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Oman was on the northern margin of a wide late Tonian Mozambique Ocean

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ABSTRACT

The closure of the Mozambique Ocean defines the final assembly of the megacontinent Gondwana and is associated with a vast region of crustal growth in the Arabian-Nubian Shield. Despite this central paleogeographic position, there are few constraints on the position of terranes within and bounding the Mozambique Ocean. We report paleomagnetic data from ca. 726 Ma dikes exposed in southern Oman. Well-resolved magnetite magnetization is constrained to be primary by a conglomerate test on mafic clasts within overlying Cryogenian diamictite. The resulting paleomagnetic pole indicates that Oman was at a paleolatitude of 37 ± 2.5°N and was rotated ~80° counterclockwise from its present-day orientation. This position is consistent with Oman forming a contiguous plate with the India and South China cratons on the northern margin of the Mozambique Ocean in a distinct tectonic domain from Arabian-Nubian arcs to the south. This position reveals an ~5500-km-wide oceanic realm prior to subsequent closure that resulted in a major zone of Neoproterozoic crustal growth.

INTRODUCTION

The Mozambique Ocean existed between the Congo and India cratons in the Neoproterozoic Era prior to the closure that formed the megacontinent Gondwana (McWilliams, 1981; Collins and Pisarevsky, 2005). Oceanic volcanic arcs were active starting from ca. 850 Ma during the Tonian Period and throughout the 717–635 Ma Cryogenian Period (Johnson, 2014). The arcs collided with each other and with continental margins in the late Tonian through the Ediacaran Period forming the East African orogen (Stern, 1994). The closure of the Mozambique Ocean led to a vast region of juvenile crust underlying northeast Africa and the Arabian Peninsula known as the Arabian-Nubian Shield (ANS; Johnson, 2014).

Despite the importance of Mozambique Ocean closure for crustal growth and paleogeography, disparate end-member models persist for basin closure geometry. In the canonical model, developed in detail by Allen (2007), Oman was on the ocean's southern margin proximal to ANS arcs in the late Tonian. That model restricts crustal growth to a narrow basin between Oman and Congo/Sahara with ocean closure through subduction under India. The alternative model places Oman on the opposite northern side of the Mozambique Ocean during the latest Tonian to Cryogenian, far from ANS terranes and conjoined with India as an extensional to passive margin (Collins et al., 2021; Merdith et al., 2021). This alternative reconstruction builds on: (1) evidence from basement geochronology for Oman being in a distinct tectonic domain from the ANS (Alessio et al., 2018; Blades et al., 2019); (2) parallelism in Ediacaran passive margin sedimentation and lithofacies between Oman's Huqf Supergroup and India's Marwar Supergroup (Cozzi et al., 2012; Gómez-Pérez and Morton, 2025); and (3) similarities in detrital zircon provenance between Ediacaran sedimentary rocks of Oman and India (Gómez-Pérez et al., 2024). In this alternative model, ANS crustal growth is associated with long-lived subduction, arc magmatism, and accretion on the southern margin of the Mozambique Ocean. Uncertainty between these models has remained due to the paucity of paleomagnetic data from the ANS and Oman. Existing paleomagnetic data from Cryogenian sedimentary rocks of Oman indicate low latitudes (Kempf et al., 2000; Kilner et al., 2005) consistent with the model of Allen (2007). However, these data give contradictory orientations and have been challenged as remagnetizations (Allen, 2007; Rowan and Tait, 2010). We present a new high-quality paleomagnetic pole for the ca. 726 Ma Shaat dikes of southern Oman. With this pole, we reconstructed Oman's late Tonian position, which enables a reassessment of models for Mozambique Ocean closure and the setting of ANS crustal growth.

GEOLOGIC SETTING

In southern Oman, Neoproterozoic crystalline rocks are exposed on the Zalawt plain between the Gulf of Aden and the Jabal Samhan escarpment (Fig. 1; Platel et al., 1987a, 1987b). The dominant lithologies are Juffa complex paragneiss and Sadah complex orthogneiss that were metamorphosed and exhumed during ca. 815–790 Ma accretionary orogenesis (Platel et al., 1987a; Denèle et al., 2017; Barbey et al., 2018). The gneisses were intruded by ca. 790 Ma calc-alkaline plutons that mark the end of large-scale ductile deformation (Mercolli et al., 2006; Barbey et al., 2018).

