# The Archean Dongwanzi Ophiolite Complex, North China Craton: 2.505-Billion-Year-Old Oceanic Crust and Mantle

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**We report a thick, laterally extensive 2505 ± 2.2–million-year-old (uranium-lead ratio in zircon) Archean ophiolite complex in the North China craton. Basal harzburgite tectonite is overlain by cumulate ultramafic rocks, a mafic-ultramafic transition zone of interlayered gabbro and ultramafic cumulates, compositionally layered olivine-gabbro and pyroxenite, and isotropic gabbro. A sheeted dike complex is rooted in the gabbro and overlain by a mixed dike–pillow lava section, chert, and banded iron formation. The documentation of a complete Archean ophiolite implies that mechanisms of oceanic crustal accretion similar to those of today were in operation by 2.5 billion years ago at divergent plate margins and that the temperature of the early mantle was not extremely elevated, as compared to the present-day temperature. Plate tectonic processes similar to those of the present must also have emplaced the ophiolite in a convergent margin setting.**

Ophiolites are a distinctive association of allochthonous rocks interpreted to form in oceanic spreading centers, back-arc basins, fore arcs, and arcs (*1, 2*). Ophiolites are one of the hallmarks of collisional mountain belts interpreted as marking the sites along which oceanic basins have closed and, therefore, demonstrating lateral motion between plates. The oldest nearly complete ophiolites so far recognized are the 1960-million-year-old (Ma) Jourma Complex, Finland (*3*), and the 1998 Ma Purtuniq ophiolite, Cape Smith Belt, Canada (*4*). The apparent lack of complete or nearly complete ophiolites in the older geological record has prompted theories that plate tectonics may have operated in fundamentally different ways in Earth's early evolution (*5*). However, numerous Archean [>2.5 billion years old (Ga)] greenstone belts contain two or more parts of an ophiolite sequence (*6–8*), which led others to theorize that parts of greenstone belts may be dismembered ophiolites formed in a manner analogous to younger dismembered ophiolites (*8*). We present a field description of a complete Archean ophiolite from the North China craton and discuss the implications of this rock suite for interpretations of Archean tectonics.

The North China craton includes a large area of Archean crust (Fig. 1), with 3.8- to 2.5-Ga gneisses, amphibolites, mica schist, dolomitic marble, banded iron formation, and metaarkose (*9*). The North China craton is divided into two major blocks separated by the Neoarchean Central orogenic belt (Fig. 1, inset). The Zunhua structural belt of the eastern Hebei Province represents the northern extension of the Central orogenic belt and is thrust over the Neoarchean Qianxi granulite facies terrain (2.5 Ga) to the southeast of the Zunhua belt. Amphibolite-grade metamorphism predominates in the eastern Zunhua structural belt (Fig. 1, inset), but granulite facies rocks, including some high-pressure assemblages (11 to 13 kbar at 850° ± 50°C) (*10, 11*) dominate the western part of the belt.

The Dongwanzi ophiolite is located 250 km northeast of Beijing, in Qinglong County, Hebei Province (Figs. 1 and 2). It forms three prominent amphibolite facies mafic-ultramafic complexes in the northeast sector of the Zunhua structural belt, previously mapped as a layered intrusion of amphibolite facies and associated rocks (*12*). The ophiolite dips steeply northwest, is ~50 km long, and is 5 to 10 km wide (Fig. 2). Previous unpublished age estimates [see (*9*) for a review of these data] indicated that the Dongwanzi ophiolite was probably Neoarchean.

The base of the Dongwanzi ophiolite is an early high-temperature shear zone intruded by the 2391 ± 50–Ma (U-Pb zircon) Cuizhangzi diorite-tonalite complex east of Shanying (Fig. 2) (*12*), then deformed again after intrusion of the diorite-tonalite complex. Diorite forms dikes and layer-parallel sills and is strongly deformed. Diorite gradually increases in abundance away from the contact until the ophiolite is only preserved as ultramafic and garnet-amphibolite inclusions in the dioritic to tonalitic gneiss.

