Late Cenozoic deformation, uplift and exhumation is localised at transpressional uplifts, thrust ridges, and restraining bends and stepovers forming a topographically discontinuous belt of intraplate mountain ranges (Cunningham, 2010).

2.3. Nemegt and Altan Nuruu

Nemegt and Altan Nuruu are characterised by dominantly Ordovician to Carboniferous greenschist facies meta-volcanic rocks, and unmetamorphosed to epidote–amphibolite facies meta-sedimentary and volcaniclastic rocks (Mongolian National Atlas, 1990). In Altan Nuruu and westernmost Nemegt Nuruu, an east–west oriented belt of ophiolitic rocks, consisting of peridotite, serpentinite, cumulate gabbros, a sheeted dyke complex, pillow basalts and jasperoids, is sandwiched between unmetamorphosed to greenschist facies volcanic-sedimentary rocks and greenschist to epidote–amphibolite facies meta-sedimentary rocks (Rippington et al., 2008). Central and eastern Nemegt Nuruu consist of unmetamorphosed to greenschist facies meta-volcanic and meta-sedimentary rocks. In northeastern Nemegt Nuruu, biotite schists lie with angular unconformity on discontinuously exposed quartzo-feldspathic orthogneiss.

Several granite intrusions are exposed in western, central and eastern parts of Nemegt Nuruu (Fig. 2). There are no published radiometric ages for the granites, but rare earth element signatures from plagiogranites in Nemegt and Altan Nuruu are enriched in Ba, U and Pb and have elevated Th/Nb ratios, suggesting the involvement of slab-derived components (Helo et al., 2006). Consequently, the granites in Nemegt Nuruu are assumed to be contemporaneous with volcanic arc activity, subduction and accretionary processes.

The ages of the rocks in Nemegt and Altan Nuruu are poorly constrained. Russian–Mongolian maps assign the meta-volcanic and meta-sedimentary rocks in the mountain ranges Ordovician to Carboniferous ages, but there is no indication of how the ages were obtained (Mongolian National Atlas, 1990). Two detrital 238U/206Pb SHRIMP ages of 421 ± 3.0 Ma and 417 ± 2.2 Ma from volcaniclastic rocks in Nemegt Nuruu, and geochemical data from meta-basalts and meta-plagiogranites in the volcanic-sedimentary sequences of Nemegt and Altan Nuruu, have been interpreted to indicate the presence of an intra-oceanic arc in the Silurian (Helo et al., 2006). This is in general agreement with palaeontological evidence for Silurian to Carboniferous volcaniclastic and shallow-marine argillaceous sediments from the surrounding region (Eenzhin, 1983; Ruzhentsev et al., 1985; Badarch et al., 2002). Sandstone petrographic data from the region indicates a transition from marine sedimentation in the early Carboniferous to terrestrial sedimentation in the Permian (Lamb and Badarch, 2001). Rippington Fig. 3. Simplified terrane map of Mongolia (modified from Badarch et al., 2002; Lehmann et al., 2010). Nemegt and Altan Nuruu are located in the Silurian–Devonian Oceanic domain in the Trans-Altai Zone.
et al. (2008) suggest that the onset of terrestrial sedimentation in the region could be evidence of a regional collisional event, coinciding with obduction of the Altan Uul ophiolite in the late Carboniferous.

Nemegt and Altan Nuruu are surrounded by extensive Jurassic–Cretaceous basins and alluvial fan conglomerates which have been assigned Cretaceous ages, based on abundant dinosaur fossils and palynomorphs (Jerzykiewicz & Russell, 1991; Owen et al., 1997; Benton et al., 2000; Johnson et al., 2001). A major northwest dipping detachment fault downthrows Cretaceous sediments against jasperoids and phyllitic metasediments along the northern front of Altan Uul (AKDF in Fig. 2; Cunningham et al., 2009). The modern mountain ranges are the expression of late Cenozoic left-lateral transpression at the right-stepping Nemegt restraining bend along the Gobi–Tien Shan Fault System (Fig. 1; Cunningham et al., 1996; Owen et al., 1999).

3. Methodology

We chose to investigate Nemegt and Altan Nuruu because the meta-volcanic and meta-sedimentary rocks within the mountain ranges are well exposed, and preserve complex tectonic fabrics and structures related to the polyphase history of tennare amalgamation, ophiolite obduction, rifing and intraplate transpressional mountain building. Consequently, the rocks within Nemegt and Altan Nuruu can help us to refine tectonic models for the evolution of the CAOB, and offer insights into the processes that consolidate and deform continental crust at different stages in its evolution. In this paper, we present new field observations on the lithology and structure of Nemegt and Altan Nuruu, and new 40Ar/39Ar data which help to constrain the mechanism and timing of tennare amalgamation and deformation. Lithological observations and structural data were collected along four transects through Nemegt and Altan Nuruu (Figs. 2, 4–6). The westernmost of these transects was summarised in Rippington et al. (2008) and is not reproduced here. Along each transect, continuous outcrop exposures were examined on foot. Structural and lithological observations were compiled on detailed panoramic sketches and on basemaps, including indications of metamorphic grade and all structural measurements. Some major structures, such as the Trans-Nemegt Fault Zone (Fig. 2) were traced between transects to determine along-strike continuity and/or variability. This aided the construction of a 3D interpretation of Nemegt and Altan Nuruu (Fig. 7). Representative samples of key rock types were taken for petrographic analysis. Visual estimation of the modal abundances of key minerals was used to determine more detailed lithological classifications after fieldwork. Outcrop and thin-section analysis of fault rocks and shear zone tectonites was carried out to determine the kinematics of deformation. Relative and absolute ages for the structures documented in Nemegt and Altan Nuruu were derived from cross-cutting relationships between structures and lithologies of known age.

In this study, the transect data are summarised for the sake of brevity. However, description of the lithological, metamorphic and structural variations across all four transects through Nemegt and Altan Nuruu can be found in Rippington (2008). Detailed descriptions of the Altan Uul Ophiolite can be found in Rippington et al. (2008). Field photographs of key features are shown in Figs. 8 and 9.

4. General structure of Nemegt and Altan Nuruu

Nemegt and Altan Nuruu have a positive flower structure in cross-section (Fig. 7). Meta-basalts and meta-andesites structurally overlie Cretaceous and late Cenozoic sedimentary strata along a long linear north-dipping thrust fault along the southern front of Altan Nuruu (Figs. 2, 7). Along the southern front of Nemegt Nuruu, the continuation of this thrust displaces hanging wall meta-andesitic breccias, volcaniclastic meta-psammites, slates and chlorite schists to the south, locally overturning late Cenozoic beds in the footwall (Fig. 2; Cunningham et al., 1996). Biotite and chlorite schists are displaced to the north over Cretaceous and late Cenozoic sediments on a south-dipping thrust fault along the northern front of Nemegt Nuruu (Figs. 2, 7, 9C). A northwest-dipping detachment fault downthrows Cretaceous sandstones against jasperoids and phyllites along the northern front of Altan Uul (AKDF in Fig. 2; Cunningham et al., 2009). To the north, the detachment fault is cut by a south-dipping thrust (Figs. 2, 7).

The Trans-Nemegt Fault is the longest continuously traceable fault within Nemegt Nuruu and is the only fault to completely traverse the range, connecting the south-directed southern frontal thrust and the north-directed northern frontal thrust, and defines the gentle z-shape of the Nemegt restraining bend (Figs. 2, 7). In the southeast, the fault dips moderately to the north and has shallow northwest plunging slickenlines, which indicate top to the southeast sinistral thrust displacements. The orientation of the fault changes along strike to the northwest; it dips progressively more steeply to the northeast, up to vertical attitudes. Further to the northwest, the fault dips steeply to the southwest, and has moderate west plunging slickenlines, which indicate top to the east sinistral oblique thrust displacements. Although it changes its strike and dip, slickenline data and kinematic indicators suggest that the Trans-Nemegt Fault maintains a left-lateral oblique-slip thrust sense over its entire length.

