GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G47070.1

Manuscript received 17 May 2019
Revised manuscript received 4 October 2019
Manuscript accepted 14 October 2019

Published online 19 November 2019

Plate-tectonic processes at ca. 2.0 Ga: Evidence from >600 km of plate convergence

An Yin[1]*, Günther Brandl[2] and Alfred Kröner[3†]
[1]Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California 90095-1567, USA
[2]Council for Geoscience, Limpopo Unit, Polokwane 0700, South Africa
[3]Department of Geosciences, University of Mainz, D-55099 Mainz, Germany, and Beijing SHRIMP Center, Chinese Academy of Geological Sciences, Beijing 100037, China

ABSTRACT

We addressed when plate-tectonic processes first started on Earth by examining the ca. 2.0 Ga Limpopo orogenic belt in southern Africa. We show through palinspastic reconstruction that the Limpopo orogen originated from >600 km of west-directed thrusting, and the thrust sheet was subsequently folded by north-south compression. The common 2.7–2.6 Ga felsic plutons in the Limpopo thrust sheet and the absence of an arc immediately predating the 2.0 Ga Limpopo thrusting require the Limpopo belt to be an intracontinental structure. The similar duration (~40 m.y.), slip magnitude (>600 km), slip rate (>15 mm/yr), tectonic setting (intracontinental), and widespread anatexis to those of the Himalayan orogen lead us to propose the Limpopo belt to have developed by continent-continent collision. Specifically, the combined Zimbabwe-Kaapvaal craton (ZKC, named in this study) in the west (present coordinates) was subducting eastward below an outboard craton (OC), which carried an arc equivalent to the Gangdese batholith in southern Tibet prior to the India-Asia collision. The ZKC-OC collision at ca. 2.0 Ga triggered a westward jump in the plate convergence boundary, from the initial suture zone to the Limpopo thrust within the ZKC. Subsequent thrusting accommodated >600 km of plate convergence, possibly driven by ridge push from the west side of the ZKC. As intracontinental plate convergence is a key modern plate-tectonic process, the development of the Limpopo belt implies that the operation of plate tectonics, at least at a local scale, was ongoing by ca. 2.0 Ga on Earth.

INTRODUCTION

The time of onset for plate tectonics on Earth has been hotly debated, with estimates ranging from >4.0 Ga to ca. 0.85 Ga (e.g., Korenaga, 2013; Cawood et al., 2018). The most commonly used proxies of plate-tectonic processes are rock records of subduction-zone–like low geothermal gradients (e.g., Hopkins et al., 2008) and modern-arc geochemical signatures (e.g., Martin et al., 2014). Since non-plate-tectonic models (e.g., Bédard, 2006; Moore and Webb, 2013) could also explain these proxies, determining the onset of plate tectonics on Earth requires direct field-based geological evidence of large-scale (more than hundreds of kilometers) horizontal crustal motion. In order to address this issue, we reexamined the tectonic development of the >600-km-long Limpopo orogenic belt in southern Africa (Fig. 1). Our result shows that modern plate tectonics, expressed as intracontinental plate convergence, occurred on Earth by ca. 2.0 Ga.

GEOLOGICAL SETTING

The Limpopo belt consists mostly of supracrustal assemblages intruded by ca. 3.2 Ga and 2.7–2.6 Ga felsic plutons (e.g., Kröner et al., 2018). These protoliths were penetratively modified by orogen-scale ductile folding, granulite-facies metamorphism, and anatexis first at 2.7–2.6 Ga and later at 2.02 ± 0.02 Ga (Kramers and Mouri, 2011; Brandt et al., 2018). The Limpopo belt of Mason (1973) (also known as the central zone of the Limpopo metamorphic complex) is bounded by the 5–10-km-wide, right-slip Tuli-Sabi and left-slip Palala mylonitic shear zones in the north and south against the northern and southern marginal zones, respectively (Fig. 2). The marginal zones are composed of granulite- to amphibolite-facies granitic-greenstone associations with the metamorphic grades decreasing away from the Limpopo belt (Mason, 1973; van Reenen et al., 2019). Granulite-amphibolite–facies metamorphism occurred at 2.7–2.6 Ga and 2.0 Ga, respectively, in the northern marginal zone, whereas similar high-grade metamorphism appears to have occurred only at 2.7–2.6 Ga in the southern marginal zone (Kramers and Mouri, 2011; van Reenen et al., 2019). Both zones have yielded ca. 2.0 Ga Rb-Sr biotite and feldspar cooling ages, which are in contrast to the 2.7–2.6 Ga Rb-Sr biotite ages obtained from Zimbabwe-Kaapvaal craton (ZKC) rocks outside the marginal zones farther away from the Limpopo belt (van Breemen and Dodson, 1972).