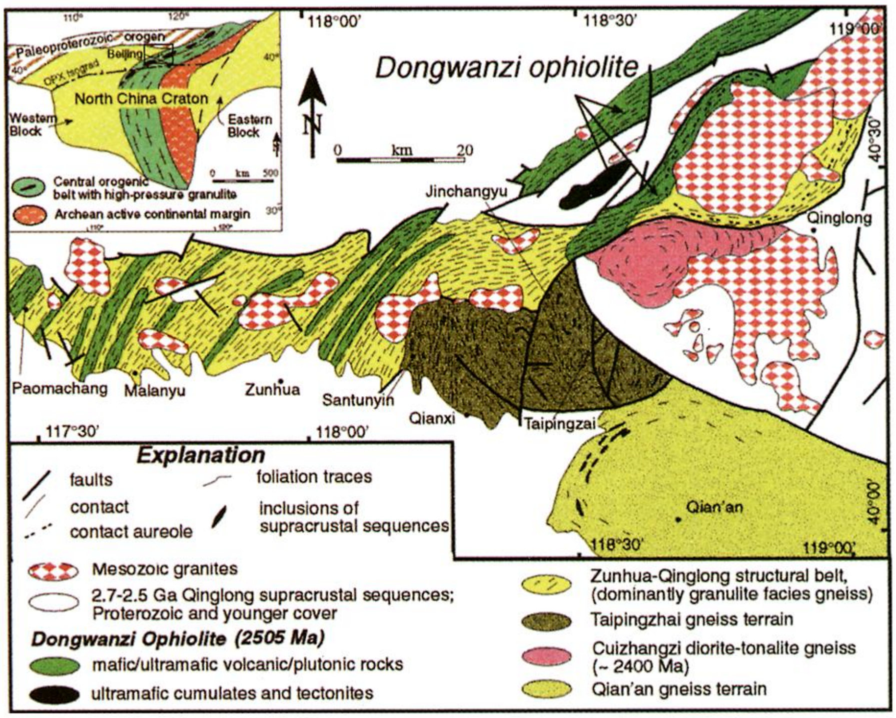


**Fig. 1.** Map of part of the eastern Hebei Province, North China craton, showing the location and tectonic setting of the Dongwanzi ophiolite. There are abundant similar belts of amphibolite-granulite–grade metabasites in the Zunhua structural belt. The inset shows major tectonic divisions of the North China craton, into the western and eastern blocks, Central orogenic belt, and Paleoproterozoic orogenic belt [after (9)].

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Deformed ultramafic rocks are exposed along the base of the Dongwanzi ophiolite (Fig. 2). These rocks include strongly foliated and lineated dunite and layered olivine-orthopyroxene harzburgite tectonite (Fig. 3A), some containing individual septa of olivine and orthopyroxene crystals (Fig. 3B). The pyroxene crystals in the peridotites are commonly aligned, and stringers of opaque phases (chrome-spinel) in dunite probably formed during early mantle deformation. The thickest harzburgite-tectonite section identified to date is a 70-m-thick unit east of the village of Gushanzi [Web fig. 1 (*13*)]. The serpentinized harzburgite tectonite has a moderately south-dipping tectonite fabric, which is cut by a nearly vertical cleavage. Deformation bands marked by centimeter-thick layers of elongate olivine crystals are visible in the outcrop. The strong foliation shows that this unit is more highly deformed than are overlying units. The harzburgite contains orthopyroxene, in contrast to clinopyroxene-dominated units in the crustal section, and preserves evidence for early high-temperature deformation. We therefore interpret this as the lower, residual mantle part of the ophiolite, from which the overlying magmatic rocks were extracted.

The lower part of the cumulate mafic-ultramafic complex [Web fig. 1 (*13*)] consists of orthocumulate pyroxenite, dunite, and minor wehrlite; lherzolite; websterite interlayered with olivine-pyroxene gabbro; and olivine gabbro–layered cumulates. Many layers grade from a dunite base up into wehrlite and clinopyroxenite tops. Thin layers and disseminated crystals of chrome-spinel are present but relatively rare [Web fig. 1 (*13*)]. The upper sections of the gabbro and mixed cumulate gabbro and ultramafic parts of the ophiolite consist of ~50% coarse-grained gabbro and ~50% pyroxenite [Web fig. 2A (*13*)]. This unit represents the transition zone between mafic rocks above and ultramafic cumulates and depleted mantle below [Web fig. 1 (*13*)]. Cumulate layers are locally cut by basaltic dikes that are of unknown age but are mineralogically and texturally similar to dikes at higher levels of the ophiolite. The leucogabbro is locally strongly foliated, and the gabbro at this level contains many centimeter- to meter-scale pods of ultramafic rocks.