The last tectonomagmatic event in the study area was intrusion of the Shaat dike swarm and the Leger Granite that has a U-Pb zircon date of 726.1 ± 0.4 Ma (Fig. 1; Mercolli et al., 2006; Bowring et al., 2007). A minor set of ENE-WSW–trending mafic dikes is cross-cut by a dominant set of NW-SE–trending dikes. The NW-SE dikes have mafic and felsic compositions with widths typically between 1 m and 15 m. Worthing (2005) interpreted dike

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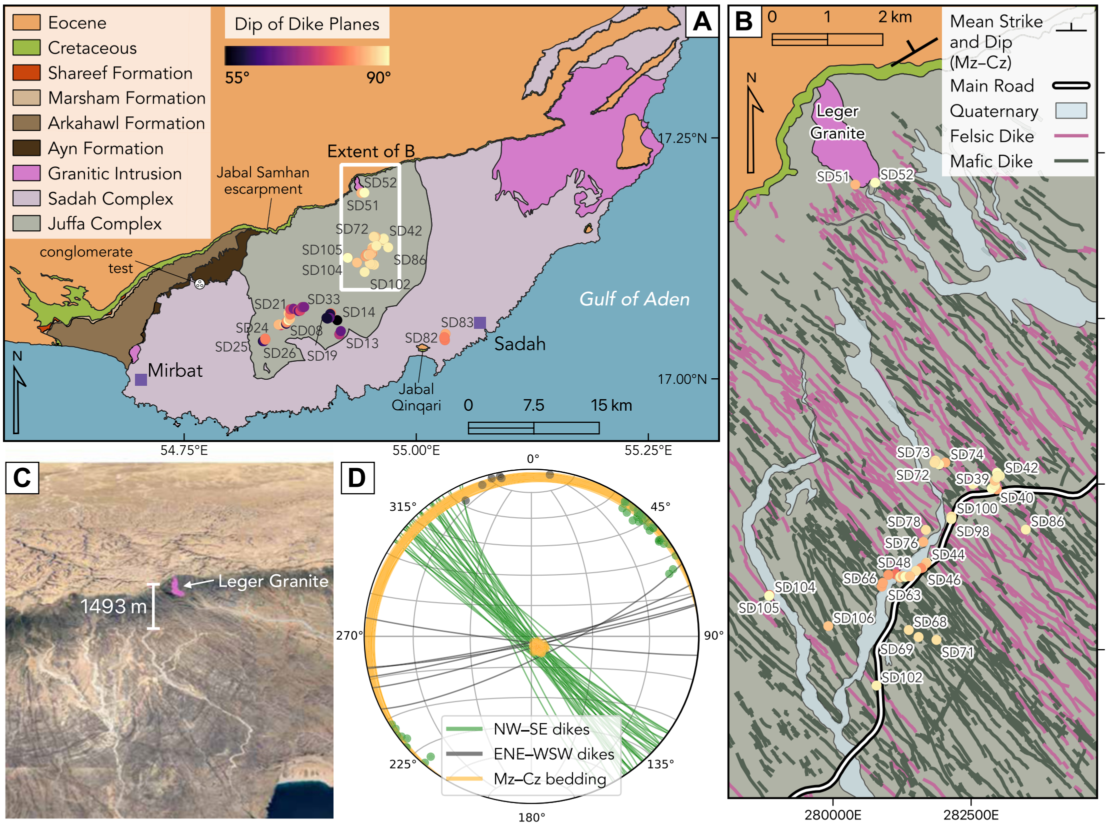