The Trans-Nemegt Fault separates the greenschist to epidote-amphibolite facies meta-sedimentary sequences in western Nemegt Nuruu from the greenschist facies volcano-sedimentary sequence in central Nemegt Nuruu (Fig. 2). In northwest Nemegt Nuruu, a granite intrusion that was emplaced into the sequences on either side of the Trans–Nemegt Fault, is thrust over itself, and displaced approximately 300 m left-laterally (Figs. 2, 9E). Slip vectors calculated using the lateral offset of the granite intrusions and slickenlines on the fault plane suggest a maximum local vertical uplift of 520–633 m and 300 m of Cenozoic left-lateral displacement along the Trans-Nemegt Fault (Fig. 9E; Rippington, 2008). The amount of displacement suggests that Cenozoic deformation did not cause major tectonic redistribution of the Paleozoic rocks in central Nemegt Nuruu.

5. Lithotectonic sequences in Nemegt and Altan Nuruu: field data

In the sections that follow, the rock types in each area are briefly outlined, before a more detailed account of the structural geology is given. Six phases of deformation can be distinguished from cross-cutting field relationships in Nemegt and Altan Nuruu. D1 and D2 structures are only developed in the orthogean sequence in northeast Nemegt Nuruu (Section 5.2.6). D3 and D4 structures are potentially developed in all Ordovician to Carboniferous rocks in the area, but are most intensely developed to the south and west of the Trans-Nemegt Fault, in north Altan Nuruu and western Nemegt Nuruu (e.g. Section 5.1.4; Fig. 2). D5 and D6 structures are developed everywhere. Structures in each lithotectonic sequence are described from oldest (D1) to youngest (D6). The rock types and structures of the lithotectonic sequences in Nemegt and Altan Nuruu are summarised in Table 1. More detailed information can be gained from the transects (Figs. 4, 5, 6), and the along-strike connectivity of structures and lithotectonic sequences is shown on a map and 3D model (Figs. 2, 7).

5.1. Altan Nuruu and western Nemegt Nuruu

The lithotectonic sequences in this area are exposed as a series of east–west trending belts. From south to north, there is a volcano-sedimentary sequence, an ophiolite and a meta-sedimentary sequence (Fig. 2).

The volcano-sedimentary sequence, exposed along the southern front of Altan Nuruu, is approximately 3 km wide. It consists of unmorphosed arkose and volcaniclastic sandstone, and greenschist facies meta-basalts, meta-andesites, meta-diorite, volcaniclastic conglomerates, phyllite and chloritic schist. In eastern Altan Nuruu, poorly consolidated Cretaceous–Cenozoic sandstones, conglomerates and
Fig. 4. The westernmost transect passes through eastern Altan Nuruu and western Nemegt Nuruu. The major structures and lithologies are marked, and stereonets of cleavage and fold axes are shown for some sections of the transect.
Fig. 5. The central transect passes through central Nemegt Nuruu. The major structures and lithologies are marked, and stereonets of cleavage and some faults are shown for some sections of the transect.
Fig. 6. The easternmost transect passes through eastern Nemegt Nuruu. The major structures and lithologies are marked, and stereonets of bedding are shown for some sections of the transect.
5.1.1. Structures with the volcano-sedimentary sequence, southern Altan Nuruu (Fig. 4A–B)

The rocks in the volcano-sedimentary sequence have a shallow south to steep north dipping cleavage (S3). In the blocky metavolcanic rocks, S3 is a spaced cleavage. In the phyllites, penetrative S3 cleavage has been folded into upright, east–west trending moderate-tight F4 folds (Fig. 4A1–B).

It is difficult to determine the relative age of the numerous thrust faults in Altan Nuruu (Fig. 4A1–B). In central Altan Nuruu, greenschist facies volcano-sedimentary rocks are thrust to the north over the Altan Uul Ophiolite on a moderately steep south dipping ductile shear zone (Fig. 2). All the unequivocal D6 structures in the region are brittle, so this ductile shear zone is tentatively attributed to D4.

Only one extensional structure was observed along the western transect in southern Altan Nuruu (Fig. 4A1–B): Unmetamorphosed volcaniclastic breccias and arkosic sandstones are downthrown to the north against meta-basalts on a moderately steep northeast-dipping normal fault (D5), which has down-dip slickenlines (Fig. 4i).

The volcano-sedimentary sequence is deformed by numerous north or northwest dipping brittle thrust shear zones with down-dip slickenlines (e.g. Fig. 4ii, iii). These thrust faults cut all other structural fabrics and are interpreted as part of the late Cenozoic positive flower structure (D6; Figs. 4, 7). The structure along the southern mountain front of Altan Nuruu is obscured by Quaternary alluvial fans in the vicinity of the western transect (Fig. 4iv). However, locally flattened and sheared pillow basalts are found adjacent to moderate-shallow north-dipping brittle thrusts (D6), which are interpreted as hanging wall imbricates of the buried southern frontal thrust fault (D6).

5.1.2. Structures in the volcano-sedimentary assemblage, westernmost Nemegt Nuruu (Fig. 4E–F)

Volcaniclastic conglomerate and chloritic schists attributed to the volcano-sedimentary assemblage are exposed in a ridge in westernmost Nemegt Nuruu. All of the rocks in this area have a penetrative bedding-
parallel cleavage (S3). On the south side of the ridge, S3 cleavage is folded into upright, east–west trending moderate-tight F4 folds (Fig. 4E). On the northern side of the ridge, S3 cleavage is intensely deformed into tight, north-vergent F4 folds (Figs. 2, 8B). Quartz–albite–chlorite schists with large feldspar clasts are exposed a few hundred metres from the northern front of the ridge, and are L–S tectonites showing top to the northwest shearing (D4).

A 1 m-wide steep northeast dipping mylonitic shear zone (D5) with northwest plunging stretching lineations downthrows the chloritic schists to the north over the Cretaceous–Cenozoic basin fill by a shallow, southward steepening D6 brittle thrust fault (Fig. 4vi).

5.1.3. Structures in the Altan Uul Ophiolite

The Altan Uul Ophiolite is best exposed in westernmost Altan Nuruu (Rippington et al., 2008). The rocks are blocky and no cleavage is developed. Moderate to steep southwest dipping ductile thrust shear zones (D4) displaced gabbros, serpentinites and meta-psammites to the north over jasperoids (Rippington et al., 2008). Cretaceous sandstones are downthrown against the jasperoids along a steep northwest dipping Cretaceous detachment fault (D5) along the northern front of Altan Uul (AKDF in Fig. 2; Cunningham et al., 2009). North-dipping and south-dipping brittle thrust faults (D6) cut the ophiolitic rocks in the centre of the ridge (Fig. 4v).

**Fig. 8.** Field photographs from Altan Uul and westernmost Nemegt Nuruu. A. Cretaceous sediments form an intramontane basin between Nemegt and Altan Nuruu. The Cretaceous sediments sit with angular unconformity on Ordovician–Carboniferous greenschists. B. Folded schists in a westward extending ridge in western Nemegt Nuruu. C. North-vergent folds of cleavage in western Nemegt Nuruu, with inset photomicrograph of folded greenschist facies chlorite schists from the same area. D. North-directed thrust shear zone excising the long-limb of a north-vergent fold in western Nemegt Nuruu. E. Brittle normal fault offsetting bedding by approximately 5 m.
of the range, and a major vertical, southwest striking strike-slip fault displaces the ophiolite sequence in a sinistral sense (D6; Fig. 2).

