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# Paleomagnetism of the Neoproterozoic diamictites of the Qiaoenbrak formation in the Aksu area, NW China: Constraints on the paleogeographic position of the Tarim Block

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ABSTRACT

The middle to late Neoproterozoic records the transition from the dispersal of supercontinent Rodinia to the subsequent assembly of supercontinent Gondwana. Determining paleogeographic positions of the major cratons during this transition is crucial to understand the displacement histories of these blocks. However, high-quality paleomagnetic results from well-dated rocks during this period remain sparse for the cratons. In this paper, we have carried out a paleomagnetic study of the succession of the Cryogenian Qiaoenbrak formation (Fm) in the Aksu area, NW China, which contains diamictites that are of probable glacial origin. The age of the studied section is constrained at around 730 Ma based on the stratigraphy and recent zircon U–Pb chronologic data. Stepwise alternating field (AF) and thermal demagnetizations generally reveal two-component magnetizations. The low temperature (coercivity) component was removed by ~300 °C (~30 mT) and the high temperature (coercivity) component decayed toward the origin, defining the characteristic remanent magnetization (ChRM). Rock magnetic data indicate that magnetite is the major remanence carrier. A negative fold test for an isoclinal soft-sediment fold, the presence of both normal and reversed polarities, and positive conglomerate tests in conjunction with the presence of pristine sedimentary features by microscopic inspections of thin sections suggest that the remanence was acquired shortly after the deposition, i.e. post-depositional remanent magnetization (pDRM), which is very close to the magnetic field at the time of deposition. Fourteen out of 17 sites yield stable ChRMs with a mean direction of $D_s = 246.1°$, $I_s = 30.4°$, $k_s = 14.1$, $\alpha_{95} = 11.0°$ in stratigraphic coordinates, corresponding to a paleopole ($Q = 6$) at $\lambda = 6.3°$S, $\varphi = 17.5°$E, $A_{95} = 9.1°$. Together with geologic constraints, the new paleomagnetic results place the Tarim Block at $16.3 \pm 5.6°$N adjacent to either the west or east of Australia (WOA or EOA) at around 730 Ma, but the WOA position is preferred based on the overall relatively favorable evidence. In addition, since the studied diamictites of the Qiaoenbrak Fm that are of probable glaciogenic origin yield a low paleolatitude, this study may lend support to the "Snowball Earth" hypothesis during the Neoproterozoic times.



## 1. Introduction

The Neoproterozoic era saw the dispersal of the supercontinent Rodinia, the subsequent re-amalgamation giving birth to another large landmass Gondwana, and the accompanying large-scale glaciations on the fragmentary landmasses (Hoffman et al., 1998; Schrag and Hoffman, 2001; Hoffman and Schrag, 2002; Torsvik, 2003; Condon et al., 2005; Deynoux et al., 2006; Trindade and Macouin, 2007; Li et al., 2008; Meert and Lieberman, 2008; Rino et al., 2008; Macdonald et al., 2010; Bradley, 2011). Precise reconstruction of the major cratons during this interval is crucial to establish the displacement histories of these cratons and to further understand the associated geodynamic processes within a supercontinent cycle. As one of the important cratons in the supercontinent Rodinia and one of three major blocks in China, the Tarim Block contains a complete Mesoproterozoic to Neoproterozoic succession (Gao et al., 1985; XBGMR, 1993; Xiao et al., 2004; Xu et al., 2005, 2009; Turner, 2010; Zhu et al., 2011), which documented the assembly and breakup of the supercontinent Rodinia, and the major glaciations in the Neoproterozoic (e.g. Xiao et al., 2004; Xu et al., 2005, 2009; Lu et al., 2008). However, the paleogeographic positions of the Tarim Block during this interval remain poorly constrained.

