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Is the Mesoarchean Mulgandinnah shear zone, Pilbara Craton, the world's oldest arc-slicing transform fault?

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ABSTRACT

Arc-slicing transform faults represent an integral component of convergent margin tectonics. They are developed above oblique subduction systems, cutting through and displacing the entire magmatic section of arcs, leading to tectonic repetition of segments of the overriding plate in the ensuing orogenic collage. Extant examples clearly show this process in Sumatra, New Zealand, and the Philippines, while ancient examples are reported from the Paleozoic Altaids and Neoarchean Superior and Yilgarn cratons. Here, we report data that document that the Paleo-Mesoarchean Eastern Pilbara craton, recently interpreted to be a preserved mid-upper crustal level of a magmatic arc, is cut and repeated by a major 3.0–2.93 Ga arc-slicing fault, the Mulgandinnah, which sliced a previously 600 × 100 km segment of a Mesoarchean arc system, laterally moving different segments to their presently juxtaposed 200 × 200 km preserved fragment. This evidence demonstrates lateral plate motions by 3.0 Ga and shows oblique subduction, arc plutonism, arc-slicing, and repetition, reflecting that crustal growth in modern-style convergent margins was in full operation by the Mesoarchean.

INTRODUCTION

There is a current debate on whether plate tectonics was operating in the Paleo-Mesoarchean. Some argue that plate tectonic activity was operating in the Hadean or at least as far as the preserved geological record (Harrison et al., 2005; Hopkins et al., 2008; Kusky et al., 2018; Windley et al., 2021), whereas others argue that plate tectonics started during the Archean (Cawood et al., 2006; van Hunen and Moyen, 2012), or even the Proterozoic (Stern and Gerya, 2024), from an earlier stagnant lid regime. The wide range in estimates of the initiation time of plate tectonics arises from a lack of clear evidence for lateral motions of plates in early times (Korenaga, 2013).

Western Australia's Pilbara craton represents a key area to address this debate, because it preserves a record of Paleo-Mesoarchean magmatism and deformation, providing significant insights into the planet's earliest preserved geological history (Hickman, 2016a). Some researchers suggest that multiple horizontal deformation events shaped the craton (Bickle et al., 1980; Krapez and Barley, 1987; Zegers et al., 1998; van Haaften and White, 1998; White et al., 1997; Blewett, 2002; Kloppenburg et al., 2001; Nijman et al., 2017; Kusky et al., 2021), whereas others propose that solid-state vertical diapirism processes during a stagnant-lid Earth shaped the craton (Hickman and Van Kranendonk, 2012; Van Kranendonk et al., 2007).

Here, we suggest that plate tectonics was operating earlier in the Archean by providing evidence for horizontal plate motions preserved in the craton-transecting strike-slip Mulgandinnah shear zone complex (MSZC), which may be the world's oldest preserved arc-slicing fault. We document tens of kilometers of horizontal offsets in the Mesoarchean and compare these with younger systems, suggesting that the MSZC is a significant tectonic boundary. The MSZC cuts through and repeats a sequence of arc-related plutons, suggesting that it is an arc-slicing strike-slip transform fault system similar to younger documented examples in the Altaids and active systems. Supporting aeromagnetic data sets and geologic maps demonstrate macro-scale brittle shear sense indicators through kinematic analysis of offset markers, documenting large horizontal displacements and demonstrating horizontal motion of rigid plates in the Mesoarchean. The Eastern Pilbara dome-and-basin province is likely part of a dissected arc and gained its presently preserved dimensions of 200 × 200 km from its previous dimensions of 100 × 600 km, or possibly even much greater.