5.1.4. Structures in the meta-sedimentary assemblage, north Altan Nuruu and northwest Nemegt Nuruu (Fig. 4C–D, G–H)

All of the rocks in the meta-sedimentary sequence have a penetrative cleavage (S3). In north Altan Nuruu, S3 cleavage strikes east–west and typically dips moderately to steeply to the south (Fig. 4C–D). Cleavage intensity increases in proximity to several north-directed ductile thrust shear zones (D4) in northeast Altan Nuruu (Fig. 4C–D).

In northwest Nemegt Nuruu, S3 cleavage is folded into tight north-vergent F4 folds (Figs. 4G–H, 8C). Moderately south and south-east dipping mylonitic thrust shear zones (D4) have excised the long limbs of many of the F4 folds (Figs. 4vii, 8D). North-dipping and south-dipping brittle normal faults (D5) cut the ductile thrust shear zones in northwest Nemegt Nuruu, and locally offset bedding by 5 m in some places (Figs. 4viii, ix, x, 8E). Numerous moderate to

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Fig. 9. Field photographs from central and eastern Nemegt Nuruu. A. East–west trending open folds of bedding in eastern Nemegt Nuruu. B. North-vergent folds within intensely deformed black shales in central Nemegt Nuruu. C. A south-dipping thrust fault places Palaeozoic schists to the north of Cretaceous sandstones at the northern front of Nemegt Nuruu. D. North-directed thrust faults place the orthogneiss over biotite schists near the northern front of Nemegt Nuruu in the east. E. A granite–schist contact is displaced 300 m left-laterally along the Trans-Nemegt Fault Zone.
### Table 1

The table shows the rock types and types of structures in each lithotectonic sequence along the three transects. GS = greenschist facies, EA = epidote–amphibolite facies, UM = unmetamorphosed.

| Western transect                      | Structures | Central transect                      | Structures | Eastern transect                      | Structures |
|---------------------------------------|------------|---------------------------------------|------------|---------------------------------------|------------|
| **Meta-sedimentary sequence**         | D3: S3 cleavage (parallel to bedding, folded) | D3: S3 cleavage (pervasive, S-dipping) | Orthogneiss | D1: S1 foliation in orthogneiss (folded) |
| (GS and EA)                           | D4: F4 folds (trend, E-W trending, N-vergent folds of S3) | D6: N-directed thrust employed schists to the north over Cenozoic–Cretaceous sandstones and gravels | • Quartzo-feldspathic, chlorite and biotite bands | D2: F2 folds (20 m wavelength, moderate, E-W trending, N-vergent folds of S1) |
| • Albite/quartz–epidote–chlorite–schists | D5: Brittle normal faults (S-dipping) |                                          |            |                                       |
| • Phyllites                           | D6: Brittle S-dipping thrusts /Trans-Nemegt Fault (SW-dipping left-lateral oblique-thrust) |                                           |            |                                       |
| • Quartz–biotite–garnet–epidote–chloritoid schist |                                          |                                           |            |                                       |
| • Meta-psammites                      | D6: N-directed thrust emplaced schists over Cenozoic–Cretaceous basin fill |                                           |            |                                       |
| Cenozoic–Cretaceous intramontane basin fill (UM) | D6: N-directed ductile thrust shear zone | Black shales | Volcano-sedimentary sequence (GS) | D3: S3 cleavage (E-W striking, parallel to bedding, penetrative, steep S-dipping) |
| • Poorly consolidated sandstones, gravels, and polymict conglomerates (pebble clasts) | D4: Brittle NE- and N-dipping thrust faults/steepest vertical E-W striking sinistral strike-slip fault (Rippington et al., 2008) | • Melange/flysch appearance | • Volcaniclastic meta-andesitic breccia and schists | D4: F4 folds (1–2 m wavelength, tight, N-vergent folds of S3) |
| The Altan Uul Ophiolite (GS and EA)   | D6: Brittle NE- and N-dipping thrust faults/steepest vertical E-W striking sinistral strike-slip fault (Rippington et al., 2008) | • Contains large limestone blocks | • Volcaniclastic meta-andesite breccia and schists | D6: Small, brittle, S-dipping left-lateral oblique-thrusts |
| • Peridote/serpentinite                | D3: S3 cleavage (folded) | Volcano-sedimentary sequence (GS) | • Volcaniclastic sequence (GS) | Volcano-sedimentary sequence (GS) | D3: S3 cleavage (E-W striking, parallel to bedding, penetrative, steep S-dipping) |
| • Cumulate gabbro                     | D4: F4 folds (1–2 m wavelength, tight, N-vergent folds of S3) | • Volcaniclastic meta-andesite breccia and schists | • Arkoic meta-psammitic | Volcano-sedimentary sequence (GS) | D6: F6 folds (100 m wavelength, open, upright folds of bedding) |
| • Sheeted dykes                       | D6: Small, brittle, S-dipping left-lateral oblique-thrusts | • Meta-andesite | • Meta-andesite breccia | 7D6: Brittle thrust faults and shear bands (moderate S-dipping) |
| • Pillow basalts                      | D3: S3 cleavage (folded) | • Volcaniclastic sequence (GS) | • Volcaniclastic breccia | 7D6: Brittle thrust faults and shear bands (moderate S-dipping) |
| • Jasperoids                          | D4: F4 folds (E-W trending, moderate-tight, upright F4 folds of S3 cleavage in phyllites) | • Volcaniclastic meta-andesite | • Volcaniclastic breccia | • Volcaniclastic breccia | 7D6: Brittle thrust faults and shear bands (moderate S-dipping) |
| Volcano-sedimentary sequence (GS)     | D5: Moderate N- and NE-dipping normal faults | • Volcaniclastic meta-andesite breccia | • Volcaniclastic breccia | • Volcaniclastic breccia | 7D6: Brittle thrust faults and shear bands (moderate S-dipping) |
| • Meta-andesite/basalt                | D6: NW-dipping brittle thrusts/ N-dipping southern range bounding thrust/ | • Volcaniclastic meta-andesite breccia | • Volcaniclastic sequence (GS) | Southern schist sequence (GS) | D3: S3 cleavage (penetrative, moderate to steep N-dipping) |
| • Meta-diorite                        | D3: S3 cleavage (folded) | • Albite–chlorite schists | Southern schist sequence (GS) | D6: F6 folds (right, E-W trending, S-vergent folds of S3) |
| • Quartz–albite–chlorite–muscovite schist | D4: F4 folds (E-W trending, moderate-tight, upright F4 folds of S3 cleavage in phyllites) | • Albite–chlorite schists | Southern schist sequence (GS) | D6: N- and NE-dipping thrust faults | 7D6: Brittle thrust faults and shear bands (moderate S-dipping) |
| • Phyllites                           | D6: NW-dipping brittle thrusts | • Albite–chlorite schists | Southern schist sequence (GS) | D6: F6 folds (right, E-W trending, S-vergent folds of S3) |
| • Volcaniclastic meta-conglomerates (andesite clasts) | D3: S3 cleavage (folded) | • Albite–chlorite schists | Southern schist sequence (GS) | D6: F6 folds (right, E-W trending, S-vergent folds of S3) |
| • Vhloritic schists                   | D3: S3 cleavage (folded) | • Albite–chlorite schists | Southern schist sequence (GS) | D6: F6 folds (right, E-W trending, S-vergent folds of S3) |
| • Volcaniclastic and arkosic sandstones (UM) | D3: S3 cleavage (folded) | • Albite–chlorite schists | Southern schist sequence (GS) | D6: F6 folds (right, E-W trending, S-vergent folds of S3) |
steep south-dipping brittle thrust faults (D6) cut all other structures in the area, and offset bedding and structures by up to 10 m. The western transect did not cross the northern front of Nemegt Nuruu (Fig. 2), but south dipping thrust faults that cut Cenozoic gravels were observed along the mountain front to the east.

