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Closure of the Mongol–Okhotsk Ocean: Insights from seismic tomography and numerical modelling

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ABSTRACT

The existence of the Palaeozoic and Mesozoic Mongol–Okhotsk Ocean is evident from the Mongol–Okhotsk suture, which stretches from central Mongolia to the Sea of Okhotsk. A lack of sufficient palaeomagnetic data and an otherwise diffuse suture with an abrupt termination to the west has led to difficulties in reconstructing the history, geometry and closure of this ocean. Both the timing and style of the ocean's closure are unclear and have led to several alternative reconstructions. Closure timing ranges between the Late Jurassic (∼155 Ma) and beginning of the Early Cretaceous (∼120 Ma), and the proposed kinematics include contemporaneous subduction along two opposite margins, subduction along only one margin or with a component of left-lateral shear. In the present study, numerical models of mantle convection are coupled with global plate reconstructions to investigate ambiguities regarding the closure of the Mongol–Okhotsk Ocean. In order to decipher the tectonic history of this enigmatic region, two end-member scenarios of subduction location – either along the present-day northern or the southern margins of the Mongol–Okhotsk Ocean – are imposed as kinematic surface boundary conditions for the past 230 Myrs. Through a comparison to seismic tomography, the results indicate a preferred subduction history along the Siberian margin (relative northern margin) of the Mongol–Okhotsk Ocean. At present-day, the slab remnant is predicted to be located farther west than previously proposed. Furthermore, we find that the subducting slabs in this region generate a hot, dense pile at the same location and with a similar shape as the Perm Anomaly.

1. Introduction

The now-extinct Mongol–Okhotsk Ocean was an ocean that existed in the Palaeozoic (542–251 Ma; Gradstein et al., 2004) and Mesozoic (251–66 Ma) eras between the continental blocks of Siberia to the north and the Amuria (or Mongolia) and North China blocks to the south (Fig. 2).[1] It is suggested to have been separated from Panthalassa (pre-Pacific ocean basin) to the east by an island arc and subduction zone (Fig. 2) (Seton et al., 2012). The existence of the palaeo-ocean is evident from the Mongol–Okhotsk suture which stretches from central Mongolia, following the boundary between the Siberian and Amuria blocks, north to the Sea of Okhotsk (Fig. 1). The suture zone comprises ophiolites (Zonenshain et al., 1990; Tomurtogoo et al., 2005) and sediments which contain marine fossils, confirming the existence of an ocean in the Palaeozoic to Mid–Late Jurassic (Halim et al., 1998, and references therein). The suture is not characterised by significant topological highs, as might be expected from a continental collision, and its continuation towards the west is unclear, as the suture appears to end at longitudes west of ∼100°E (e.g., van der Voo et al., 2015).

A lack of sufficient palaeomagnetic data of the surrounding continental blocks, in addition to the suture containing geological evidence for subduction along both its relative northern and southern margins (Zorin, 1999), has made it difficult to reconstruct the history, geometry and closure of the ocean. Previous studies have proposed contemporaneous subduction along both margins and subduction along only one margin (e.g. Zhao et al., 1990; Zonenshain et al., 1990; Seton et al., 2012; van der Voo et al., 2015).

In the present study, global numerical models of mantle convection are coupled with two alternative tectonic plate reconstructions for the closure of the Mongol–Okhotsk Ocean to investigate whether the tectonic evolution of the Mongol–Okhotsk subduction zone, and the fate of the corresponding slab, can be determined from comparing the resultant numerical models, at present-day, with seismic tomography. Two competing end-member tectonic

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[1] Unless specified, the relative locations of terranes and boundaries are discussed relative to the present-day locations.

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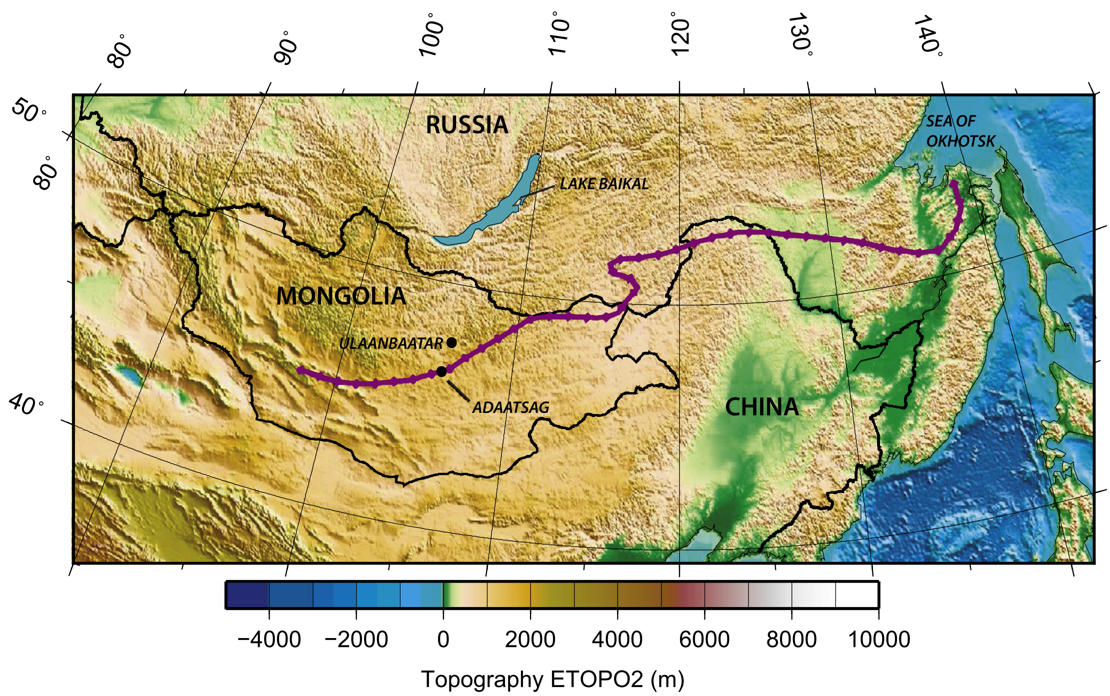

