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Giant sheath-folded nappe stack demonstrates extreme subhorizontal shear strain in an Archean orogen

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ABSTRACT

Giant sheath-folded nappes are associated with suture zones and emplacement of far-traveled allochthons in Phanerozoic orogens, demonstrating a rare but significant geologic phenomenon indicative of modern-style plate tectonics. We document the world's oldest-known subhorizontal mega-scale sheath fold from Archean Alpine-style nappes of the Central orogenic belt, North China craton. The Zanhuang nappes are recumbent Alpine-style forearc-affinity metabasaltic and metasedimentary nappes emplaced over a passive continental margin in the Archean, marking an ancient suture zone. Field evidence shows multiscale sheath folds from decimeters to tens of meters in size, and our three-dimensional fence profile, fold hinges, kinematic lineations, and lithological traces define an ~1-km-long (parallel to the *x*-axis) sheath fold in the core of the nappe stack. Structural analysis statistically demonstrates the macro-scale recumbent sheath-folded nappe preserves a complete 180° hinge-line curvature. The giant sheath fold plunges northwest, reflecting its formation during non-coaxial, top-to-the-southeast shearing with extremely high shear strain ($\gamma \geq 10$), equated to >10 km of ductile slip on the bounding surfaces. Slip vectors derived from S-C fabrics on overturned limbs are consistent with rotation into the southeast-directed transport direction, parallel to the similarly rotated fold hinges. Comparison of the giant sheath-folded nappes from the Archean Zanhuang example with mega-scale sheath folds in Phanerozoic and Proterozoic orogens shows that Neoarchean lithosphere was stiff enough to allow tectonics to operate in a manner analogous to modern-style plate tectonics.

INTRODUCTION

There has been a long-lasting debate on the early Earth's tectonic regime and how long the modern plate-tectonic mode has been in operation (Lenardic, 2018; National Academies of Sciences, Engineering, and Medicine, 2020; Sun et al., 2021). The rarity of diagnostic hallmark features of modern plate tectonics identified in Precambrian basement inevitably hinders reaching geological consensus on whether or not plate tectonics operated on early Earth (e.g., Weller and St-Onge, 2017; Lenardic, 2018; Korenaga, 2021). Giant (mountain-scale) recumbent sheath folds represent a rare geologic phenomenon known to be associated with emplacement of some large allochthonous thrust nappes in Phanerozoic orogens, including beneath the Semail ophiolite (Oman), in several European Alpine examples, and in the Neoproterozoic Lapland-Kola orogen (Baltic Shield) (Cornish and Searle, 2017; Warren et al., 2003; Mudruk et al., 2013). All are associated with suture zones and the emplacement of distant, generally forearc nappes over passive-margin sequences and exhibit large horizontal strain associated with plate-tectonic displacements (Table S1 in the Supplemental Material[1]). We document a pile of kilometer-scale subhorizontal sheath-folded nappes in an Archean orogen and compare it with other well-established large sheath folds globally in orogens of all ages. Large-scale recumbent sheath folds are diagnostic of long-distance (plate tectonic) lateral displacement, and we demonstrate that the same large-scale subhorizontal shear strain and displacements are preserved in Phanerozoic, Proterozoic, and, based on our study, Archean orogens, hinting that those similar structures may have formed by similar processes, under similar conditions, throughout geologic time. Our results are compatible with other evidence for large subhorizontal thrusts, nappes, and displacements in the Archean, especially well documented from Greenland and the Pilbara craton (Western Australia) (e.g., Hanmer and Greene, 2002; Nutman et al., 2020; Kusky et al., 2021b), but this is the first example of a subhorizontal mega-scale sheath-folded nappe pile known from the Archean, adding one more feature of modern-style tectonics to the Archean record.