GEOLOGICAL SETTING

NW Australia's Pilbara craton (3.59–2.77 Ga) is characterized by several well-preserved, low-grade Paleoarchean greenstone belts and is well-known for its granitoid gneiss domes in the east (Hickman, 2016a; Van Kranendonk et al., 2007; Hickman and Van Kranendonk, 2012). The craton (Fig. 1) is divided into the Western, Central, and Eastern tectonic zones (Beintema, 2003; Hickman, 2016b; Kusky et al., 2021), all cut by a network of strike-slip shear zones (Fig. 1). The Western Pilbara is interpreted as a ca. 3.3–3.2 Ga accretionary orogen (Kusky et al., 2018; Windley et al., 2021) that documents the early growth of the craton, with a notable similarity of the accreted oceanic terranes from the Western Sierra Metamorphic Belt and Klamaths of western North America and the Coast Ranges of British Columbia (Kusky et al., 2021). The Central Pilbara tectonic zone (Fig. 1) is covered mainly by the volcanic-sedimentary units of the ca. 3066–2919 Ma De Grey basin (Hickman, 2016b).

The Eastern Pilbara terrane (3.59–3.16 Ga), roughly the shape of a 200 × 200 km (40,000 km^2) block (Fig. 1), contains three main 3.53–3.33 Ga volcano-sedimentary groups collectively known as the Pilbara Supergroup. This term includes the Warrawoona, Kelly, and Sulphur Springs Groups, which are complexly deformed and wrap around ten different composite granitic, gneiss, and greenstone domes, each of which range from <35 to 120 km in

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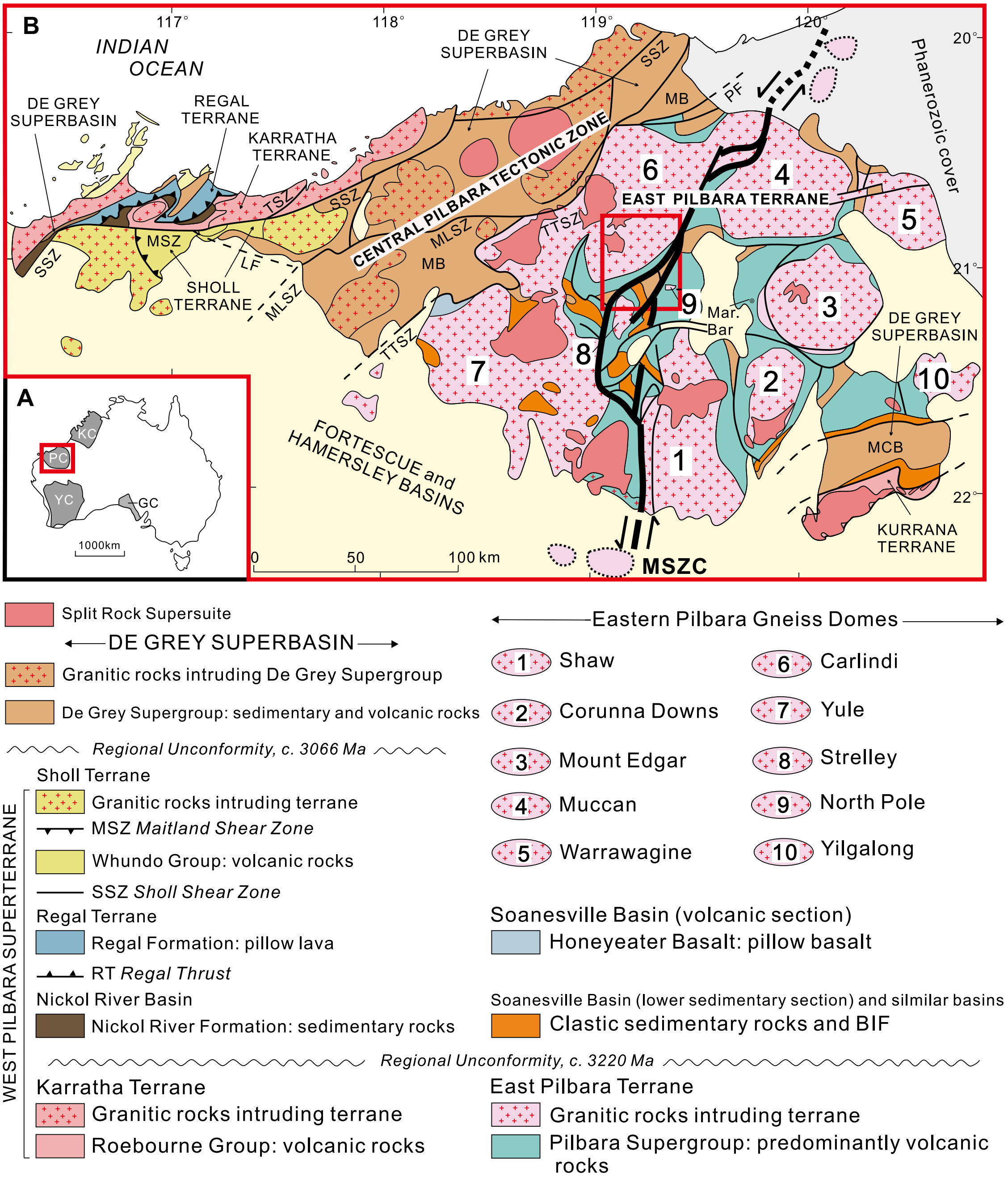