The origin of the Limpopo belt has been attributed to 2.7–2.6 Ga north-south Zimbabwe-Kaapvaal collision (Light, 1982), protracted north-south terrane accretion from 2.7 Ga to 2.0 Ga (Barton et al., 2006), two-stage, glacier-like, gravity-driven ductile flow from east to west at 2.7–2.6 Ga and 2.0–1.8 Ga (McCourt and Vearncombe, 1987; van Reenen et al., 2019), and ca. 2.0 Ga intracontinental transpression (Schaller et al., 1999). A key piece of evidence for the 2.7–2.6 Ga Limpopo orogenic event is the presence of seemingly undeformed 2.7–2.6 Ga plutons (van Reenen et al., 2019), but such an interpretation does not consider the possible role of rheological contrasts among different lithologies in the Limpopo belt in controlling the style and distribution of deformation. A major issue with the existing models is that they all assume the orogen-bounding shear zones to have maintained their original geometry. As shown here,

*E-mail: ayin54@gmail.com
†Deceased on 20 May 2019

CITATION: Yin, A., Brandl, G., and Kröner, A., 2020, Plate-tectonic processes at ca. 2.0 Ga: Evidence from >600 km of plate convergence: Geology, v. 48, p. 103–107, https://doi.org/10.1130/G47070.1

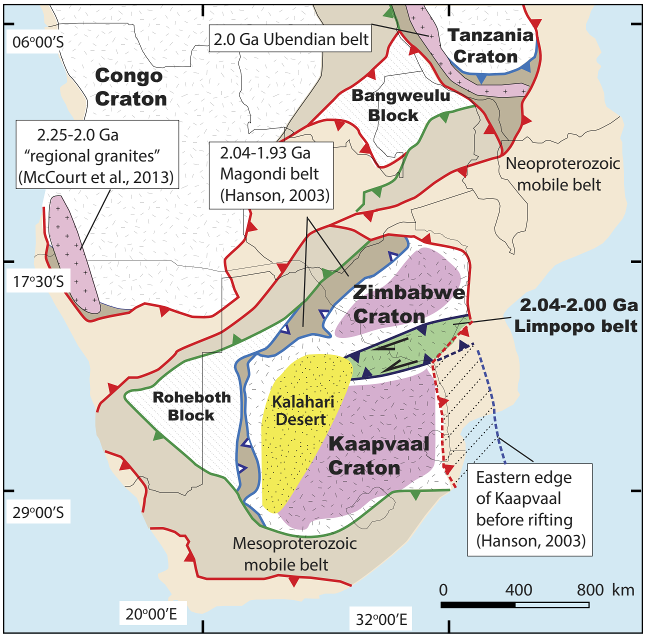

Figure 1. Tectonic map of southern Africa, modified from Hanson (2003) and McCourt et al. (2013).

this assertion is inconsistent with the regional geologic relationships, which require the orogen to have been tightly folded by later compression.

POSTOROGENIC FOLDING OF THE LIMPOPO OROGENIC BELT

Four lines of evidence suggest that the Limpopo orogen was folded by north-south compression at ca. 1.97–1.88 Ga (Fig. 1). First, the 1.97–1.88 Ga Blouberg Formation, unconformably resting on top of the Limpopo belt, was folded and then overlain by undeformed ca. 1.88 Ga upper Waterberg Group strata (Figs. 3A and 3B). Rotation of the dominantly vertical Blouberg beds to their original horizontal positions requires the nearby vertical "left-slip" Palala shear zone to have a prefolding subhorizontal geometry with top-to-the-west thrust kinematics. The folding event postdates the youngest cooling age of the Palala shear zone at ca. 1.97 Ma (Schaller et al., 1999) and the youngest detrital zircon age of the Blouberg Formation at ca. 2.04 Ga (Corcoran et al., 2013) but predates a mafic dike intruding the undeformed overlying Waterberg Group strata at ca. 1.88 Ga (Fig. 3A; Hanson et al., 2004).

Second, the lower Waterberg Group, located directly south of the Palala shear zone (unit Ptw in Fig. 2), was also folded by north-south compression between ca. 2.02 Ga and ca. 1.93 Ga (Dorland et al., 2006). This timing is similar to the aforementioned Blouberg folding event (Fig. 3A).