GEOLOGICAL SETTING

The Archean Zanhuang nappe stack in northern China is one of the most ancient, well-preserved, Alpine-style subhorizontal fold-thrust nappe belts known (Zhong et al., 2021), although remnants or traces of similar orogenic structures have been reported (e.g., Windley et al., 2021). It is situated at the front (foreland) of the Central orogenic belt in the North China craton. The Central orogenic belt is an ~1600-km-long, nearly north-south–trending Neoarchean orogen (Fig. 1A) formed during convergence and collision between an intra-oceanic arc terrane in the west and the ancient continental Eastern block in the east (Kusky et al., 2016, 2020; Wang et al., 2017). The Neoarchean Central orogenic belt exhibits a well-defined tectonic zonation comparable with classical Phanerozoic orogenic belts (e.g., the Cenozoic Austro-Alpine orogen), grading from hinterlands of strongly deformed intra-oceanic arc magmatic rocks through zones of ca. 2.5 Ga ophiolitic-tectonic mélange with local paired metamorphic, high-pressure and ultrahigh-pressure assemblages (Kusky et al.,

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[1]Supplemental Material. Table S1 (global examples of subhorizontal mega-scale sheath folds). Please visit https://doi.org/10.1130/GEOL.S.18823514 to access the supplemental material, and contact editing@geosociety.org with any questions.

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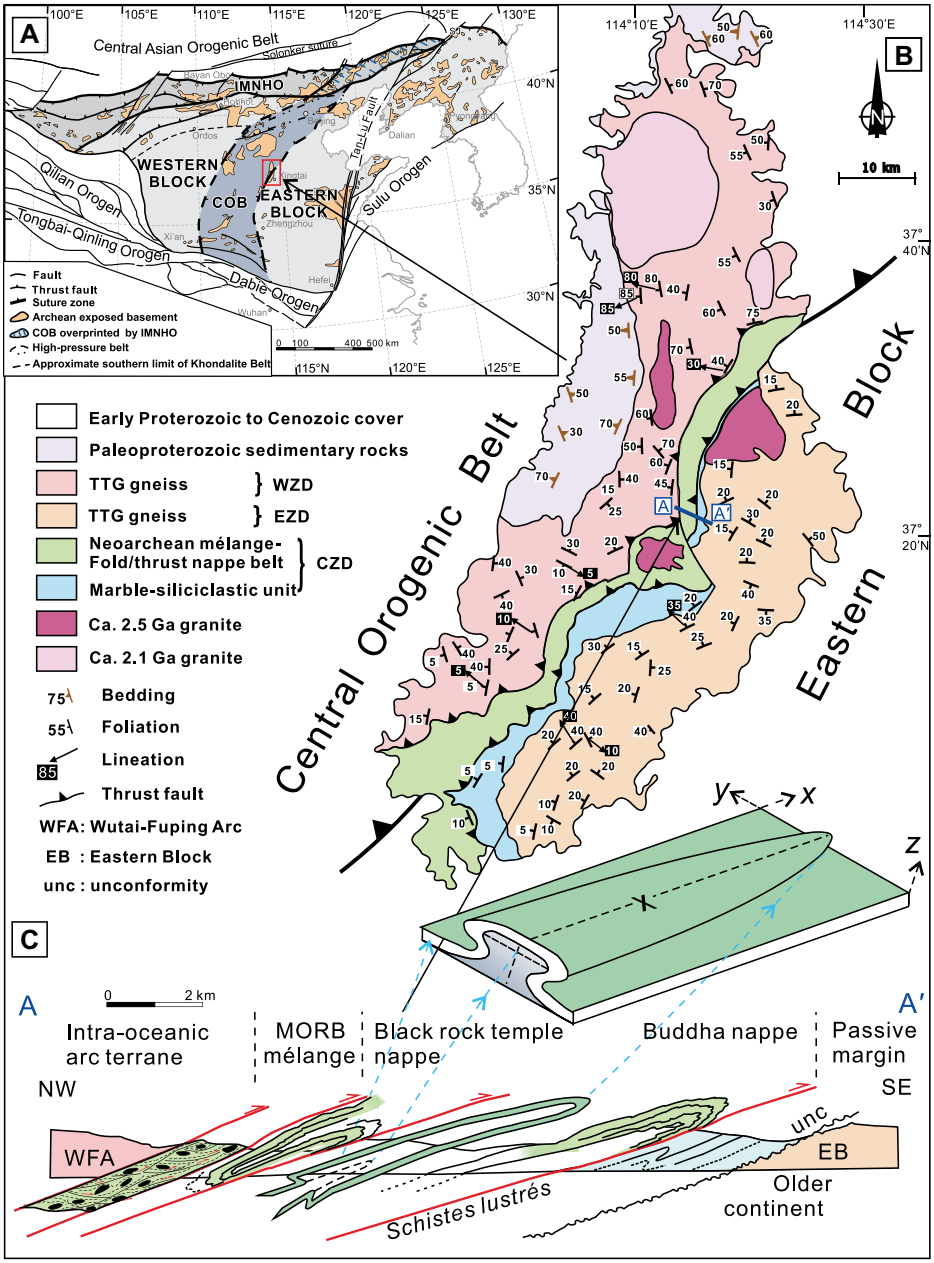