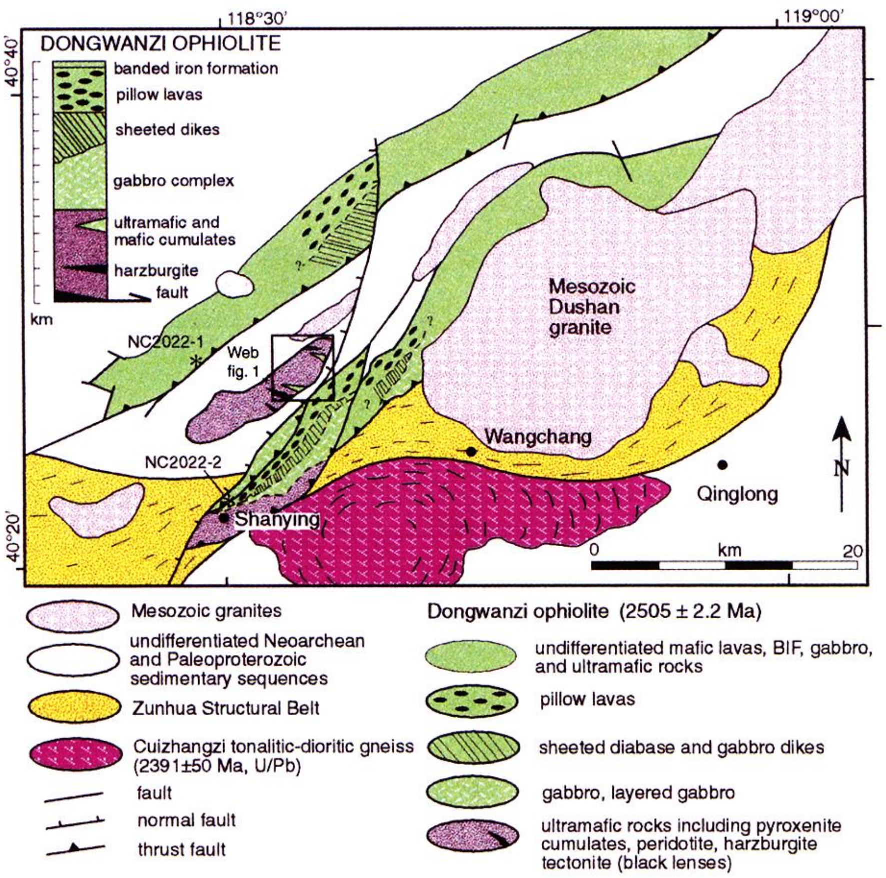


**Fig. 2.** Reconnaissance map of the Dongwanzi ophiolite, showing belts of pillow lavas, sheeted dikes, gabbro complex, cumulate ultramafic rocks, and harzburgite tectonite. The column to the top left shows the thickness of units on the basis of map patterns. The Dongwanzi ophiolite is intruded by the (deformed) ~2.4-Ga Cuizhangzi gneiss (*12*). We have obtained a U-Pb zircon age of 2505 ± 2.2 Ma for gabbro from the Dongwanzi ophiolite (sample locations shown by an asterisk). Sites NC2022-1 and NC2022-2 show locations of geochronology samples. Question marks indicate approximate boundaries of mapping where internal units of ophiolite have been delineated.

The gabbro complex of the Dongwanzi ophiolite is up to 5 km thick (calculated from the dip of layering and the map thickness of the unit). It grades upward from the mafic-ultramafic transition zone of mixed layered gabbro and cumulate ultramafic rocks into strongly layered gabbro (Fig. 3C), then faintly layered gabbro [Web fig. 2B (*13*)], and finally isotropic gabbro. The layering in the gabbro ranges from several-centimeter-thick discontinuous layers, through decimeter-thick layers, to faint layers on the order of several meters thick. The layers include centimeter- to meter-thick alternations between clinopyroxenite and anorthosite. In some locations in the thinly layered gabbro, where the layering is on the order of several centimeters thick, the gabbro exhibits folds that could be slumps resulting from layers that accumulated along the walls or sides of the magma chamber sliding down to the chamber floor. Thin, relatively homogeneous gabbro dikes a few centimeters to decimeters thick intrude the layered gabbro at small angles to the compositional layering, and pods of gabbro-pegmatite occur locally.