The Tarim Block has been qualitatively positioned adjacent to the northwestern Australia at a high latitude based on the similar tectonostratigraphies of both blocks (Hoffman, 1991; Li et al.,

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1996, 2008; Li and Powell, 2001) or the southeastern Australia at a low latitude based on proposed radiating dyke swarms (Lu et al., 2008). Paleomagnetic studies of the Neoproterozoic rocks provide crucial quantitative constraints on the paleopositions of the Tarim Block (Chen et al., 2004; Huang et al., 2005; Zhan et al., 2007). Chen et al. (2004) obtained a paleopole from the Aksu dyke swarms and placed the Tarim Block to the north of Australia at an intermediate latitude of 43 ± 6°N at ~800 Ma. Huang et al. (2005) conducted a paleomagnetic study of the Baiyisi volcanic rocks in the Quruqtagh area and obtained an equatorial paleolatitude for the Tarim Block at ~740 Ma. However, it is not possible that both paleopoles from these two studies can fit the apparent polar wander path (APWP) of Rodinia in one single reconstruction (Evans, 2009). One has to fit one paleopole with the Rodinian APWP and invoke a tectonic or overprinting event to explain the departure of the other pole from the Rodinian APWP (Evans, 2009). The difficulty in reconciling these two poles partly arises from the large age uncertainties of studied rocks. For instance, the Aksu dyke swarms were previously assigned an age of 807 ± 12 Ma (Chen et al., 2004), and was later revised to 785 ± 31 Ma (Zhan et al., 2007). More recently, zircon U–Pb chronologic studies show that the Aksu dyke swarms likely emplaced at ~760 Ma (Zhang et al., 2009a) or even younger than ~730 Ma (Zhu et al., 2011).

The difficulties in reconciling the available paleomagnetic poles emphasize an urgent need to obtain more reliable paleomagnetic data from well-dated strata in the Tarim Block. In this study, we have carried out a detailed paleomagnetic investigation of a succession of the Qiaoenbrak Fm in the Aksu area (Fig. 1a) that contains the Neoproterozoic diamictites, which are of probable glaciogenic origin (Gao et al., 1981, 1985; XBGMR, 1993; Carroll et al., 2001; Gao and Chen, 2003; Zhu and Wang, 2011). The age of the studied section can be fairly well constrained with the new U–Pb zircon ages from the Aksu area and its equivalent stratigraphic interval in the Quruqtagh area of the northeastern Tarim Block (Fig. 1a). This study contributes to constrain the paleogeographic position of the Tarim Block in the Neoproterozoic and could further test the snowball earth hypothesis.

## 2. Geological setting and sampling

The pre-Cambrian rocks of the Tarim Block mainly crop out along its northern margin and consist of the Neoarchean to Mesoproterozoic metamorphic basement and the Neoproterozoic-Cambrian unmetamorphosed sedimentary cover (Lu et al., 2008; Long et al., 2010; Cao et al., 2011; Shu et al., 2011; Ge et al., 2012; He et al., 2012; Long et al., 2012; Ma et al., 2012; Zhang et al., 2012; Zhao and Guo, 2012; Zhao and Cawood, 2012). In the Aksu area (Fig. 1a), the well-exposed pre-Cambrian successions are composed of, from the bottom to the top, the Proterozoic Aksu Group, the lower Sinian Qiaoenbrak Fm and the Yuermeinak Fm, and the upper Sinian Sugetbrak Fm and the Chigebrak Fm (Fig. 1b). The lower and upper Sinian successions in the Tarim Block correspond to the Cryogenian (Nanhua) and Ediacaran strata, respectively (Fig. 1b) (the Stratigraphy Committee of China, 2001; Gradstein et al., 2004). The Aksu Group consists of metasedimentary rocks, greenschists, and blueschists, and was intruded by a series of NW-trending mafic dykes. The Qiaoenbrak Fm and the Yuermeinak Fm are mainly composed of feldspathic arenite, siltstone, lithic feldspar sandstone, and conglomerates. These two formations also contain diamictites, within which flat-iron stones, striated clasts, and drop stones occur, suggesting that the diamictites were probably of glaciogenic origin (Gao et al., 1981, 1985; XBGMR, 1993). The Sugetbrak Fm is 400–450 m thick and comprises the red conglomerates, fluvial sandstones interbedded with three layers of 15–20 m thick basalt, and the gray lacustrine mudstones. The overlying Chigebrak Fm is composed mainly of thickly bedded, pale gray stromatolitic dolomite which was deposited in an extensive lake or a marine transgressional environment (Gao et al., 1985; Turner, 2010).