Figure 1. (A,B) Geological map and tectonic setting of the study area, North China craton (modified after Kusky et al., 2016; Wang et al., 2017). (C) Cross section showing Archean fold nappes stacked upon one another, marking suture zone between Wutai-Fuping arc and Eastern block. Giant sheath fold occupies core of nappe stack. Schematic diagram of sheath fold is portrayed based on coordinate system in our fence profile that we adopt for detailed mapping. COB—Central orogenic belt; IMNHO—Inner Mongolia-North Hebei Orogen; TTG—tonalite-trondhjemite-granodiorite; WZD—Western Zanhuang Domain; EZD—Eastern Zanhuang Domain; CZD—Central Zanhuang Domain; MORB—mid-oceanic ridge basalt.

2018; Wang et al., 2019; Huang et al., 2020; Kusky et al., 2020, 2021a) to a 15–20-km-wide belt of ductile fold nappes and thrusts with forearc-affinity assemblages (Zhong et al., 2021) and eventually into a relatively undeformed 2.5 Ga foreland basin now preserved as several relict sequences including the Qinglong and Songshan sequences (2.50–2.45 Ga) (Kusky et al., 2016; Huang et al., 2019). The foreland basin deposits locally overlie passive-margin sediments and the unconformably underlying crystalline basement of the Eastern block of the North China craton (Kusky et al., 2016).

The Archean Alpine-style allochthons form a pile of recumbent fold nappes bearing a classical forearc subduction-initiation sequence (ca. 2.7 Ga mid-oceanic ridge basalt, picritic-boninitic and island-arc tholeiitic basalt) that glided along highly sheared thrust zones to be emplaced over a Neoarchean passive-continental-margin sequence at ca. 2.52 Ga (Zhong et al., 2021). The location of the nappe pile marks the suture zone between the Wutai-Fuping arc and Eastern block continent. Rocks within the suture zone are dominated by intense southeast-directed subhorizontal thrust-sense shear evidenced by the ubiquity of structures including rotated porphyroclasts and/or blasts, S-C fabrics, asymmetric folds and duplex structures, and consistent regional northwest-plunging mineral lineations and southeast fold vergence (Figs. 1C and 2A). The folds are non-cylindrical, extremely tight to isoclinal structures, indicating high strain. The associated deformation is interpreted to have been developed at ca. 2.50 Ga, constrained by (1) geological crosscutting relationships (Wang et al., 2013), and (2) maximum depositional ages from the Alpine-style *schistes lustrés* unit underlying the fold-nappe stack (Zhong et al., 2021).

GEOMETRY OF A MOUNTAIN-SCALE ARCHEAN SHEATH FOLD

Sheath folds are non-cylindrical cone-shaped structures, characterized by highly curvilinear fold hinges (>90°) with parabolic noses and closed layers revealed by elliptical cross sections (eye structures) when viewed perpendicular to the shearing direction (Cobbold and Quinquis, 1980; Alsop and Holdsworth, 2004, 2006; Adamuszek and Dabrowski, 2017). Our detailed structural mapping reveals that mesoscopic elliptical folds are commonly exposed in the mechanically layered Zanhuang fold nappe–thrust belt (Fig. 2A). Tongue-like morphologies with apical angles of ~30°, identified on the *XY* planes of decimeter-scale sheath folds, together with fold hinge lines systematically varying and rotating toward major culminations (Figs. 2B, 2C, and 2D) display the curvilinearity of fold hinges accentuated toward the stretching direction (Fig. 2E). The hinge lines show a 180° rotation from northeast-southwest (orogen parallel) to southeast, parallel to the stretching direction (Fig. 2F).