5.2. Central and eastern Nemegt Nuruu

The lithotectonic sequences in this region are exposed in a series of arcuate southeast to east trending belts. From south to north, there is a narrow southern schist sequence, a volcano-sedimentary sequence, a northern schist sequence and a belt of discontinuously exposed orthogneiss (Fig. 2).

The southern schist sequence is a narrow belt of green schist facies albite-chlorite schists up to several hundred metres thick in southwest and southeast Nemegt Nuruu (Figs. 2, 6A–A1). It is not exposed in southern central Nemegt Nuruu.

The volcano-sedimentary sequence in central and eastern Nemegt Nuruu varies from 3–8 km wide (Figs. 2, 5A–D, 6A1–C). It consists of green schist facies meta-psammites, volcaniclastic meta-andesitic conglomerate, fine-grained tuff, albite–epidote–chlorite schist, with and without andesitic pebbles, and rhyolite. The volcano-sedimentary sequence is thrust to the north over black shales and the northern schist sequence (Figs. 2, 5E–F).

A 100 m thick belt of black shales is sandwiched between the volcano-sedimentary sequence and the northern schist sequence in central Nemegt Nuruu (Figs. 2, 5I). The shales have a melange, or flysch-like appearance, and contain large blocks of limestone. The contact between the shales and the northern schist belt is obscured by a downthrown block of unconsolidated polymict conglomerate and sandstone, of presumed Cretaceous–Cenozoic age.

The northern schist belt is exposed in a 1.5 km wide belt along the northern front of Nemegt Nuruu (Fig. 2). In central Nemegt Nuruu, it consists of feldspathic epidote–chlorite schists (Fig. 5E–F). In eastern Nemegt Nuruu, it consists of albite–chlorite–muscovite schist and biotite schist, which sits with angular unconformity on quartzo-feldspathic orthogneiss (Fig. 6D–E). The orthogneiss is exposed in a discontinuous east–west belt, and was only seen in two places in northeast Nemegt Nuruu (Fig. 2).

5.2.1. Structures in the southern schist sequence, southern Nemegt Nuruu

South of the central transect in southwest Nemegt Nuruu, schists exposed along the southern mountain front have a penetrative S3 cleavage, which is deformed into moderate to tight steeply northwest-plunging F4 folds with a 20 m wavelength, between a series of north dipping brittle thrust faults (D6). The D6 faults form a duplex which connects the Trans-Nemegt Fault (D6) and an east–west trending thrust fault (D6), which cuts Cretaceous basin fill between the southern fronts of Nemegt and Altan Nuruu (Fig. 2).

In southeast Nemegt Nuruu, the schists have a penetrative moderate to steep north dipping S3 cleavage (Fig. 6A–A1). Near the southern front, S3 cleavage is deformed into metre-wavelength south-vergent F6 folds, associated with south-directed D6 thrusts along the southern front of the range. Along the eastern transect, Quaternary alluvium obscures the southern frontal thrust (Fig. 6i). However, along strike to the west, between the central and eastern transects, the moderate north dipping frontal thrust (D6) carried schists to the south, causing local overturning of Cretaceous–Cenozoic sediments in its footwall (Figs. 2, 7; Cunningham et al., 1996).

5.2.2. Structures in the volcano-sedimentary sequence, central Nemegt Nuruu (Fig. 5A–D)

The finely meta-volcanic rocks in this area have a spaced northwest or southeast dipping S3 cleavage. Meta-sedimentary rocks have a dominantly southeast dipping penetrative S3 cleavage (Fig. 5A–D).

It is difficult to determine the relative age of many of the dominantly southeast dipping thrust faults in the volcano-sedimentary sequence along the central transect. At the northern boundary of the volcano-sedimentary sequence, rhyolites are thrust to the north over intensely deformed black shales along a northwest striking moderately dipping 30 cm-thick zone of fault gouge (Fig. 5i). Structures within the black shales suggest that D4 and D6 deformation may have occurred along this fault (see Section 5.2.4). To the south, a series of moderate to steeply southwest dipping brittle thrusts (D6) displace chlorite schists to the north over poorly consolidated sandstones and conglomerates of presumed Cretaceous–Cenozoic age (Fig. 5i, iii).

5.2.3. Structures in the volcano-sedimentary sequence, eastern Nemegt Nuruu (Fig. 6A1–C)

In southern parts of the volcano-sedimentary sequence, bedding is folded into east–west trending open and upright F3 folds (Fig. 9A). Steep east–west striking axial planar cleavage is developed in the hinge zone of the F3 folds (Fig. 6A1–B). No unequivocal D4 structures were observed. However, moderate northwest dipping cm-wide thrust shear zones could be D4 or D6 structures (Fig. 6ii, iii).

Moderate to steep southwest dipping normal faults (D5) were observed in the northern part of the volcano-sedimentary sequence along the eastern transect (Fig. 6iv, v). A series of wide east–west trending linear valleys cut through the area, and define major contacts and lineaments. The northernmost of these valleys marks the northern boundary of the volcano-sedimentary sequence in eastern Nemegt Nuruu (Fig. 6C), and can be traced for tens of kilometres along strike to the west, where it is defined by a thrust fault that dips moderately to the south. A granite intrusion has an apparent left-lateral offset of 1.5 km along the fault, suggesting that the fault can be attributed to D6 (Fig. 2).

5.2.4. Structures in the black shales and northern schist sequence in central Nemegt Nuruu (Fig. 5D–F)

The black shale unit records evidence of multiple deformation events. Penetrative S3 cleavage is folded into tight north-vergent mesoscale F4 folds (Fig. 9B). Weakly consolidated polymict conglomerate is downthrown to the north against the shales by a steep normal D5 fault (Fig. 5i). The shales are cut by numerous small south-dipping brittle thrust faults and calcite veins, which have southwest plunging slickenlines, indicating a later phase of left-lateral oblique thrust deformation (D6). To the south, rhyolites are thrust to the north over the black shales (see Section 5.2.2; Fig. 5i). The relative age of this thrust is unknown, but the polyphase deformation in the shales beneath it suggests that it may have been active during D4 and D6.

North of the shales, a pervasive moderate to steeply south dipping S3 cleavage is developed in the rocks in the northern schist sequence (Fig. 5E–F). At the northern front of the range, the schists are thrust to the north over steepened and locally overturned Cretaceous basin fill, on a moderate to shallow south-dipping D6 thrust fault (Figs. 5iv, 9C).

5.2.5. Structures in the northern schist sequence, northeast Nemegt Nuruu (Fig. 6D–E)

The schists have a pervasive bed-parallel steep south dipping cleavage (S3). Moderate to steeply south dipping brittle thrust faults and shear bands (D6) cut all other fabrics (Fig. 6vii). Along the eastern transect, approximately 400 m from the northern front of Nemegt Nuruu, biotite schists sit with angular unconformity on an approximately 300 m wide, discontinuously outcropping belt of orthogneiss (Fig. 6viii).