The sheeted dike complex of the Dongwanzi ophiolite is at least 5 km long and 2 km thick and may extend in length for >20 km (Fig. 2). The Dongwanzi dike complex exhibits diabase dikes that are chilled predominantly on their northeast sides but are intruded by other dikes along their southwest margins [Fig. 3D and Web fig 2, C and D (*13*)]. Most of the dikes in the sheeted complex exhibit one-way chilling. Gabbro screens, forming remnants of the rocks into which the sheeted dikes intruded, are also common in the dike complex, with diabase dikes exhibiting double- and single-chill margins chilled against the gabbro [Fig. 3D and Web fig. 3 (*13*)]. The number and thickness of gabbro screens generally increase downward in the ophiolite, marking a gradual transition from the dike complex into the gabbroic fossil magma chamber (Fig. 2). In many locations, the gabbro also exhibits dike structures, with coarse-grained gabbro becoming finer grained toward chilled margins that also show a preferential one-way chilling along their northeast margins and intrusion by other gabbroic dikes along their southwest margins. The gabbro is variable in mineralogy, with some phases being feldspar rich, whereas others show abundant, several-centimeter-long crystals of clinopyroxene. Trondhjemite occurs as amorphous pods in the gabbro and diabase dike complex and also as veins along contacts between some dikes.

Diabasic dikes commonly cut the gabbro, but in places, gabbro also cuts and includes xenoliths of diabasic dikes, which suggests that the gabbro and diabase are comagmatic phases and that both are related to magmatic extension. Numerous thin discontinuous diabase veins anastomose through coarser grained gabbro near the base of the sheeted dike complex, which suggest that the diabase intruded a crystal-liquid mush. The gabbro and diabase dike complex is cut by abundant epidote and clinozoisite veins, similar to veins formed from the interaction of seawater with magmatic fluids in other ophiolites (*14*).

The upper part of the Dongwanzi ophiolite consists of pillow lavas, pillow tubes, pillow breccias, interflow chert, banded iron formation, and metapelite (Fig. 2). Thick units of banded iron formation are located near the stratigraphic top of the ophiolite, but structural complications preclude determination of whether they are part of the ophiolitic sequence. The pillow lavas, pillow breccias, and interpillow sediments are altered to chlorite schists, and most are deformed. Pillows are in many cases difficult to recognize and are also interbedded with more massive flows or sills. Where well preserved, the pillows show cuspate lower boundaries and lobate upper contacts, defining stratigraphic younging (Fig. 3E). In many places, pillows are delineated by 2- to 3-cm-thick epidote-rich selvages surrounding fine-grained 0.5- to 1.0-m-wide pillow cores.