Figure 1. (A) Geologic map of the Zalawt plain of southern Oman; modified from Platel et al., (1987a, 1987b). Sampled Shaat dike locations (circles) are colored by dike plane dip. In the western portion of the region, Cryogenian to Ediacaran sedimentary rocks (Ayn, Arkahawl, Marsham, and Shareef Formations) are preserved. (B) Enlarged geologic map of the area in the white rectangle in panel A, highlighting the dense Shaat dike swarm in the Leger Granite region with coordinates shown in UTM zone 40N (WGS 84). Mz—Mesozoic; Cz—Cenozoic. (C) An oblique view of satellite imagery showing the steep Jabal Samhan escarpment with Shaat dikes in the plain. (D) Dike orientations and bedding of overlying Mesozoic to Cenozoic (Mz–Cz) carbonates for the region in panel B. NW-SE–trending dikes are indistinguishable from vertical. In contrast, ENE-WSW dikes have dips to the SSE of ~85°. This dip is consistent with post-Eocene tilt constrained by the overlying Mz–Cz bedding dip direction of 329° and a dip of 6°. This agreement is seen by gray ENE-WSW dike plane poles plotting along orange Mz–Cz bedding planes.

geochemistry to reflect melt generated during extension from subduction-modified lithospheric mantle. The 1 × 2 km Leger Granite pluton, interpreted to be comagmatic with the dikes (Mercolli et al., 2006), is elongate in a similar trend to the NW-SE dikes, which it cross-cuts.

Above the majority of the Zalawt plain, crystalline rocks are overlain by Cretaceous through Paleogene carbonates (Fig. 1A; Platel et al., 1987b). In the western portion of the plain, there is an intervening succession of Neoproterozoic siliciclastic sedimentary rocks of the Mirbat Group (Rieu and Allen 2008). The lowermost Mirbat Group formation is the glacigenic Ayn Formation, which is likely correlative to the ca. 711 Ma Ghubrah Formation and therefore the ca. 717–660 Ma Sturtian Snowball Earth (Rieu and Allen, 2008); although it has alternatively been correlated with the ca. 640–635 Ma Marinoan Snowball Earth (Gómez-Pérez et al., 2024). The study area is east of the Ediacaran–Cambrian Western Deformation Front of Oman (Gómez-Pérez et al., 2025). The Western Deformation Front is interpreted as a major suture between Oman and the ANS (and therefore east Gondwana with west Gondwana) in the alternative model (Cawood et al., 2021; Gómez-Pérez et al., 2025). Neoproterozoic sedimentary rocks gently dip to the north in coherent dip panels. Cretaceous–Paleogene strata have a similar shallow, northward dip direction resulting from Cenozoic rifting that opened the Gulf of Aden (Lepvrier et al. 2002).

RESULTS AND INTERPRETATION

Dike Orientations

Shaat dikes are tabular vertical to steeply dipping bodies that cross-cut older metamorphic fabric. Dike orientation plane data (1702 measurements on 85 dikes; Figs. 1A and 1D) reveal that NW-SE dikes are indistinguishable from vertical in the Leger Granite region (i.e., the Fisher mean of dike plane poles overlaps with 0° plunge; Fig. 1D). In contrast, to the west near Mirbat Group exposures, and to the south near the Cretaceous–Paleogene Jabal Qinqari outlier, NW-SE dikes deviate from vertical (Fig. 1A).

In the Leger Granite region, a subsidiary set of mafic ENE-WSW dikes is cross-cut by vertical NW-SE dikes (Fig. 1). The nearly orthogonal orientation of these dikes provides constraints on tilt beyond what is possible with one set, given that dikes can be tilted in their trend direction without departing from vertical. These ENE-WSW dikes are distinguishable from vertical and have dips to the SSE of ~85°. This tilt is consistent with the bedding of the overlying Cretaceous–Paleogene strata (dip direction = 329°; dip = 6°; n = 56). Reconstructing the basement using this bedding orientation brings the ENE-WSW dikes to vertical while retaining NW-SE dike verticality. This result indicates that the only event that appreciably tilted this structural panel was Cenozoic rifting. We focus our study where these structural constraints can be used to confidently tilt correct the paleomagnetic data (Fig. 1B).