5.2.6. Structures in the orthogneiss, northeast Nemegt Nuruu (Fig. 6D–E)

The orthogneiss is dominated by quartzo-feldspathic gneissic bands (S1), which are deformed into moderate to open, metre- to outcrop-
scale north-vergent F2 folds (Fig. 6viii). The cleavage in the overlying biotite schists is unfolded. Therefore, the orthogneiss is interpreted to have undergone two phases of deformation (D1 and D2) prior to deposition of the biotite schist protolith, and the cleavage in the biotite schists is interpreted as S3.

The unconformable contact relationship between the biotite schists and the orthogneiss is tectonically duplicated approximately 150 m from the northern front with orthogneiss thrust north over biotite schist on a series of moderate to steep south to southwest dipping thrust faults (Figs. 6x, 9D). It is not certain if these faults formed during D4 or D6. The biotite schists and orthogneiss are onlapped by Quaternary alluvium along the northern front (Figs. 2, 6x).

6. \(^{40}\text{Ar}/^{39}\text{Ar}\) radiometric data

Following completion of the fieldwork element of this study, an opportunity to carry out a radiometric dating pilot study arose. Material collected during the 2004 and 2005 field seasons was re-examined to locate suitable samples to date using the \(^{40}\text{Ar}/^{39}\text{Ar}\) method. Two samples of schist from the meta-sedimentary sequence in westernmost Nemegt Nuruu (Section 5.1.4; Fig. 2), were selected with the objective of constraining the timing of deformation. Sample 23-1 is a muscovite-rich pelitic schist collected from within a D4 ductile thrust zone at 43°41.712N, 100°39.845E (Fig. 2). Sample 23-3 is a phylite taken from a package of schists folded into tight north-vergent F4 folds at 43°41.798N, 100°39.591E (Fig. 2).

Whole rock \(^{40}\text{Ar}/^{39}\text{Ar}\) analysis was carried out on sample 23-1, and K-feldspar \(^{40}\text{Ar}/^{39}\text{Ar}\) ages were obtained for sample 23-3. Step by step heating of single mica grains was not possible, due to the extremely fine grained nature of the rocks. Consequently, the data are unable to constrain the timing of metamorphism in the region. However, the data provide a useful constraint on the resetting of the \(^{40}\text{Ar}/^{39}\text{Ar}\) system, which is related to cooling following deformation.

6.1. Analytical protocol

Samples were crushed, sieved and washed in acetone and distilled water. For sample 23-3 K-feldspar was separated using standard techniques and fresh inclusion-free mineral grains were handpicked under the binocular microscope.

The transformation \(^{39}\text{K}\) (n, p)\(^{39}\text{Ar}\) was performed during irradiation at the IFE Kjeller reactor in Norway, using the Taylor Creek Rhyolite as flux monitor (28.619±0.034 Ma; Renne et al., 2010). Samples were step heated in the \(^{40}\text{Ar}/^{39}\text{Ar}\) laboratory at the Geological Survey of Norway using a Merchantek MIR-10 CO2 laser. The extracted gases were swiped over getters (SAES AP-10) for 2 min, and then for 9 min in a separate part of the extraction line. The peaks were determined by peak hopping (at least 8 cycles) on masses 44\(^{Ar}\) to 35\(^{Ar}\) on a Balzers electron multiplier on a MAP 215-50 mass spectrometer.

Data from unknowns were corrected for blanks (every 4th analysis is a blank) prior to being reduced with the IAAA software package (Interactive Ar Analysis, written by M. Ganerød, NGU Trondheim, Norway) that implements the equations in McDougall and Harrison (1990). Data reduction in IAAA incorporates corrections for interfering isotopes (based on K2SO4 and CaF2 salts included in the irradiation package), mass discrimination, error in blanks and decay of \(^{37}\text{Ar}\) and \(^{40}\text{Ar}\).

We define a plateau according to the following requirements: at least three consecutive steps, overlapping at the 95% confidence level, together comprising at least 50% of total \(^{39}\text{Ar}\) and mean square of weighted deviates (MSWD) less than the two tailed student T critical value. We use the weighted York-2 method to calculate the inverse isochron results, with statistically valid isochrons having a MSWD value less than the two tailed F-test critical value.

6.2. Results

Data for both samples yield statistically valid plateau and isochron ages (Fig. 10). Sample 23-1 has a whole rock \(^{40}\text{Ar}/^{39}\text{Ar}\) isochron age of 223.3±2.5 Ma (2\(\sigma\)) and a plateau age of 222.4±2.4 Ma (2\(\sigma\)). The similar isochron and plateau ages of sample 23-1, imply rapid cooling of the whole rock below the closure temperature of the least retentive mineral in the late Triassic. Sample 23-3 has a \(^{40}\text{Ar}/^{39}\text{Ar}\) K-feldspar isochron age of 262±3.1 Ma (2\(\sigma\)) and a plateau age of 263.6±4.2 Ma (2\(\sigma\)). The trapped argon component indicated by both isochrons overlaps the atmospheric value of Lee et al. (2006), although for sample 23-1, the uncertainty is large (178±138.3, 2\(\sigma\)) due to clustering of the data points, indicating high radiogenic content. Sample 23-3 cooled below the 125–300 °C closure temperature of K-feldspar (after Copeland and Harrison, 1990) in the middle Permian.

6.3. Interpretation of \(^{40}\text{Ar}/^{39}\text{Ar}\) ages

The \(^{40}\text{Ar}/^{39}\text{Ar}\) ages date cooling of the samples, below the closure temperature of K-feldspar in the case of sample 23-3, and below the closure temperature of all the constituent minerals in sample 23-1. The samples are from an area of western Nemegt Nuruu that was affected by D3 to D6 deformation (Fig. 2, Table 1), suggesting that the ages constrain the timing of cooling following one of these deformation events. Cross-cutting relationships of D5 and D6 structures, with strata of known age, indicate that they developed in the Cretaceous and Late Cenozoic respectively. This post-dates the \(^{40}\text{Ar}/^{39}\text{Ar}\) ages, and indicates that they had nothing to do with resetting the \(^{40}\text{Ar}/^{39}\text{Ar}\) system. S3 cleavage in this area is typically defined by the alignment of bands of recrystallized quartz and metamorphic minerals, the most common of which are muscovite and chlorite, suggesting that peak metamorphism occurred shortly before, or during D3 deformation. Therefore, both of the samples would have been heated above their closure temperatures during D3. However, both samples were then deformed during D4. Sample 23-1 was collected from a D4 ductile thrust shear zone in westernmost Nemegt Nuruu, and sample 23-3 was collected from a block of schists deformed into tight north-vergent F4 folds. Consequently, the \(^{40}\text{Ar}/^{39}\text{Ar}\) ages are tentatively interpreted to constrain cooling following D4.

Sample 23-1 is a fine grained muscovite-rich rock, so the whole-rock age represents cooling below a higher closure temperature than the K-feldspar age obtained for sample 23-3. It is therefore interesting that sample 23-1 cooled below its closure temperature approximately 39 Ma after sample 23-3, especially when the sample locations are so close together. The high frequency of faults identified on the nearby transect northwest Nemegt Nuruu (Fig. 4G–H), indicates that the most likely explanation is that the two sample locations are separated by faults, and were brought closer together by deformation which occurred after they had cooled below their respective closure temperatures. Sample 23-1 was collected from a D4 ductile thrust shear zone. D4 shear zones are typically found to excise the long-limb of F4 folds. Therefore, the late Triassic age of sample 23-1 is interpreted to date the culmination of D4 contractional deformation. Sample 23-3 was collected from an area of schists deformed into tight north-vergent F4 folds. The middle Permian age for sample 23-3 may represent exhumation of a different block during an earlier stage of D4.