Figure 1. Geologic map of the Pilbara craton (PC) showing the location of the Mulgandinnah shear zone complex (MSCZ). Modified from Kusky et al. (2021), after Hickman (2016b). Pink area with dashed lines outside exposed craton show domes under younger cover at a depth of 8 km inferred from geophysical data (Supplemental Material; see text footnote 1). KC—Kimberley craton; YC—Yilgarn craton; GC—Gawler craton; BIF—banded iron formation. Abbreviations of shear zones and Basins of the Western and Central Pilbara include: TSZ—Terenar shear zone; TTSZ—Tabba Tabba shear zone; SSZ—Sholl shear zone; MSZ—Maitland shear zone; LF—Loudens fault; MLSZ—Mallina shear zone; PF—Pardoo fault; MB—Mallina Basin; MCB—Mosquito Creek Basin. Red box shows location of map in Figure 2.

diameter, with shear zones or younger intrusive rocks ubiquitously separating the gneiss and granite domes from the greenstones (Kloppenburg et al., 2001). It is remarkable in that in the Eastern Pilbara terrane the ten exposed gneiss domes preserve three major (and several minor) magmatic events that span a time interval of more than 300 m.y., with other sporadic magmatic events extending for >500 m.y., a history remarkably similar in multi-stage duration to the South American Cordilleran Andes with its predecessor peri-Gondwanan Pampean (Cambrian) and Famatinian (Cambro-Ordovician) arcs, later affected by Permian to Mesozoic intrusive series of the Peruvian coastal batholith (Demouy et al., 2012; Otamendi et al., 2012). This similarity formed the basis for interpreting the Eastern Pilbara as a long-lived, multi-phase continental margin arc system (Kusky et al., 2021).

MULGANDINNAH SHEAR ZONE

The MSZC cuts the Eastern Pilbara into two rather equidimensional parts, with broadly similar histories on either side (Fig. 1). It has an exposed length of 200 km, but our geophysical analysis shows it extends at least another 150 km to the north and a similar distance to the south under Protozoic and Phanerozoic cover (Fig. S1 in the Supplemental Material[1]) and is thus a craton-transecting structure. Previous work on the MSZC (Bickle et al., 1980; Zegers et al., 1998; Van Kranendonk and Collins, 1998) assessed the geometry, ages, and kinematic features, defining the MSZC as a major ~8-km-wide, N-NE–striking sinistral-slip shear zone, with kinematic indicators including rotated porphyroclasts, S-C fabrics, and rotation of pegmatitic dikes (Zegers et al., 1998) documenting ductile sinistral motion between 2.95 and 2.93 Ga (Fig. 2). Geological evidence indicates that the shear zone has had a long-lived history and these younger structures reactivate older structures, with a history extending to ca. 3.27 Ga (White et al., 1997; Zegers et al., 1998) or even 3.42 Ga (Wijbrans and McDougall, 1987; Beintema, 2003). Sediments of the Lalla Rookh basin, deposited in

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[1] Supplemental Material. Supporting geophysical data. Please visit https://doi.org/10.1130/GEOL.S.XXXX to access the supplemental material; contact editing@geosociety.org with any questions.