U-Pb Zircon Geochronology

Zircon U-Pb dates from NW-SE felsic dikes were acquired using laser ablation–inductively coupled plasma–mass spectrometry (LA-ICPMS) (see the Supplemental Material[1] for methods). The dates of 725 ± 9 Ma (site SD39) and 727 ± 16 Ma (site SD50) are within uncertainty of the 726.1 ± 0.4 Ma Leger Granite isotope dilution–thermal ionization mass spectrometry (ID-TIMS) date of Bowring et al. (2007). An LA-ICPMS date for the Leger Granite (SD52) of 724 ± 7 Ma reproduces the ID-TIMS date within uncertainty (see the Supplemental Material). While NW-SE felsic dikes dominantly cross-cut NW-SE mafic dikes, some mafic dikes cross-cut felsic ones. Additionally, felsic and mafic dikes give paleomagnetic direc-

[1]Supplemental Material. Methods, results tables, and supporting figures for geochronology and paleomagnetic data. Please visit https://doi.org/10.1130/GEOL.S.29824985 to access the supplemental material; contact editing@geosociety.org with any questions.

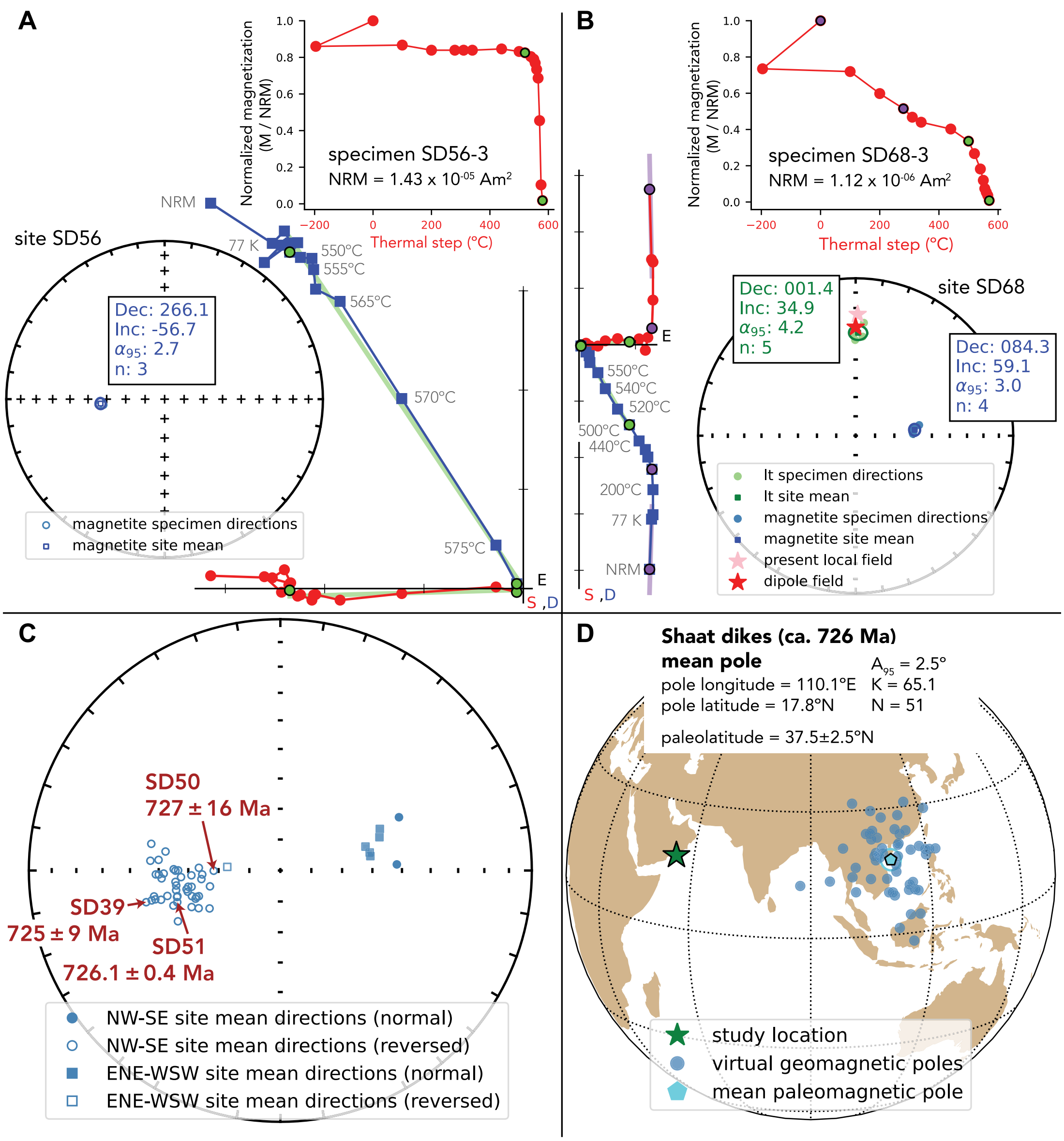

Figure 2. (A, B) Vector component diagrams, thermal demagnetization curves, and site-summary equal area plots for two representative Shaat dike sites and specimens in southern Oman. Data are shown in geographic coordinates, which emphasizes the similarity between the low-temperature component (lt) and the modern-day field in specimen SD68-3 (B), in contrast to the magnetite component that is of opposite polarity in sites SD56 (A) and SD68 (B). NRM—natural remanent magnetization; Dec—declination; Inc—inclination. (C) Tilt-corrected site mean directions for dikes in the Leger structural panel. Sites with associated U-Pb dates are labeled. (D) Virtual geomagnetic poles and the mean pole (pole longitude = 110.1°E; pole latitude = 17.8°N; A_{95} = 2.5°; N = 51).