Macroscopic elliptical folds are shown by cascading fold limbs wrapping around eye-type sheath folds (Fig. 2G) whose fold asymmetry (S- and Z-shaped on opposing fold limbs) viewed on *YZ* surfaces varies systematically, together with reversals in facing associated with the relative position of culminations and/or depressions on the enveloping sheath fold (Figs. 2G and 2H). This geometry of the large-scale sheath structure is corroborated by the lower-hemisphere projection of hinge lines measured along the entire fold nappe–thrust belt, which define a well-developed fold hinge girdle with 180° of hinge-line curvature, plunging northwest, depicting a regional-scale sheath geometry formed by extremely high shear strain in the mechanically stratified sequence (cf. Dell'Ertole and Schellart, 2013) (Fig. 2F) with a top-to-the-southeast shear sense.

Figure 3 is a three-dimensional fence profile based on detailed mapping and analysis of

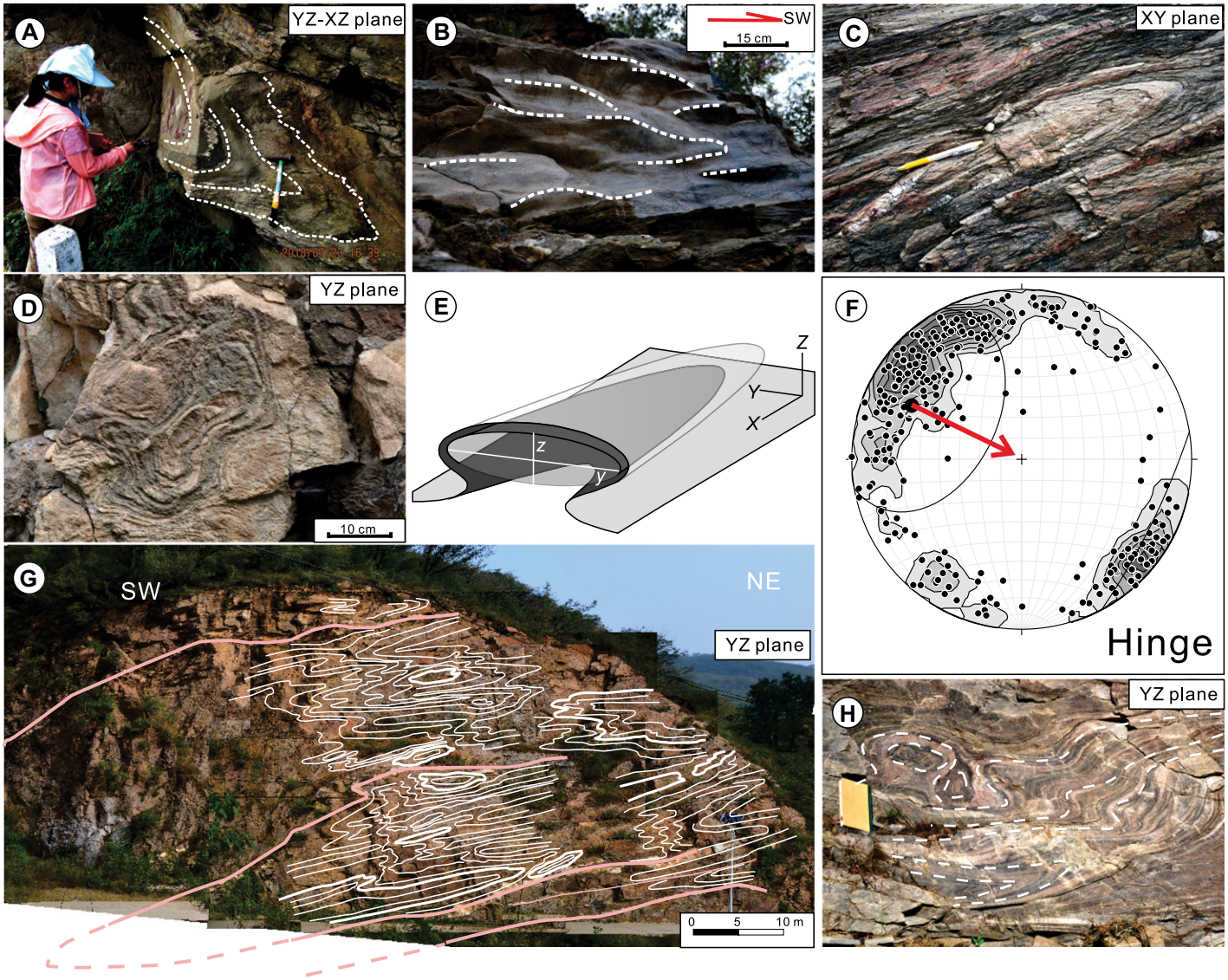

Figure 2. Field photos illustrating views of sheath folds at various scales (Zanhuang nappe stack in northern China). (A) Three-dimensional perspective illustrating conical sheath form. (B) Sheath-fold surface displaying curvilinearity of fold hinges. (C) Curvilinear folds, which are convex up when viewed in inclined (*XY* plane) axial surface. (D) Elliptical "eye-type" shape exposed perpendicular to the long axis of sheath folds. (E) Three-dimensional model and corresponding geometric orientation in (*X*-*Y*-*Z*) coordinate of simple sheath folds. (F) Equal-area plot of fold hinge lines (1% area contour interval) showing a great-circle girdle with 180° of hinge line curvature; large black point represents sheath fold axis about a conical best fit, and red arrow shows transport direction. (G) Transport-normal photograph offering a view of an elliptical fold indicative of a macroscopic sheath fold form marked by white lines; pink lines represent folded quartz vein forming isoclinal recumbent folds wrapping around those sheaths (photo looking northwest, outcrop strike 65°). (H) Fold asymmetry viewed on surfaces perpendicular to the *x*-axis varies systematically, corresponding to discrete fold limbs from a distinct elliptical sheath fold; Ω-shaped sheath fold is shown at top left corner above a notebook (36 cm long).