We conducted a detailed paleomagnetic investigation of a section in the Qiaoenbrak Fm that contains diamictites in the Aksu area (Fig. 1a and c). The diamictites are represented by two conglomerate beds that are separated by a ~30 m thick sedimentary sequence, which is composed of thinly bedded, greenish siltstones and mudstones and contains a soft-sediment fold (Fig. 1c). Both the lower and the upper conglomerate beds consist of subangular to subrounded, poorly sorted clasts of various lithologic compositions. The lower conglomerate bed is about 20 m thick and is dominated by gray sandstone and red granitic pebbles/cobbles. The upper conglomerate bed is ~50 m thick and contains three 1–2 m thick fine- to coarse-grained sandstone layers that are intercalated within the upper segment of this conglomerate bed. The number of pebbles/cobbles in the uppermost of the conglomerate bed decreases gradually upsection. Below and above the diamictite unit are thin- to medium-bedded red or yellowish sandstones (Fig. 1c).

We collected eight sites from the ~80 m thick red sandstone sequence below the diamictite unit and six sites from the ~90 m thick red sandstone sequence above the diamictite unit. Two sites from the interbedded sandstones within the upper conglomerate bed and one site from the greenish siltstone sequence that separates the two conglomerate beds were collected. Since these beds show little variations in attitudes and generally dip toward 240–250° at about 50–60°, we collected samples from the two conglomerate beds and the soft-sediment fold to perform conglomerate tests and a fold test to constrain the age of remanence (Fig. 1c). Two sites were collected from the two conglomerate beds (sites AK9 and AK18) and about 10 pebbles/cobbles of different lithologies were sampled at each site. For the soft-sediment fold, samples were collected from both limbs and the hinge of the fold (site AK16). All samples were collected with a portable gasoline-powered rock drill and generally 8–12 cores were drilled at each site. The orientation of each core was measured with a magnetic compass mounted on a Pomery orientation device.

## 3. Laboratory techniques

In the laboratory, cores were cut into standard cylindrical specimens of 2.5 cm in diameter and 2.2 cm in length. To characterize magnetic mineralogy, representative specimens were chosen for several rock magnetic experiments. The isothermal remanent magnetization (IRM) acquisition was measured with an ASC IM-10-30 impulse magnetizer and a JR-6A spinner magnetometer. Spectral analyses of IRM acquisition curves are performed to identify different coercivity components (Kruiver et al., 2001). Thermo-magnetic properties were determined using a KLY-3S kappabridge susceptibility meter coupled with a CS-3 furnace. To further constrain the magnetic mineralogy, representative samples were magnetized sequentially along *Z*-, *Y*-, and *X*-axis at fields of 2.4 T, 0.4 T, and 0.12 T, respectively, and then were subjected to stepwise thermal demagnetization (Lowrie, 1990). The anisotropy of magnetic susceptibility (AMS) was measured using the KLY-3S kappabridge.

Both thermal and alternating filed (AF) demagnetizations were used to isolate the characteristic remanent magnetization (ChRM). Progressive thermal demagnetization was carried out in 16–22 steps at a 50 °C increment for low temperatures (<300 °C) and a 20 or 30 °C increment for high temperatures (>300 °C) up to 600–680 °C. AF demagnetization was conducted in about 18 steps up to 90–100 mT. Since pilot experiments show that thermal demagnetization is more effective in isolating ChRMs than AF demagnetization, the majority of specimens were then subjected to thermal demagnetization. Remanence of specimens