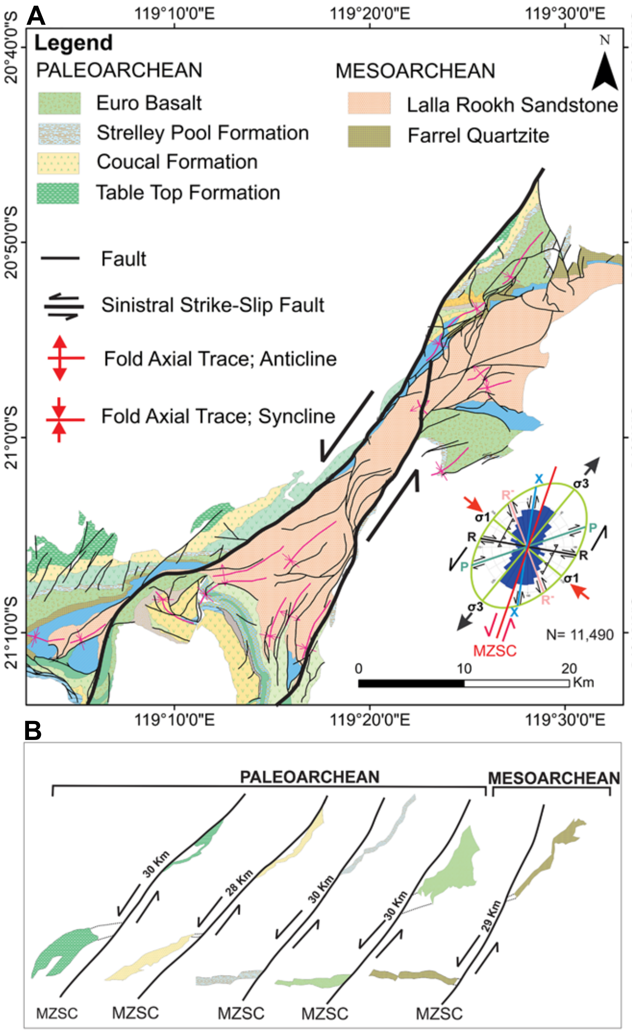

Figure 2. (A) Map of the Lalla Rookh segment of the Mulgandinnah shear zone complex (MSZC), showing associated faults and transpressional folds. Drawn from Hickman (2021) database. Inset shows rose-diagram of measured brittle structures on the Woodcock and Schubert (1994) transpressional strain plot, indicating sinistral motions. (B) Details of offsets of specific units. See Figure 1 for location.

a transpressional restraining-bend thrust basin along the MSZC (Kusky et al., 2021), have ages of 3.00–2.96 Ga (Krapez and Barley, 1987), showing sinistral motion on the MSZC at least back to 3.0 Ga. The 3.27–3.22 Ga adamellites of the Cleland Supersuite in the Carlindi Dome and ca. 3.45 Ga tonalite sheets of the Callina and Tambina Suites on the north margin of the Shaw dome may have intruded into extensional jogs during early motions on strands of the MSZC (Zegers et al., 1998; Kusky et al., 2021), indicating a long-lived history of translation along the fault system.