profiles cutting through the giant sheath fold sequence in various orientations, allowing unique views into the heart of the structure. This technique shows that the structure consists of at least three stacked sheath folds within the larger sheath structure. The ellipsoidal sections are preserved at high angles to the *x*-axis of the sheath fold as shown in Figures 3A and 3B, while recumbent isoclinal anticlines stacked upon one another are exposed subparallel to the *x*-axis as shown in Figure 3D. The doubly verging geometries illustrated on the profiles nearly orthogonal to each other show typical sheath-fold forms, explaining the opposite vergence shown in Figures 3D and 3E. Therefore, the large-scale sheath fold extending for a distance of ~1 km across strike provides a minimum estimate for the length of the (southeast stretching) *x*-axis of the macroscale sheath fold (Fig. 3). Based on comprehensive regional-scale structural analysis, the geometrical similarity between individual and domain-scale sheath folds and mesoscopic- and macroscopic-scale sheath folds implies that sheath folding is common at all scales in the fold nappe–thrust belt and the giant sheath fold mapped here is perhaps just the core of an even larger structure including the entire fold nappe–thrust stack (Fig. 1C).

The regional fold nappes are tight to isoclinal and recumbent with highly attenuated overturned limbs, which typically display S-C fabrics. The sense of shearing, inferred by the S-C fabrics on the reversed limbs of recumbent nappes, shows rotational axes that differ on either side of the main direction of shearing, corresponding to the strain gradient, or strain-rate gradient, during sheath folding and high-strain shearing, with the main transport direction bisecting the curved arc of the S-C intersection lineations (Fig. 4).