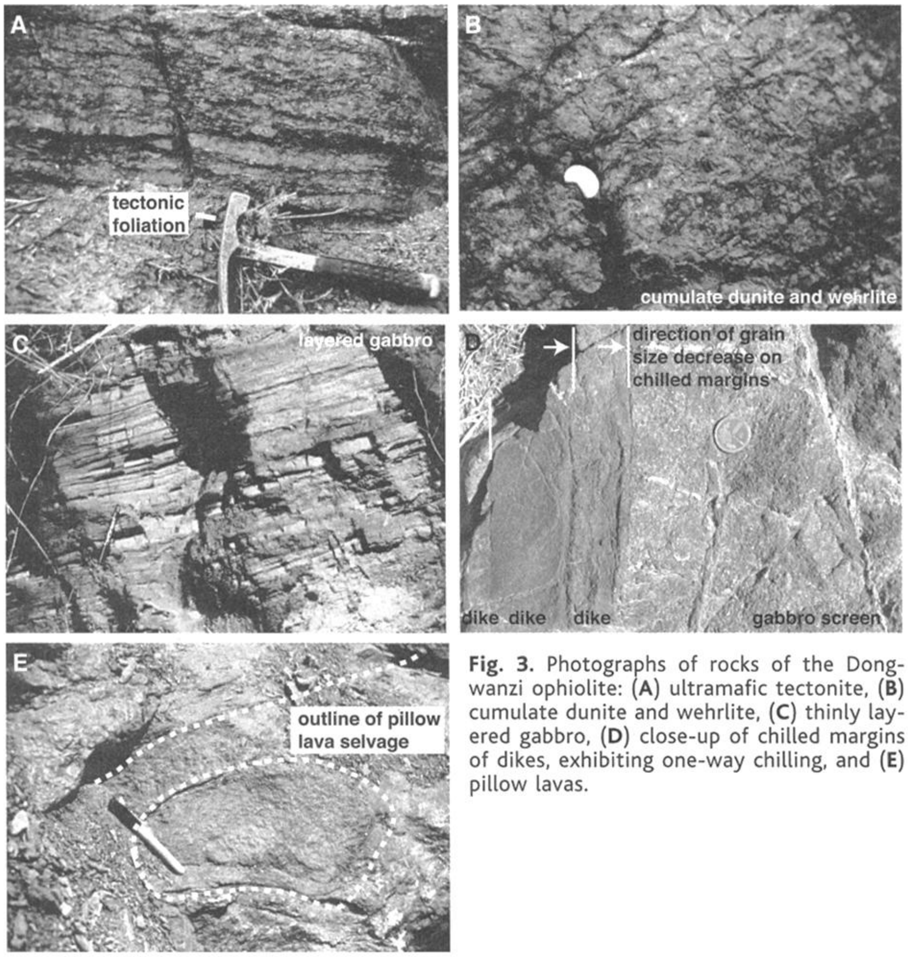


**Fig. 3.** Photographs of rocks of the Dongwanzi ophiolite: (**A**) ultramafic tectonite, (**B**) cumulate dunite and wehrlite, (**C**) thinly layered gabbro, (**D**) close-up of chilled margins of dikes, exhibiting one-way chilling, and (**E**) pillow lavas.

The upper contact of the main thrust sheet containing the Dongwanzi ophiolite is a fault but is in part Proterozoic or younger, as pillow lavas of the ophiolite are imbricated with Paleo-Mesoproterozoic quartzites of the Changcheng system. Regional relations show that this is a Mesozoic deformation belt (*9*, *15*).

Two samples of gabbro were collected from the Dongwanzi ophiolite for U-Pb zircon geochronology. The samples were collected from widely separated localities (Fig. 2), with the idea being that if the belt is ophiolitic, then the samples should have similar crystallization ages. Sample NC2022-1 is from the base of the northwestern thrust sheet (40°26′05.1″N, 118°29′41.2″E) and is a coarse-grained foliated leucogabbro, with visible compositional layering and ultramafic pods in outcrop. Clinopyroxene grains are mostly altered to hornblende. Sample NC2022-2 is from a gabbro at the top of the southeastern sheet (40°22′26.2″N, 118°29′43.8″E) and is a dark, highly deformed gabbro with broken feldspars and aligned hornblende (after clinopyroxene). Zircons from both samples consist of pale pink and clear rounded prisms.

Six zircon grains were separated, abraded, and analyzed [Web table 1 (*13*)] in a VG Sector-54 mass spectrometer (*16*). The age of gabbro sample NC2022-1 was established by four analyses of single prismatic zircon grains [fractions 1 through 4 in Web table 1 (*13*)], three of which are concordant and define a weighted mean $^{207}Pb/^{206}Pb$ age of ~2504 Ma. The $^{207}Pb/^{206}Pb$ ages of two other zircon analyses from NC2022-2 are indistinguishable from analyses 1 through 4, and thus, all six analyses are regressed together to yield a Concordia plot indicating an age of 2505 ± 2.2 Ma for the Dongwanzi ophiolite (Fig. 4).

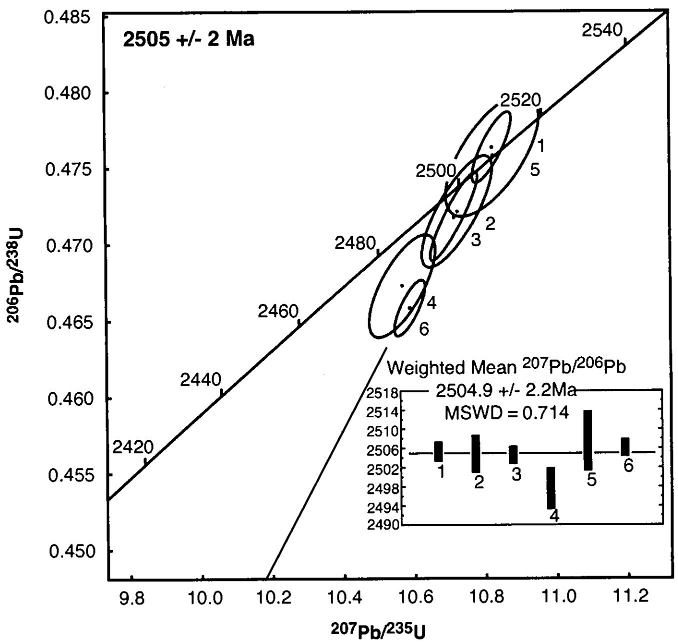


**Fig. 4.** Concordia plot of zircons from the Dongwanzi ophiolite gabbros, showing an age of 2505 ± 2.2 Ma for the ophiolite. MSWD, mean square weighted deviation.