tions consistent with being from a single population, as does the SD51 mafic dike baked by the Leger Granite (Fig. 2C). The U-Pb dates and these relationships indicate that Shaat dike and Leger Granite emplacement was broadly comagmatic ca. 726 Ma.

Dike Paleomagnetism

The majority of paleomagnetic sites contain a well-behaved origin-trending magnetization that unblocked between 500°C and 580°C (Fig. 2). This component is consistent with being held by magnetite and was isolated from 51 dikes in the Leger structural panel for which tilt is well-constrained (Fig. 2C). Forty-five of these dikes are from the NW-SE population (43 reversed and 2 normal polarity) and six are from the ENE-WSW population (1 reversed and 5 normal polarity). The virtual geomagnetic poles (VGPs) from these two populations share a common mean, consistent with a similar age. Considering all 51 sites, the normal and reversed directions pass a reversal test (with strong support using the Heslop and Roberts [2018] Bayesian framework). The paleomagnetic pole calculated from tilt-corrected VGPs (pole longitude: 110.1°E; pole latitude: 17.8°N; A_{95} confidence ellipse: 2.5°; K: 65.1; N: 51) corresponds to a paleolatitude of 37.5 ± 2.5°N. The VGPs are consistent with a Fisher distribution (positive Q-Q test; Tauxe et al., 2016) and are within the precision envelope proposed by Deenen et al. (2011) to indicate averaging of geomagnetic secular variation.

An interpretation of primary thermal remanent magnetization for the magnetite component is supported by a positive conglomerate test. Magnetite directions from 16 fine-grained mafic clasts (likely sourced from the dikes) within diamictite of the overlying Cryogenian Ayn Formation are consistent with a random distribution (R of 3.9 < Ro_{95} of 6.4; Fig. SI2 in the Supplemental Material) indicating pre-depositional magnetization. This result supports that the magnetite magnetization is primary and that the pole can be used to reconstruct Oman's ca. 726 Ma paleogeography.