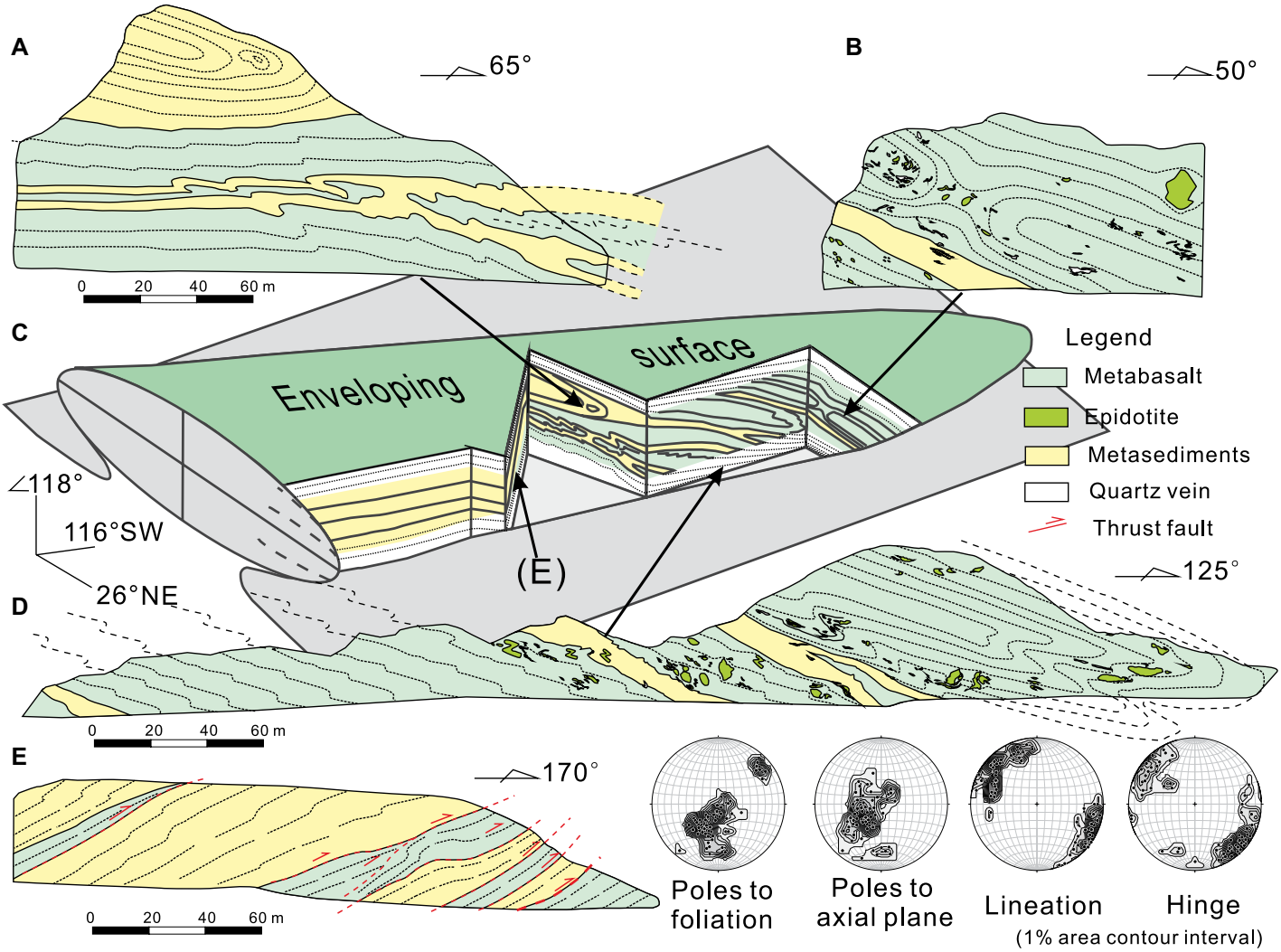

Figure 3. Fence profile cut through a sheath fold sequence in various orientations allowing unique views into the heart of the structure.