We integrated high-resolution magnetic data sets and detailed geologic measurements (compiled from Hickman, 2021; Supplemental Material) to investigate macro-kinematic features, including offset markers (Fig. 2) and Riedel shear analysis, and determined the lateral displacement along the MSZC, as a prelude to making a palinspastic restoration of the Pilbara craton during the Paleo-Mesoarchean period. We used high-resolution magnetic data sets to delineate shallow and deep structures and link them with surface geology to clarify and validate the results (Figs. S2–S4). Our compilation of structural information from the 1:100,000 geology map (Hickman, 2021) was compared with new information from the magnetic data sets. We collected all the fault information and created a frequency-weighted rose diagram (Fig. S4B) to identify the dominant azimuth frequency of the fault structures, showing that the dominant fault trend is NNE across the width of the entire deformation zone, followed by N, NW, and ENE directions. The spatial pattern of the fault system can be clarified using a sinistral simple-shear tectonic model (Woodcock and Schubert, 1994). The regional stress field is characterized by a compressive NW-SE maximum horizontal stress (Blewett, 2002); thus, the dominant system of NNE-trending faults is interpreted as secondary synthetic sinistral P-shear fractures, and the N-trending lineaments are interpreted as synthetic sinistral R-shear fractures. The NW-trending lineaments can be interpreted as antithetic dextral R′-shear fractures, and the ENE-trending lineaments are interpreted as secondary antithetic dextral X-shear fractures (Fig. 3).

The 1:100,000 scale geological map clearly shows sinistral offsets of marker geological units (Fig. 2), with displacements similar to those observed on the magnetic anomaly map. We document lateral displacement (Fig. 2) along the MSZC from the geology map and show ~31 km sinistral offset of Paleoarchean amphibolite of the Coonternuah Subgroup—Table Top Formation; ~28 km sinistral offset of Paleoarchean metafelsic volcanic rocks of the Coonternuah Subgroup–Coucal Formation; ~30 km sinistral offset of Paleoarchean metasediments of Strelley Pool Formation; ~30 km sinistral offset of the Paleoarchean Euro basalt of the Kelly Group; ~29 km sinistral offset of the Paleoarchean Farrel quartzite of the Kangaroo Caves Formation; ~29 km sinistral offset of Mesoarchean metasediments of the Cleaverville Formation; and ~31 km sinistral offset of Mesoarchean metasediment of Lalla Rookh sandstone. The MSZC cuts different ages of lithological units with a documentable sinistral offset of ~30 km, but due to the wide and complex nature of the fault zone, and the similarity of intrusive units, these estimates are conservative for earlier displacements. We regard this as a minimum displacement, as the 8-km-wide shear zone displaces many Paleo-Mesoarchean units but few preserved recognizable distinctive features for quantifying early displacements, as is typical of younger arc-slicing fault systems (Mann, 2012; Şengör et al., 2018).

COMPARISON BETWEEN MSZC AND OTHER ACTIVE AND ANCIENT ARC-SLICING FAULT SYSTEMS

Arc-slicing transform faults form above oblique subduction systems, and partition strain from typical contraction in the forearc-sliver, to translation along the arc-slicing fault, accommodating plate motions between the overriding and subducting plates. As defined by Şengör et al. (2018, p. 457) “arc-slicing faults cut and displace the entire magmatic arc,” whereas arc-shaving faults “displace fragments of magmatic arcs without penetrating into the entire arc structure.” Extant arc-slicing faults are well documented in the Philippine arc system formed above the obliquely subducting Philippine Sea plate (Fig. 3A), where the Philippine fault is slicing the overriding plate and moving more eastward components of the arc system northward relative to those farther west (Aurelio, 2000). Another extant example is the Great Sumatra fault (Fig. 3B), which is slicing the arc system through the arc axis above the obliquely subducting India-Australia plate, translating the frontal arc sliver northward (Mann, 2012). In New Zealand (Fig. 3C), the Alpine and related faults slice the upper plate into several tectonic sections, partitioning oblique convergence between the Australian and Pacific plates into areas of convergence and strike-slip offsets of hundreds of kilometers (Lamb et al., 2016). Interestingly, the scale of the offsets we document on the Mulgandinnah fault system are