7. Discussion

7.1. Deformation history

Six distinct deformation events are interpreted from cross-cutting field relationships in Nemegt and Altan Nuruu. A summary of these events follows.
7.1.1. D1 and D2 compression

In northeast Nemegt Nuruu, east–west trending folds of foliation in slivers of orthogneiss (Fig. 6viii) record evidence for two phases of contractional deformation which occurred prior to deposition of the Ordovician to Carboniferous strata exposed in the area (Mongolian National Atlas, 1990). Biotite schists sit with angular unconformity on the orthogneiss (Fig. 6viii, xi). The first deformation event (D1) formed the foliation in the orthogneiss. The second deformation event (D2) formed east–west trending folds of the foliation, so is interpreted to have had a north–south principal horizontal maximum stress orientation (present day orientation).

7.1.2. D3 compression (late Carboniferous)

D3 formed east–west striking S3 cleavage and formed open upright F3 folds of bedding in southeast Nemegt Nuruu. Throughout Nemegt and Altan Nuruu, the alignment of metamorphic minerals to form the S3 cleavage suggests that peak metamorphism occurred shortly before, or contemporaneously with D3 deformation in a north–south compressional regime (present day orientation). Rippington et al. (2008) attributed a regional transition from marine deposition in the early Carboniferous to terrestrial deposition in the Permian (Lamb and Badarch, 2001; Helo et al., 2006) to a collisional event caused by initiation of ophiolite obduction in Altan Nuruu. The highest grade meta-sedimentary rocks in the region are greenschist to epidote–amphibolite facies schists located directly to the north of the Altan Uul Ophiolite. We suggest that peak metamorphism in northwest Nemegt Nuruu, and D3 contractional deformation, occurred as the rocks in this region were overthrust during the northward obduction of the Altan Uul Ophiolite in the late Carboniferous (Rippington et al., 2008).

7.1.3. D4 compression (middle Permian–late Triassic)

In northwest Nemegt Nuruu, S3 cleavage is deformed, and bedding is refolded, into tight east–west trending, north-vergent F4 folds. In several places, north-directed D4 ductile thrust shear zones cut the long limbs of these folds (Fig. 8D). This suggests that the F4 folds tightened and locked up under top-to-the-north shear, causing north-directed shear zones (D4) to form to accommodate further contractional strain. D4 structures are parallel to D3 structures, suggesting D4 may have progressed from D3 under the same north–south compressional regime (present day orientation). However, unlike D3, D4 produced tight folding, culminating in the formation of major ductile thrust shear zones. A middle Permian K-feldspar 40Ar/39Ar isochron age of 262±3.1 Ma (2σ) from a phyllite in northwest Nemegt Nuruu is tentatively interpreted to date an early stage of D4. A late Triassic whole rock 40Ar/39Ar isochron age of 223.3±2.5 Ma (2σ) obtained from pelitic schist within a D4 ductile thrust shear zone is tentatively interpreted to date cooling following the final stage of D4 deformation. It is important to note that only two 40Ar/39Ar ages were obtained. Therefore, we recommend that further geochronological studies are undertaken to test the veracity of our interpretation.

Middle Permian to late Triassic contractional deformation is recognised throughout the Gobi-Altai Zone, to the north and west of Nemegt and Altan Nuruu (Lehmann et al., 2010), and east of Nemegt Nuruu, Late Triassic 40Ar/39Ar white mica ages constrain the timing of movement along sinistral shear zones (Webb et al., 2010). The onset of north–south Permo-Triassic shortening and strike-slip deformation has been attributed to the relative northward movement of the North China Craton, resulting in oroclinal bending, anti-clockwise rotation and left-lateral displacement of accreting terrane fragments in southern Mongolia (see Lehmann et al., 2010).
7.1.4. D5 extension (Cretaceous)

S3 cleavage, F4 folds and D4 ductile thrust shear zones are all cut by extensional shear zones and brittle normal faults (Fig. 8E) formed during the first extensional deformation event documented (D5). The extensional shear zones and normal faults in Nemegt and Altan Nuruu are broadly parallel to Cretaceous basin forming faults to the north and south of the ranges, including a northeast–southwest trending basement-bounding extensional detachment fault which defines the northern front of northwest Altan Nuruu (AKDF in Figs. 2; Cunningham et al., 2009). These faults are interpreted to reflect broadly north–northwest to south–southwest extensional deformation (present day orientation) during mid-Cretaceous basin formation, which is reported to have occurred widely across southern and southeastern Mongolia and adjacent regions of China (Meng, 2003).

7.1.5. D6 transpressional mountain building (Late Cenozoic)

Nemegt Nuruu is bound to the north and south by basinward-directed thrust faults that deform and locally overturn late Cenozoic alluvial sediments (Figs. 2, 7). Altan Nuruu is also bound to the south by a south-directed thrust fault (Figs. 2, 7). Within Nemegt Nuruu, several thrust faults place metamorphosed Paleozoic rocks over poorly thrust movement along the Trans-Nemegt Fault (Figs. 2, 9E), are associated with late Cenozoic transpressional mountain building at the Nemegt restraining bend (Cunningham et al., 1996; Owen et al., 1999; Cunningham, 2007; Rippington, 2008).

7.2. Evidence for the Dzolen–Edrengin terrane boundary in Nemegt and Altan Nuruu

The Trans-Nemegt Fault marks a major boundary between different lithotectonic sequences in Altan and western Nemegt Nuruu, and central and eastern Nemegt Nuruu (Fig. 2; Table 2). The volcano-sedimentary sequence in Altan Nuruu and western Nemegt Nuruu comprises greenschist facies meta-basalt, meta-andesite and metabasalt, and unmetamorphosed volcanoclastic and arkosic sandstones, which are interpreted as common products of intra-oceanic arc magmatism, volcanism and sedimentary reworking. This indicates that the terranes must have reached their approximate present-day positions during terrane accretion and amalgamation. Consequently, the terranes must have reached their approximate present-day positions during terrane accretion and amalgamation. This indicates that the Trans-Nemegt Fault marks the boundary between different lithotectonic sequences in Altan and western Nemegt Nuruu, and central and eastern Nemegt Nuruu (Fig. 2; Table 2). 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Table 2

| Dzolen subzone (described by Lehmann et al., 2010) | Altan Nuruu/western Nemegt Nuruu (this paper and Rippington et al., 2008) | Edrengin subzone (described by Lehmann et al., 2010) | Central and eastern Nemegt Nuruu (this paper) |
|---------------------------------------------------|--------------------------------------------------------------------------|------------------------------------------------|-----------------------------------------------|
| Silurian–Devonian                                  | ?Silurian–Devonian (Mongolian National Atlas, 1990)                      | ?Devonian                                      | Orthogenesi (?Precambrian)                    |
| • Sponges                                         | • Schists and phyllites                                                  | Volcano-sedimentary sequence;                 | • Schists                                     |
| • Quartz–hematite                                 | The Altan Uul Ophiolite;                                                 | • Tuff                                        | • Volcaniclastic breccia and conglomerate     |
| • Radiolarian jaspilite                            | • Jaspeoids                                                              | • Tuffite                                     | • Arkosic meta-psammite (with shelly fragments) |
| • Pillow lava                                      | • Pillow basalt                                                         | Tuffface sandstone (with Emsian brachiopods)  | • Meta-andesite                               |
| • Basaltic tuff                                    | • Sheeted dykes (basalt)                                                 | Dacite,                                      | • Rhyolite                                    |
| • Gabro                                           | • Cumulate gabbro                                                       | Andesite                                     | • Shales                                      |
| • Strongly serpentinised peridotite fragments      | • Serpentinitised peridotite                                             | Basaltic pillow lava                          |                                              |
| Carboniferous                                      | Carboniferous (Mongolian National Atlas, 1990)                           |                                              |                                              |
| • Basalt                                          | Volcano-sedimentary sequence;                                           |                                              |                                              |
| • Andesite                                        | • Tuff                                                                   |                                              |                                              |
| • Volcanoclastic sandstone and siltstone          | • Tuffite                                                                |                                              |                                              |
| • Volcanoclastic conglomerate                      | Tuffface sandstone (with Emsian brachiopods)                            |                                              |                                              |
|                                                   | Dacite,                                                                 |                                              |                                              |
|                                                   | Andesite                                                                |                                              |                                              |
|                                                   | Basaltic pillow lava                                                    |                                              |                                              |
7.3. An evolutionary model for the Nemegt and Altan Nuruu