Despite the presence of dismembered and partial Archean ophiolites in some greenstone belts (*8*), no complete and laterally extensive Archean ophiolites had been previously described from the geologic record, leading some workers to conclude that the Archean tectonic style was fundamentally different than that from younger times (*5*). The 50-km-long and 5-km-wide 2505 ± 2.2–Ma Dongwanzi ophiolite is the oldest recognized complete Archean ophiolite described from the geological record. The Dongwanzi ophiolite is identified on the basis of field data, consistent with the original definition and classical use of the term (*1*). As such, we interpret the ophiolite as representing a sample of oceanic crust and mantle, and we offer the following observations of regional relations that bear on the specific tectonic environment.

The Dongwanzi ophiolite forms a steeply northwest-dipping, northwest-facing sequence, in structural contact with underlying and overlying units. The ophiolite is located at the eastern edge of the Zunhua structural belt, interpreted as the Neoarchean suture between the eastern and western blocks of the North China craton (*9*). The eastern block has a Neoarchean magmatic arc built on its western margin, with the Zunhua belt in a structural position analogous to Phanerozoic accretionary wedges built on the edges of contemporaneous arcs. The Dongwanzi ophiolite and related rocks therefore likely represent fore-arc ophiolites formed in a suprasubduction zone setting or oceanic slivers accreted in the accretionary wedge and then thrust over the eastern block during collision of the eastern and western blocks of the North China craton.

The Dongwanzi ophiolite has a substantially thicker crustal section than that of younger ophiolite sequences (Fig. 2), suggesting that slightly higher mantle temperatures may have led to higher degrees of partial melting in the Archean mantle, forming thicker oceanic crust. The Dongwanzi ophiolite and similar Archean greenstone sequences provide important constraints on the thickness, thermal structure, chemistry, and petrogenesis of oceanic lithosphere in the Archean and offer rare insights for understanding heat loss mechanisms from early Earth.

### References and Notes


1. Anonymous, *Geotimes* **17**, 24 (1972).
2. L. M. Parson, B. J. Murton, P. Browning, Eds., *Geol. Soc. Spec. Publ. London* **60**, 1 (1992).
3. A. Kontinen, *Precambrian Res.* **35**, 313 (1987).
4. D. J. Scott, H. Helmstaedt, M. J. Bickle, *Geology* **20**, 173 (1992).
5. M. J. Bickle, E. G. Nisbet, A. Martin, *J. Geol.* **102**, 121 (1994).
6. G. D. Harper, *Ophioliti* **10**, 297 (1985).
7. M. J. de Wit, R. A. Hart, R. J. Hart, *J. Afr. Earth Sci.* **6**, 681 (1987).
8. T. M. Kusky, A. Polat, *Tectonophysics* **305**, 43 (1999).
9. J. H. Li, X. L. Qian, X. N. Huang, S. W. Liu, *Acta Petrol. Sin.* **16**, 1 (2000).
10. J. H. Li, A. Kröner, X. L. Qian, P. O'Brien, *Acta Geol. Sin.* **274**, 246 (2000).
11. R. Y. Zhang, B. L. Cong, *Sci. Sin.* **25**, 37 (1982).
12. Q. C. Wang, S. Q. Zhang, in *Regional Geology of China* (Geological Publishing House, Beijing, 1995), pp. 173–180.
13. Supplemental Web material is available at www.sciencemag.org/cgi/content/full/292/5519/1142/DC1.
14. G. D. Harper, *Rev. Econ. Geol.* **8**, 53 (1999).
15. G. A. Davis *et al.*, in *The Tectonic Evolution of Asia*, A. Yin, T. M. Harrison, Eds. (Cambridge Univ. Press, New York, 1996), pp. 253–280.
16. We determined U-Pb zircon ages using methods developed by Krogh (*17, 18*), with modifications described in (*19*). Pb and U were loaded on single outgassed Re filaments and analyzed in a VG Sector-54 mass spectrometer by using a single-collector procedure with a Daly photomultiplier detector operating in ion-counting mode. In general, an ion beam between $0.5 \times 10^{-14}$ and $1.5 \times 10^{-13}$ Å was maintained for $^{206}$Pb during data acquisition, and a beam between 0.5 and $1.5 \times 10^{-13}$ Å was maintained for U. Average total procedural blanks of 2 pg of Pb and 0.2 pg of U were maintained during the period of analysis; total common-Pb concentrations for all analyses are reported in Web table 1 (*13*). Initial-Pb corrections used the Pb isotopic composition estimated in (*20*) at the indicated age of the rock. In nearly all cases, the uncertainty in the amount of and composition of common Pb calculated in this manner represents an insignificant contribution to the error of the calculated ages. Error propagation is similar to that developed in (*21*), and age errors are reported at 95% confidence limits. Analytical reproducibility at $1\sigma$ confidence levels of replicate samples confirms that the parameters used in data reduction (laboratory blank, fractionation, and Daly mass discrimination) and their errors have been evaluated correctly.
17. T. E. Krogh, *Geochim. Cosmochim. Acta* **37**, 485 (1973).
18. ———, *Geochim. Cosmochim. Acta* **46**, 637 (1982).
19. R. D. Tucker *et al.*, *Earth Planet. Sci. Lett.* **158**, 175 (1998).
20. J. S. Stacey, J. D. Kramers, *Earth Planet. Sci. Lett.* **26**, 207 (1975).
21. K. R. Ludwig, *Earth Planet. Sci. Lett.* **46**, 212 (1980).