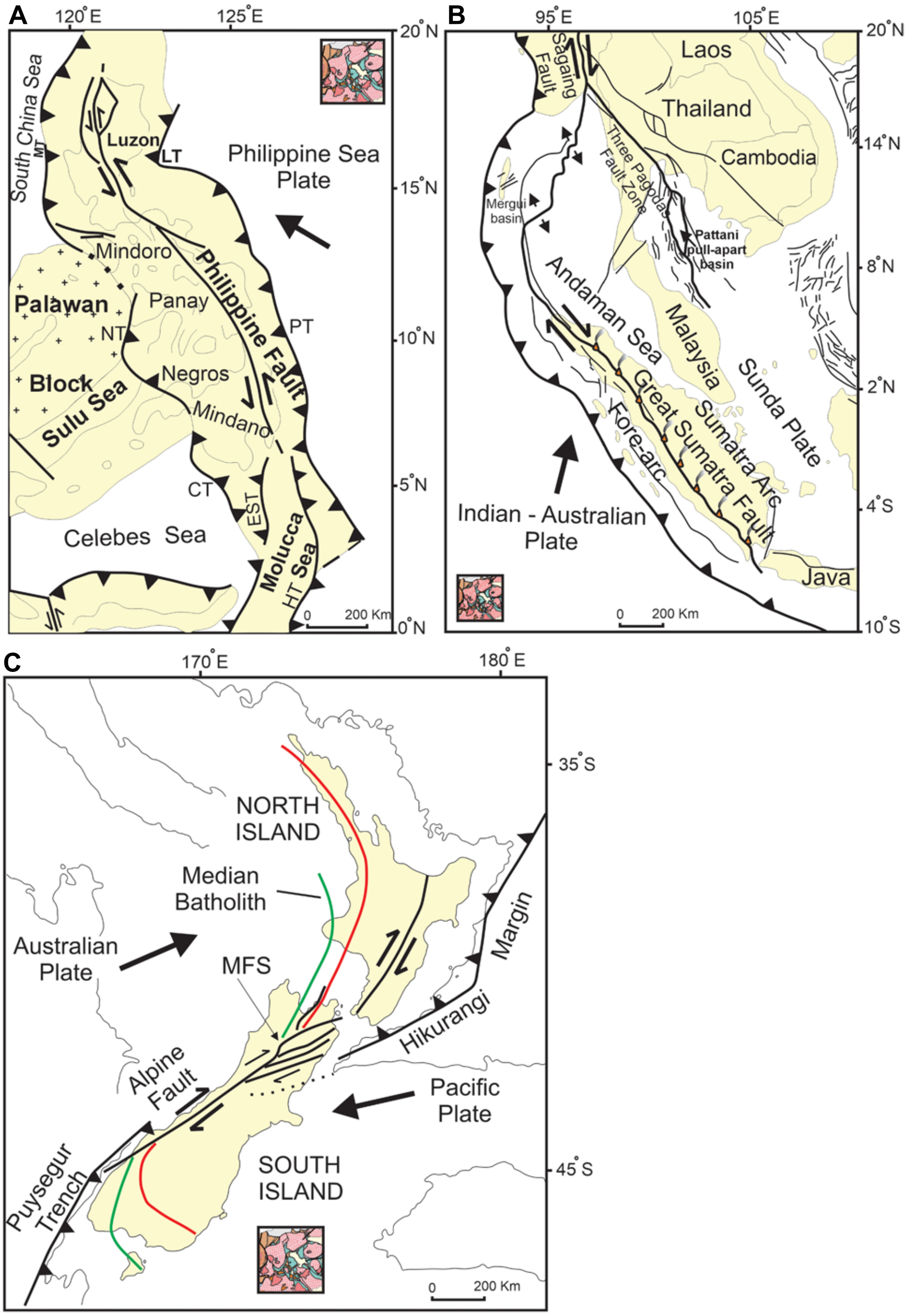

Figure 3. Maps showing extant arc-slicing faults in oblique subduction systems of the (A) Philippine arc (modified from Aurelio, 2000); (B) Sumatra (modified from Mann, 2012); and (C) New Zealand (modified from Lamb et al., 2016). CT—Cotabato Trench; EST—East Sangihe Thrust; HT—Halmahera Trench; LT—Luzon Trench; MFS—Marlborough fault system; NT—Negros Trench; PT—Philippine Trench. Colorful inset box is a map of eastern Pilbara at the same scale.

similar to those of the Marlborough fault system (MFS on Fig. 3C), part of the Alpine fault zone, partly accommodating the oblique subduction of both the Pacific and Australian plates beneath the island (Lamb et al., 2016).