DISCUSSION

The Shaat dikes paleomagnetic pole constrains the orientation and paleolatitude of Oman, placing the modern-day western margin to the south, with the study locality at a paleolatitude of 37.5 ± 2.5°N (Fig. 3). This orientation and paleolatitude supports the model of Collins et al. (2021) that puts Oman in a distinct tectonic domain from the ANS and that it formed the northern margin of the Mozambique Ocean in the latest Tonian (Fig. 3). When compared to late Tonian poles for India and South China from the ca. 760 Ma Malani igneous suite (Meert et al., 2013) and the ca. 780 Ma Liantuo Formation (Jing et al. 2015; Park et al. 2021), the ca. 726 Ma Oman pole is consistent with the

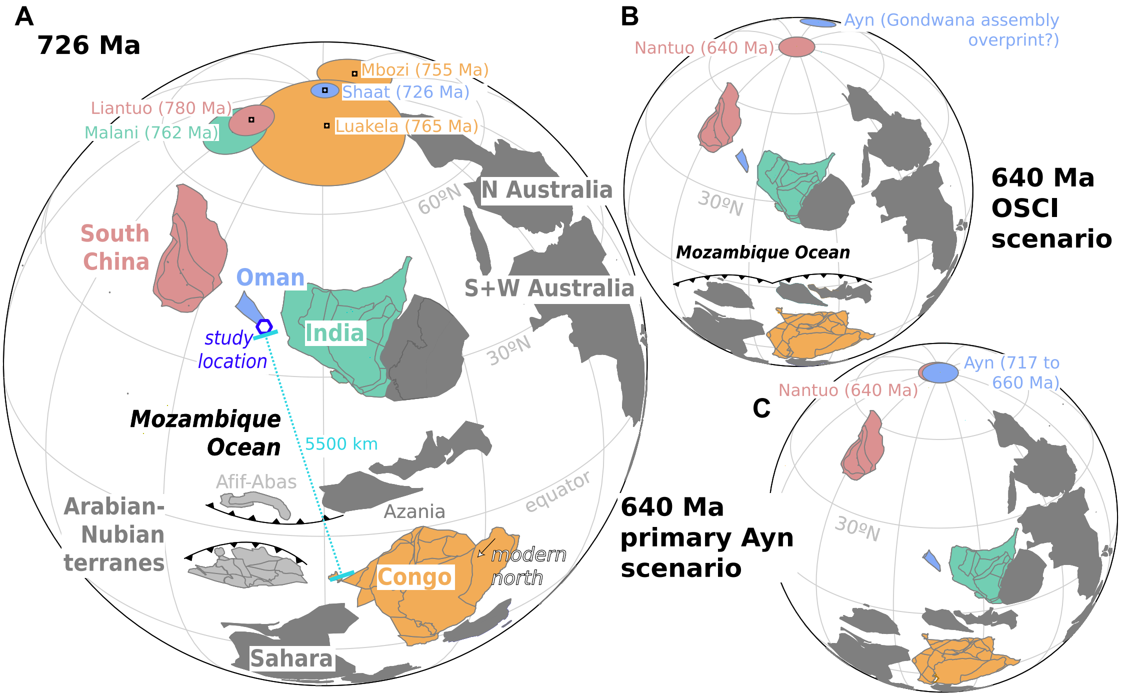

Figure 3. (A) Paleogeographic reconstruction at ca. 726 Ma that incorporates the Oman Shaat dikes paleomagnetic pole. Poles that inform the reconstruction are shown for Oman, South China, and India (OSCI), and Congo. As in Merdith et al. (2021), and as advocated by others (e.g., Gómez-Pérez et al., 2024), Oman is conjoined with India in the same relative position as in Gondwana. The reconstruction follows Merdith et al. (2021) with modifications to the relative position of South China and India to improve the agreement between Tonian paleomagnetic poles; India's position at 726 Ma constrained by the new Oman pole; and Congo's position at 726 Ma to be closer to the equator given the Tonian paleomagnetic poles. Two options are shown for ca. 640 Ma (B and C). (B) The OSCI hypothesis that maintains a mid-latitude position based on the ca. 640 Ma South China pole. This scenario maintains a wide Mozambique Ocean throughout the Cryogenian. (C) The primary Ayn pole hypothesis, which requires substantial Cryogenian southward motion of Oman distinct from that of South China.