22. Funding and support were provided by the Chinese National Natural Science Foundation, Academica Sinica, Peking University, St. Louis University, and Washington University. We thank X. Huang and Z. Zhang for assistance in the field and Z. X. Peng for assistance with the mass spectrometry and geochronology sample preparation.

30 January 2001; accepted 26 March 2001


# Simultaneous Rupture Along Two Conjugate Planes of the Wharton Basin Earthquake


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**Analysis of broadband teleseismic data shows that the 18 June 2000 Wharton Basin earthquake, a moment magnitude 7.8 intraplate event in the region of diffuse deformation separating the Indian and Australian plates, consisted of two subevents that simultaneously ruptured two near-conjugate planes. This mode of rupture accommodates shortening by a mechanism different from that previously known elsewhere in the region. The larger subevent occurred on a fossil fracture zone, with a relatively high stress drop of about 20 megapascals, showing that large stresses can accumulate in regions of distributed deformation.**


Plate motions in the Indian Ocean have been shown to be inconsistent with a rigid Indo-Australian plate (*1*). Additional diffuse boundaries splitting this plate into Indian, Australian, and Capricorn plates have been proposed (*2, 3*). The unexpectedly large earthquake under study here was located just west of the Investigator Fracture Zone (IFZ) (Fig. 1) in the Wharton Basin, near the southern edge of the region of deformation separating the Indian and Australian plates, and is far from all major plate boundaries. We use the term "intraplate" to refer to earthquakes that are not directly associated with the major plate boundaries. The earthquake occurred in a relatively old portion (~65 million years old) (*4*) of the oceanic crust. The general region is characterized by diffuse intraplate seismicity, mostly with earthquakes of magnitude <6, and no large earthquake has previously been recorded near the epicentral region. On the basis of the disturbance to the sedimentary cover obtained from sonar imagery combined with other available geophysical data, the region ~1000 km to the northwest of this earthquake has been inferred to be deforming predominantly along long N-S–trending left-lateral strike-slip faults (*5*). We recognize the long N-S features seen in the bathymetry between the Ninetyeast Ridge (90ER) and the IFZ, which includes the epicentral region, as fossil transform faults (*4, 5*). The compressional axes of earthquakes between longitudes of 90° and 100°E are consistently oriented NW-SE (Fig. 2), indicating that the intraplate stresses in this region are primarily inherited from the India-Asia collision. The long-wavelength (150 to 300 km) undulations seen in the gravity field, trending NE-SW in the Wharton Basin, have been proposed to indicate NW-SE shortening (*2*).

Most of the relocated aftershocks [see section 1 of Web material (*6*)] form a linear zone of ~110 km in length, trending ~345° (Fig. 3), suggesting that rupture occurred on a plane with


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