One of the best documented orogens that gained its present architecture through repetition on arc-slicing faults is the Altaids of central Asia. Here, Şengör et al. (2018) show that the Kipchak and Tuva-Mongol arcs, initially developed in the Ediacaran-Cambrian, were repeated numerous times along many arc-slicing faults through the Paleozoic to form the present orogenic collage of the Altaids. Thus, arc-slicing faults are major contributors to orogenic structure and must be considered in any orogenic reconstruction (e.g., Xiao et al., 2015), and ignorance of their presence or significance can result in incorrect interpretations of prior relationships between presently juxtaposed units.

Figure 4 shows our palinspastic reconstructions of the Pilbara craton from 3.25 Ga to 2.90 Ga. Based on available geologic, geochronologic, and geophysical data, it is clear that the MSZC is a major, crust/lithosphere penetrating structure that separates similar parts of the magmatic core of the Eastern Pilbara, which we previously show is an upper-mid crustal segment of a Mesoarchean arc sequence (Kusky et al., 2021). Like extant arc systems of the Philippines and Sumatra and ancient systems of the Altaids, this arc became sliced through its axis (the weakest part of the system, because of the abundance of melts) and repeated above an oblique subduction system. Regional relationships suggest that the subduction zone was located to the west, beneath the accretionary orogenic wedge of the Western Pilbara terrane, which is cut by numerous arc-shaving faults (TTSZ, SSZ, MSZ, MLSZ, PF: Fig. 1). These show a remarkable similarity to arc-shaving faults in the forearcs of the Altaids (Xiao et al., 2015), producing map patterns similar to those of the entire Pilbara craton (Fig. 1). These similarities suggest the possibly that the Paleo-Mesoarchean Pilbara oblique subduction system was more complex, and like the Altaids, may have involved more than one subducting plate. Since the eastern side of the Pilbara orogen is no longer preserved, our suggestion may be regarded as one potential solution to understanding a complex ancient orogenic system.

Our assessment of the giant MSZC (Fig. 4) is that it is perhaps the world's most-ancient preserved arc-slicing fault, repeating two parts of a once linear orogenic arc system with later events resulting in the preservation of only a 200 × 200 km segment that haphazardly preserves geological and geophysical evidence of its former length. The next oldest reported arc-slicing faults are from the Neoarchean of the Superior and Yilgarn cratons (Kusky et al., 2018). Documentation of this Mesoarchean arc-slicing transform is a key indicator of large-scale horizontal plate motions by 3.0 Ga, and perhaps by 3.42 Ga, consistent with paleomagnetic data from the Pilbara indicating plate motions at modern velocities by 3.25 Ga (Brenner et al., 2022) and evidence for giant subduction earthquakes extending at least to the Paleoarchean (Lamb and de Ronde, 2024). These documented translational motions along a major arc-slicing fault in the Paleo-Mesoarchean demonstrate early operation of plate tectonics and provide no support for a stagnant lid on the early Earth.