Progressive nappe propagation under top-to-the-southeast simple and/or general shear initially led to tight to isoclinal, recumbent fold forms and extreme thinning of rotated overturned limbs of the pile of recumbent folds. Continuous high shear strain further resulted in the base of noncylindrical sheath folds forming recumbent fold nappes at advanced stages and high shear strain ($\gamma \geq 10$). Consequently, the convex-up culmination surface coupled with an antiformal closure is present (Figure 2 showing the real outcrop data, and Figure 4 as a schematic model), on which mineral lineations became discordant with the rotated fold hinges during noncylindrical folding, while the majority formed parallel to the fold axis (*x*-axis). This is indicative of intensive rotation of fold hinges toward the mineral lineation that initiated at a high angle to shear during progressive non-coaxial deformation, and ended up with parallel hinges and mineral lineations (Fig. 4). Slip vectors, determined by the direction on the C-planes oriented 90° from the intersections between S-planes and C-planes, are rotated correspondingly, indicating that the entire nappe system slipped parallel to the fold axis while others slipped clockwise or anticlockwise on either side of the main direction of shearing.

TECTONIC SIGNIFICANCE

Sheath folds are associated with shear zones and indicate exceptionally high strain. They are typically considered to be developed by the rotation of fold hinges toward the transport direction during progressive non-coaxial deformation (Cobbold and Quinquis, 1980; Lacassin and Mattauer, 1985; Carreras et al., 2005; Alsop and Holdsworth, 2006; Dell'Ertole and Schellart, 2013; Adamuszek and Dabrowski, 2017; Maino et al., 2021). Given that large shear strain ($\gamma \geq 10$) is required by the simple shear mechanism, the development of a subhorizontal kilometer-scale sheath fold corresponds to no less than 10 km of subhorizontal displacement in this Archean orogen. This does not account for additional displacements along thin shear zones, which are significant (Zhong et al., 2021).

Giant kilometer-scale sheath folds are rare and mainly reported from high-shear-strain zones in orogenic belts. By compiling case studies of well-known large-scale sheath folds worldwide (Table S1), we show that kilometer-scale sheath folding coincides with collisional processes in a horizontal compressional regime during orogeny, and all known occurrences of large-scale sheath folds are tectonically situated in suture zones marking places where two, once widely separated tectonic blocks (arcs, continents, plateaus, upper-plate ophiolites, etc.) have collided, with the sheath folds forming along the boundaries (sutures) between the different terranes (Cornish and Searle, 2017; Searle and Alsop, 2007; Lacassin and Mattauer, 1985; Seno et al., 1998; Maino et al., 2015; Bonamici et al., 2011; Mudruk et al., 2013). Documentation of large-scale subhorizontal sheath folds essentially demonstrates a long-distance tectonic transport of the allochthonous unit. The case studies (Table S1) verify that other kilometer-scale sheath-fold structures have been documented in younger orogens of all ages, from