Fig. 1. Topographic map of present-day NE Asia with the location of the Mongol–Okhotsk suture in purple, stretching from middle Mongolia to the Sea of Okhotsk, and political borders in grey. The location of the Adaatsag ophiolite studied by Tomurtogoo et al. (2005) is also plotted. Suture zone location was digitized from the map of Tomurtogoo et al. (2005). Global topography data from ETOPO2v2 (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center, 2006). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

histories for the period 230–0 Ma are investigated with subduction along the northern or southern margin together with a range of subduction parameters.

1.1. The tectonic evolution of the Mongol–Okhotsk subduction zone

Estimates for the opening timing of the Mongol–Okhotsk Ocean range from Cambrian (∼540–490 Ma) (Harland et al., 1990), Ordovician (∼485–445 Ma) (Cocks and Torsvik, 2007) to Permian (∼300–250 Ma) (Zorin, 1999; Kravchinsky et al., 2002). Seton et al. (2012) point out that part of the timing ambiguity is related to different definitions of the Mongol–Okhotsk Ocean, i.e. at what time the associated terranes were in the configuration needed to form the ocean. ^{207}Pb/^{206}Pb dating of zircons in the Adaatsag ophiolite located on the western part of the suture (Fig. 1), reveals an age of ∼325 Ma (Tomurtogoo et al., 2005), indicating active seafloor spreading in the Carboniferous. This narrows the estimate of the active seafloor spreading and ocean basin opening to the Early–Middle Palaeozoic (Domeier and Torsvik, 2014).

Evidence of subduction related magmatism is found on both sides of the Mongol–Okhotsk suture (Zorin, 1999) indicating that subduction, and thus ocean closure, may have occurred underneath both the Siberian and Amurian margins. This has been interpreted as bivergent subduction in which both margins were active during an overlapping time period (Zorin, 1999). Subduction beneath the southern Amurian margin is thought to have ceased in the Late Permian and Triassic (∼260–200 Ma) as the North China block accreted to the Amuria block, resulting in a passive Amurian margin during the final stage of the Mongol–Okhotsk Ocean closure. In this model, final consumption of the ocean is therefore thought to have been along its northern margin, completed when the combined Amuria–North China blocks collided with Siberia (Zorin, 1999; Zonenshain et al., 1990). In contrast, the reconstruction of Seton et al. (2012) features a single polarity of subduction, which is focused uniquely along the northern margin, under Siberia.

Final closure of the ocean is suggested to have occurred sometime between the Late Jurassic (∼155 Ma) and beginning of the Early Cretaceous (∼120 Ma) (Zonenshain et al., 1990; Kravchinsky et al., 2002; van der Voo et al., 2015). Zhao et al. (1990) proposed a gradual closure of the Mongol–Okhotsk Ocean as a result of the counterclockwise rotation of Amuria relative to Siberia of 117°. Palaeomagnetic data from the study also indicated that the closure started in the west and ended in the east due to the coincidence of the Late Permian, Early Triassic and Late Jurassic poles of rotation. This is supported by intrusions and marine fossils found within the suture which young from west to east (Zhao et al., 1990; Zonenshain et al., 1990; Halim et al., 1998; Tomurtogoo et al., 2005). Kravchinsky et al. (2002) also suggested a rapid increase in subduction velocity in the Late Jurassic, due to large differences in palaeolatitude in the palaeomagnetic data from the Trans-Baikal area, resulting in the final closure of the ocean.

1.1.1. Seismic tomography of the Mongol–Okhotsk slab

Global seismic tomography models image a positive seismic anomaly under Siberia located between 1500 (mid-mantle) and 2890 km (CMB; core mantle boundary) (e.g. S20RTS from Ritsema et al., 2004, 2007, GypsumS from Simmons et al., 2010, and S40RTS from Ritsema et al., 2011). This feature has previously been interpreted as the Mongol–Okhotsk slab (e.g. van der Voo et al., 1999; van der Meer et al., 2010) (Fig. 3), based on the assumption that slabs sink vertically in the lower mantle with a constant sinking rate. However, lateral mantle flow generated by neighbouring subduction zones and the global mantle flow field may have affected the sinking of the Mongol–Okhotsk slab, leading to non-vertical sinking of the slab remnant, and thus a misinterpretation of positive seismic anomalies in the tomographic model.

Shephard et al. (2014) performed coupled surface and deep mantle convection models, enabling the possibility to track subducting slabs through time, and aid in determining the origin of the slab remnant. The authors found that the Mongol–Okhotsk slab might be located farther west (no farther east than 35°)