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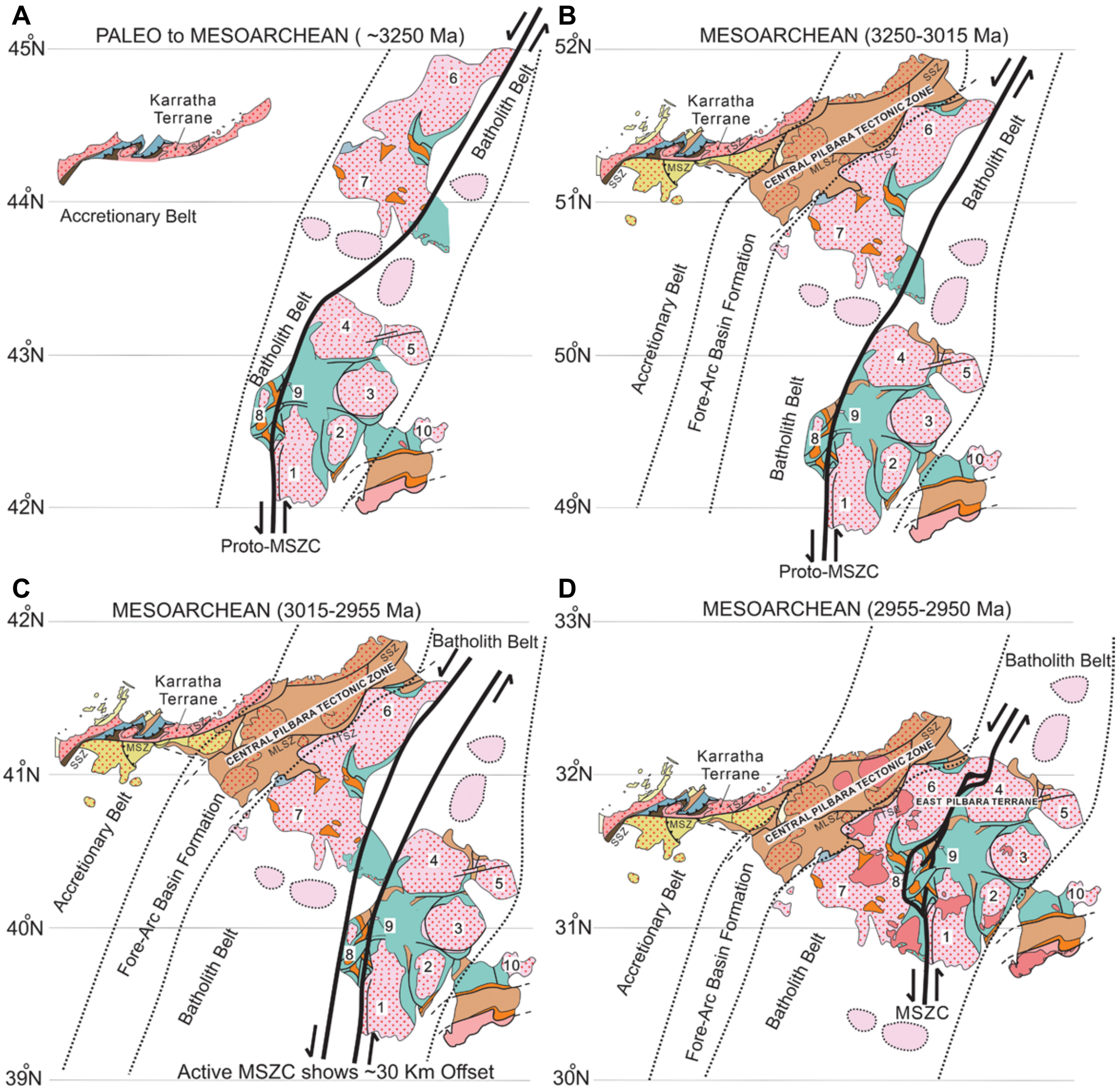

Figure 4. Formation of the present-day preserved Pilbara craton by arc-slicing of a formerly linear magmatic arc batholith belt and outboard accretionary complex, during Paleo-Mesoarchean oblique plate motions. The pink plutonic complex with dashed lines is based on the geophysical interpretation of rocks under younger cover (Supplemental Material; see text footnote 1). MSZC—Mulgandinnah shear zone complex. Names of numbered domes are shown in Figure 1.

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