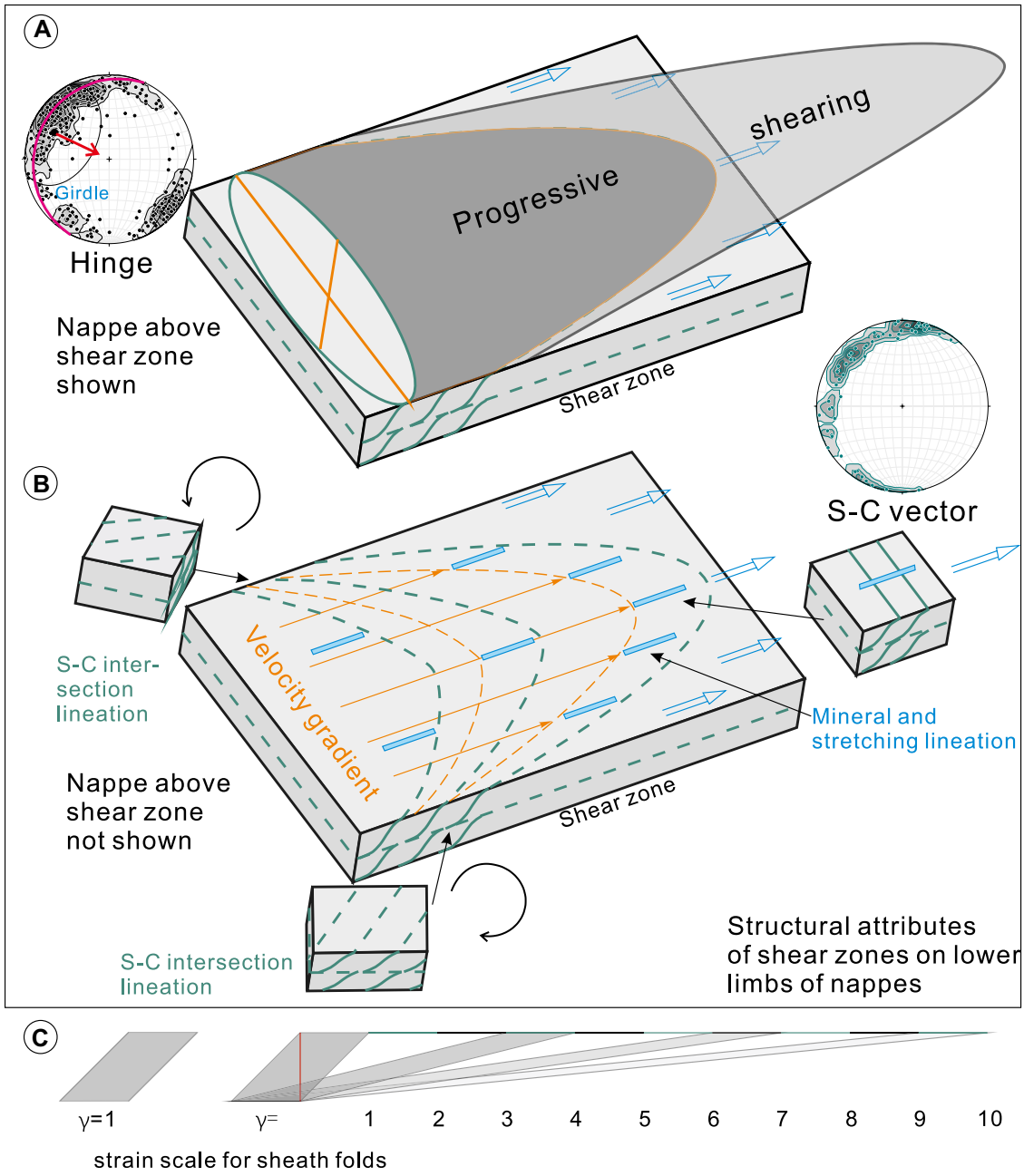

Figure 4. (A,B) Diagrams illustrating the geometric elements of sheath folding during progressive high-strain shearing of the Zanhuang fold nappe stack (north China craton). Velocity gradient is marked by the curvilinearity of hinge rotation toward the transport direction (A). S-C intersection lineation (B) is curved, corresponding to the process of sheath folding, illustrated by the equal-area plot of the S-C vector, which is the direction perpendicular to the intersections the between S- and C-planes on the C-planes, which are rotated systematically about the transport direction (stereonet in B with 1% area contour interval). (C) Strain (γ) from 1 to 10, graphically illustrating that because sheath folds form at γ ≥10 and the sheath fold is ~1 km in scale, structures record subhorizontal displacement of ≥10 km in this zone of the Zanhuang thrust nappe stack.

the Phanerozoic, the Proterozoic, and, with this discovery, now the Archean. It is therefore suggested that crustal-scale lateral motions can be documented back to the Archean and provide positive evidence for the operation of horizontal plate motions in the ancient Earth.

This is the oldest-known giant recumbent sheath-folded nappe in the world that explicitly demonstrates extreme subhorizontal shear strain. The structural style and kinematic evolution restored in this contribution dramatically differ from those suggested in the Archean hot-orogen model (Chardon et al., 2009) by the presence of (1) strain localization along large-scale thrusts in a convergent setting, (2) lateral variation in metamorphic grade, and (3) reversal of structural and stratigraphic successions (Zhong et al., 2021). Additionally, a remarkable long distance (>3500 km) of relative displacement between the arc and continent has been proposed (Zhong et al., 2021). Combined with identification of paired metamorphism in the North China craton (Huang et al., 2020) and of seismic reflection of relict slabs in the Slave and Superior cratons (Canada) (Percival et al., 2012), the evidence for the operation of ancient plate tectonics is compelling.

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