A working model for the evolution of Nemegt and Altan Nuruu from the Silurian to late Triassic is presented in Fig. 11. Paleomagnetic constraints imply that the Tuva–Mongol and Dzabkhan–Baydrag blocks and the terranes to the south were oriented north–south in the Paleozoic in present day coordinates (Fig. 3, Zorin et al., 1993; Lehmann et al., 2010). If the Silurian to Carboniferous arc rocks in Nemegt and Altan Nuruu (Helo et al., 2006) are reconstructed to this orientation, they must have sat above a west-dipping subduction zone (Fig. 11A). The location of the Altan Uul Ophiolite indicates that oceanic crust lay to the east, separating these intra-oceanic arc segments from the arc segments and micro-continent fragments that lie to the north at the present day (Figs. 3, 11A; Badarch et al., 2002; Lehmann et al., 2010). Helo et al. (2006) suggest that the arc rocks in Nemegt Nuruu are geochemically indistinguishable from arc rocks along strike to the east (present day orientation). We assume that the Nemegt arc segment also existed adjacent and along-strike to the basic to intermediate arc rocks in Altan Nuruu. However, the two arc segments are compositionally different, so were probably separated, perhaps by a transfer zone (the proto-Trans-Nemegt Fault; Fig. 11A). Sandstone petrographic data from mountain ranges to the south of Nemegt and Altan Nuruu indicate the presence of arc activity in the Devonian (Lamb and Badarch, 2001), suggesting that the Nemegt and Altan Nuruu arc segments were part of an extensive series of volcanic arcs, analogous to the tectonic situation in the southwest Pacific today (e.g. Hall, 2009).

By the late Carboniferous, the arc in Altan Nuruu had begun to collide with another arc or micro-continental fragment to the north, and the Altan Uul Ophiolite was being obducted (Fig. 11B). D3 structures are parallel in Nemegt and Altan Nuruu, and have a similar north–south contracational style (present day orientation). We therefore, tentatively suggest that the arc rocks in Nemegt Nuruu docked with the terrane to the north at approximately the same time as the Altan Uul Ophiolite was obducted. The nature of the orthogneiss in northeast Nemegt Nuruu remains uncertain, but it is likely a fragment of the arc basement or micro-continent that the Nemegt arc segment collided with.

In the middle Permian to late Triassic, D4 deformation deformed S3 cleavage into tight north-vergent F4 folds, and culminated in north-directed thrusting along D4 ductile shear zones. D4 deformation may have occurred in central Nemegt Nuruu, but is most intensely developed in northern Altan Nuruu and northwest Nemegt Nuruu, between the Altan Uul Ophiolite and the boundary (the proto-Trans-Nemegt Fault) with the Nemegt arc/Edrengin terrane. This suggests that D4 was driven by the juxtaposition of the Dzolen (Altan) and Edrengin (Nemegt) terranes, possibly driven by the northward migration of the distal North China Craton to the south. Nemegt and Altan Nuruu were rotated into their approximate present day orientations at this time.

Fig. 11. A working model showing the evolution of the Nemegt and Altan Nuruu region during terrane accretion and amalgamation. A. Silurian–Devonian intra-oceanic arc volcanism occurred in Nemegt and Altan Nuruu, which were situated above a west dipping subduction zone. The two arc segments may have been separated by a transfer fault (the proto-Trans-Nemegt Fault). B. Late Carboniferous ophiolite obduction in front of the Altan (Dzolen) arc segment. The Nemegt (Edrengin) arc segment probably collided with a micro-continent fragment of arc root at the same time. Anticlockwise oroclinal bending may already have been underway. C. Middle Permian to late Triassic shortening, oroclinal bending and lateral redistribution of terranes along the proto-Trans-Nemegt Fault, caused by the northward migration of the distal North China Craton to the south. Nemegt and Altan Nuruu were rotated into their approximate present day orientations at this time.
movement of the distal North China craton (Fig. 11C; Cocks and Torsvik, 2007; Lehmann et al., 2010). This is consistent with the interpretation of Permo-Triassic shortening, oroclinal bending, anticlockwise rotation, and the lateral displacement of terranes in the Trans-Alta Zone to the west (Lehmann et al., 2010), and with documented late Triassic sinistral strike-slip deformation along strike to the east of Nemegt Nuruu (Webb et al., 2010).

A complex process of east-to-west terrane accretion began with the obduction of the Altai Uul Ophiolite in the late Carboniferous and culminated in south-to-north shortening, oroclinal bending and lateral displacement of terranes in the late Triassic. The relative deformation sequence in Nemegt and Altan Nuruu is well constrained, but further geochronological studies are required to determine the absolute age range of each deformation event in the Dzolen and Edrengen terranes. This study demonstrates that the southern Mongolian sector of the CAOB has had a protracted and complex history of crustal growth and subsequent crustal reactivation that continues to the present day. Additional structural, geochemical and geochronological studies of other relatively unstudied basement-cored ranges in the present day. Additional structural, geochemical and geochronological studies of other relatively unstudied basement-cored ranges in the southern Gobi Altai are required to further constrain the region's polyphase geological history.