hypothesis that these blocks were co-located at moderate to high latitudes (Fig. 3). This position is far from the Congo craton whose present-day eastern margin was at the equator as indicated by the ca. 765 Ma Luakela volcanics pole (Wingate et al., 2010) and the ca. 750 Ma Mbozi complex pole (Fig. 3; Meert et al., 1995). These bounds constrain the width of oceanic domain to ~5500 km at the Cryogenian–Tonian boundary (Fig. 3). Oman's orientation at ca. 726 Ma supports the idea that subsequent ocean basin closure was largely orthogonal to the margin, eventually sandwiching ANS terranes between Oman on one side and the Congo craton and Sahara blocks on the other.

Paleomagnetic data from Cryogenian sedimentary rocks of Oman have the potential to test proposed connections, track post–726 Ma motion, and establish paleolatitude at the time of Snowball Earth glaciation. Data developed predominantly from ca. 635 Ma strata in northern Oman were interpreted to constrain a low-latitude position (Kilner et al., 2005). These data imply an orientation of Oman similar to that of the present-day, in contrast to the rotated orientation revealed by the ca. 726 Ma pole. This orientation implies an unlikely vertical axis rotation of ~87° from 726 Ma to 635 Ma, and back again by 550 Ma to be in position for Gondwana assembly. The pole position falls on the Late Cretaceous pole path, which is concerning given the potential for remagnetization due to Samail Ophiolite obduction. Moreover, Rowan and Tait (2010) developed paleomagnetic data demonstrating that the magnetization underlying the Kilner et al. (2005) pole fails a fold test, confirming that it is an overprint.

Sparse paleomagnetic data from ten specimens of the Cryogenian Ayn Formation developed by Kempf et al. (2000) near our conglomerate test locality yielded a hematite-held direction with a similar declination to the Shaat dikes. The inclination is shallower than the dike direction, indicating a paleolatitude of ~9° (or 10° to 22° if a range of typical inclination shallowing is applied; Pierce et al. 2022). Given that the Ayn Formation conglomerate test is relevant to magnetite magnetization in fine-grained mafic clasts, it does not apply to this hematite magnetization, leaving the direction without a field test. It could be interpreted as indicating either: (1) a low-latitude position at the time of Cryogenian glaciation resulting from southward movement of Oman that closed the Mozambique Ocean during the Sturtian glaciation (Fig. 3); or (2) remagnetization during Gondwana assembly with closure of the Mozambique Ocean solely constrained to have occurred prior to the early Cambrian Angudan orogeny that formed the Western Deformation Front (Gómez-Pérez and Morton, 2025). The similarity between the Ayn Formation pole and the Sinyai metadolerite pole of Meert and Van der Voo (1996), which reflects magnetization acquired at ca. 550 Ma within the collisional Mozambique belt (Fig. SI5 in the Supplemental Material), could support the latter interpretation.

The model of a long-lived Tonian-Cryogenian connection between Oman, South China, and India (OSCI) predicts that Oman remained at similar moderately high latitudes as in the late Tonian through the Cryogenian. This constraint comes from the ca. 640 Ma Nantuo Formation South China pole (Zhang et al. 2013) that implies minimal latitudinal motion of the block over the preceding 100 m.y. (Fig. 3). In this scenario, Mozambique Ocean closure would have occurred throughout the Ediacaran rather than the Cryogenian. The standstill of the OSCI plate would indicate a lack of its southward subduction under the northern margin of the ANS that would have pulled it toward the equator. Subduction during this time would have been concentrated between ANS arc terranes and the Afif–Abas block. This subduction would have led to the collision that formed the Hulayfah-Ruwah suture at ca. 640 Ma and a significant interval of East African orogeny contractional deformation (Fig. 3; Johnson, 2014). After terrane collision and slab break-off, the initiation of south-directed subduction of the OSCI plate under the Afif–Abas block would have closed the Mozambique Ocean over the ensuing 100 m.y., leading to the formation of Gondwana.

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