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References

Badarch, G., Cunningham, D., Windley, B.F. 2002. A new terrane subdivision for Mongolia: implications for the Phanerozoic crustal growth of Central Asia. Journal of Asian Earth Sciences 21, 87–110.
Benton, M.J., Shishkin, M.A., Unwin, D.M., Kurochkin, E.N. 2000. The Age of Dinosaurs in Russia and Mongolia. Cambridge University Press.
Buslov, M.M., Saphonova, I.Y., Watanebe, T., Obut, O.T., Fujiwara, Y., Iwata, K., et al., 2001. Evolution of the Paleo-Asian Ocean (Altai-Sayan Region, Central Asia) and collision of possible Gondwana-derived terranes with the southern marginal part of the Siberian continent. Geosciences Journal 5, 203–224.
Cocks, L.R.M., Torsvik, T.H. 2005. Balta from the late Precambrian to mid-Paleozoic times: the gain and loss of a terrane's identity. Earth-Science Reviews 72, 39–66.
Cocks, L.R.M., Torsvik, T.H. 2007. Siberia, the wandering northern terrane, and its neighbors: late Precambrian to early Paleozoic. Earth-Science Reviews 62, 29–74.
Coney, P.J. 1989. Structural aspects of suspect terranes and accretionary tectonics in western North America. Journal of Structural Geology 11, 107–125.
Copeland, P., Harrison, M. 1990. Episodic rapid uplift in the Himalaya revealed by 40Ar/39Ar analysis of detrital K-feldspar and muscovite, Bengal fan. Geology 18, 354–357.
Cunningham, W.D. 2007. Structural and topographic characteristics of restraining bend mountain ranges of the Altai, Gobi Altai and easternmost Tian Shan. In: Cunningham, W.D., Mann, P. (Eds.), Tectonics of Strike-Slip Restraining and Releasing Bends: The Geological Society, London, pp. 219–236.
Cunningham, D. 2010. Tectonic setting and structural evolution of the late Cenozoic Gobi Altai orogen. In: Rusky, T.M., Zhai, M.-G., Xiao, W. (Eds.), Understanding Processes of Continental Growth: Geological Society of London, Special Publications, pp. 35–45.
Cocks, L.R.M., Torsvik, T.H. 2005. Balta from the late Precambrian to mid-Paleozoic times: the gain and loss of a terrane's identity. Earth-Science Reviews 72, 39–66.
Cocks, L.R.M., Torsvik, T.H. 2007. Siberia, the wandering northern terrane, and its neighbors: late Precambrian to early Paleozoic. Earth-Science Reviews 62, 29–74.
Coney, P.J. 1989. Structural aspects of suspect terranes and accretionary tectonics in western North America. Journal of Structural Geology 11, 107–125.
Copeland, P., Harrison, M. 1990. Episodic rapid uplift in the Himalaya revealed by 40Ar/39Ar analysis of detrital K-feldspar and muscovite, Bengal fan. Geology 18, 354–357.
Cunningham, W.D. 2007. Structural and topographic characteristics of restraining bend mountain ranges of the Altai, Gobi Altai and easternmost Tian Shan. In: Cunningham, W.D., Mann, P. (Eds.), Tectonics of Strike-Slip Restraining and Releasing Bends: The Geological Society, London, pp. 219–236.
Cunningham, D. 2010. Tectonic setting and structural evolution of the late Cenozoic Gobi Altai orogen. In: Rusky, T.M., Zhai, M.-G., Xiao, W. (Eds.), Understanding Processes of Continental Growth: Geological Society of London, Special Publications, pp. 35–45.
Cocks, L.R.M., Torsvik, T.H. 2005. Balta from the late Precambrian to mid-Paleozoic times: the gain and loss of a terrane's identity. Earth-Science Reviews 72, 39–66.
Cocks, L.R.M., Torsvik, T.H. 2007. Siberia, the wandering northern terrane, and its neighbors: late Precambrian to early Paleozoic. Earth-Science Reviews 62, 29–74.
Coney, P.J. 1989. Structural aspects of suspect terranes and accretionary tectonics in western North America. Journal of Structural Geology 11, 107–125.
Copeland, P., Harrison, M. 1990. Episodic rapid uplift in the Himalaya revealed by 40Ar/39Ar analysis of detrital K-feldspar and muscovite, Bengal fan. Geology 18, 354–357.
Cunningham, W.D. 2007. Structural and topographic characteristics of restraining bend mountain ranges of the Altai, Gobi Altai and easternmost Tian Shan. In: Cunningham, W.D., Mann, P. (Eds.), Tectonics of Strike-Slip Restraining and Releasing Bends: The Geological Society, London, pp. 219–236.
Cunningham, D. 2010. Tectonic setting and structural evolution of the late Cenozoic Gobi Altai orogen. In: Rusky, T.M., Zhai, M.-G., Xiao, W. (Eds.), Understanding Processes of Continental Growth: Geological Society of London, Special Publications, pp. 35–45.
Cocks, L.R.M., Torsvik, T.H. 2005. Balta from the late Precambrian to mid-Paleozoic times: the gain and loss of a terrane's identity. Earth-Science Reviews 72, 39–66.
Cocks, L.R.M., Torsvik, T.H. 2007. Siberia, the wandering northern terrane, and its neighbors: late Precambrian to early Paleozoic. Earth-Science Reviews 62, 29–74.
Coney, P.J. 1989. Structural aspects of suspect terranes and accretionary tectonics in western North America. Journal of Structural Geology 11, 107–125.
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Rojas-Agramonte, Y., Kröner, A., Demoux, A., Xia, X., Wang, W., Donskaya, T., et al., 2011. Detrital and xenocrystic zircon ages from Neoproterozoic to Paleozoic accreted terranes of Mongolia: significance for the origin of crustal fragments in the Central Asian Orogenic Belt. Gondwana Research 19, 751–763.

Ruzhentsev, S.V., Badarch, G., Voznesenskaya, T.A., 1985. Tectonics of the Trans-Altai zone of Mongolia (Gurvansaykhan and Dzolen ranges). Geotectonics 19, 276–284.

Ruzhentsov, S.V., Pospelov, L.I., 1992. The south Mongolian variscan fold system. Geotectonics 26, 383–395.

Şengör, A.M.C., Natal’in, B.A., 1996. Paleotectonics of Asia: fragments of a synthesis. In: Yin, A., Harrison, M. (Eds.), The Tectonic Evolution of Asia. Cambridge University Press, Cambridge, pp. 486–640.

Şengör, A.M.C., Natal’in, B.A., Burtman, V.S., 1993. Evolution of the Altai tectonic collage and Palaeozoic crustal growth in Eurasia. Nature 364, 299–307.

Tappinnier, P., Molnar, P., 1979. Active faulting and Late Cenozoic tectonics of the Tien Shan, Mongolia, and Baykal region. Journal of Geophysical Research 84, 3425–3459.

Weber, L.E., Johnson, C.L., Minjin, C., 2010. Late Triassic sinistral shear in the East Gobi Fault Zone, Mongolia. Tectonophysics 495, 246–255.

Wilhelmi, C., Windley, B.F., Stampfli, G.M., 2012. The Altaiids of Central Asia: a tectonic and evolutionary innovative review. Earth-Science Reviews 113, 303–341.

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

Xiao, W., Windley, B.F., Hao, J., Zhai, M., 2003. Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: termination of the central Asian orogenic belt. Tectonics 22, 1069.

Xiao, W.J., Windley, B.F., Huang, B.C., Han, C.M., Yuan, C., Chen, H.L., et al., 2009a. End-Permian to mid-Triassic termination of the accretionary processes of the southern Altaiids: implications for the geodynamic evolution, Phanerozoic continental growth, and metallogeny of Central Asia. International Journal of Earth Sciences 98, 1189–1217.

Xiao, W.J., Windley, B.F., Yuan, C., Sun, M., Lin, S., Chen, H.L., et al., 2009b. Paleozoic multiple subduction– accretion processes of the southern Altaiids. American Journal of Science 309, 221–270.

Xiao, W.J., Windley, B.F., Allen, M.B., Han, C., 2012. Paleozoic multiple accretionary and collisional tectonics of the Chinese Tianshan orogenic collage. Gondwana Research (http://dx.doi.org/10.1016/j.gr.2012.01.012).

Yakubchuk, A., Seilmann, R., Shatov, V., Cole, A., 2001. The Altaiids: tectonic evolution and metallogeny. Society of Economic Geologists, Newsletter 46, 7–14.

Zonenshain, L.P., Suyetenko, O.D., Jamyandamba, L., Fëngin, G., 1975. Structure and the axial part of South Mongolian eugeosyncline in the Dzolen Range. Geotectonics 9, 214–220.

Zonenshain, L.P., Kuzmin, M.I., Natapov, L.M., 1990. Geology of the USSR: a plate-tectonic synthesis. American Geophysical Union. (Geodynamic Series 21).

Zorin, Yu.A., Belichenko, V.G., Turutanov, E.Kh., Kochevenskii, V.M., Ruzhentsev, S.V., Dergunov, A.B., et al., 1993. The South Siberia–Central Mongolia transect. Tectonophysics 225, 361–378.