Third, the Limpopo gneissic foliation defines an orogen-scale fold structure (e.g., McCourt and Vearncombe, 1987; see also Fig. 2), expressed by the gneissic foliation oriented at high angles to the orogen-bounding shear zones along the central section of the Limpopo belt, which becomes subparallel to the shear zones approaching the edges of the belt (Fig. 2). Rotation of the nearly vertical gneissic foliation near the orogen margins to a horizontal position would require the nearby bounding shear zones to have had a subhorizontal geometry before orogen-scale folding. This reconstruction is consistent with restoring the folded Blouberg and lower Waterberg strata mentioned above, which places the currently vertical Palala shear zone into a prefolding subhorizontal orientation.

Fourth, gravity and seismic-reflection surveys show that the low-density Limpopo belt lies above the high-density ZKC craton, separated by a synformal thrust with the Tuli-Sabi and Palala shear zones as its surface traces (de Beer and Stettler, 1992). The inferred Limpopo belt thickness above the fault is <8 km (de Beer and Stettler, 1992).

Although our own field observations corroborate the earlier work showing that the Tuli-Sabi (Fig. 3C) and Palala (Fig. 3D) shear zones are right- and left-slip features, respectively, in their current orientations (McCourt and Vearncombe, 1987), contradictory right-slip shear bands in the overall left-slip Palala shear zone were reported locally by Schaller et al. (1999). The minor right-slip indicators, used as the supporting evidence for a right-slip transpressional model of the Limpopo belt (Kramers et al., 2011), could have resulted from postshear folding or development of antithetic structures (Figs. 3E and 3F).

TECTONIC MODEL

Unfolding the currently oriented east-northeast–trending Limpopo belt and the steep bounding Tuli-Sabi and Palala shear zones requires the Limpopo belt to have formed by west-southwest–directed thrusting, placing the Limpopo belt over the ZKC (Figs. 3E and 3F). Because the Limpopo rocks are dominated by supracrustal assemblages in the hanging wall that do not match the granitic-greenstone rocks of the ZKC and the marginal zones in the footwall (Kröner et al., 2018; van Reenen et al., 2019), the total motion on the Limpopo thrust must have exceeded 600 km (Fig. 1). This interpretation raises the question of whether the Limpopo belt was part of the ZKC or a separate craton. For the Limpopo belt to be a separate continent, its collision with the ZKC would require the presence of a magmatic arc immediately predating the ca. 2.0 Ga Limpopo thrust. The absence of such an arc in either the Limpopo belt or the ZKC and marginal zones rules out this possibility. In contrast, the presence of the diagnostic 2.7–2.6 Ga felsic plutons and the records of coeval granulite metamorphism in the hanging-wall Limpopo belt and footwall marginal zones (Kröner et al., 2018; van Reenen

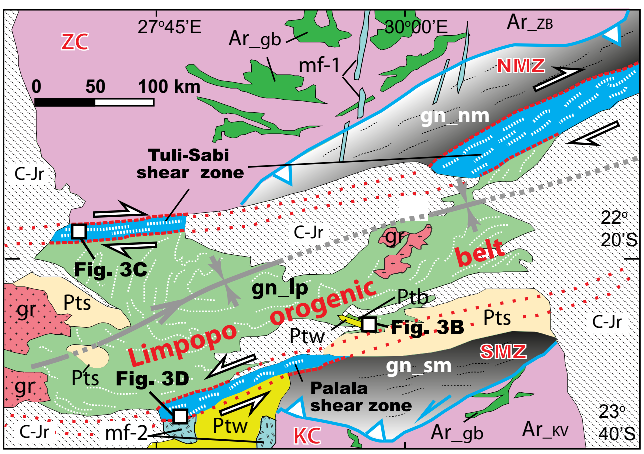

Figure 2. Tectonic map of the Limpopo belt, southern Africa, compiled from Dorland et al. (2006), Kramers et al. (2011), and van Reenen et al. (2019): mf-1—ca. 2.58 Ga Great Dyke; Ar_KV, Ar_ZB, and Ar_gb—Archean granitic gneiss; gn_lp, gn_nm, and gn_sm—metamorphic rocks of the Limpopo belt and northern and southern marginal zones; gr—2.70–2.61 Ga granitic plutons; Ptb, Ptw, and Pts—Paleoproterozoic Blouberg Formation (1.97–1.88 Ga), Waterberg Group (2.02–1.88 Ga), and Soutpansberg Group (1.83–1.6 Ga), respectively; mf_2—ca. 2.0 Ga Bushveld igneous complex; C-Jr—Carboniferous–Jurassic strata; KC—Kaapvaal craton; ZC—Zimbabwe craton; NMZ and SMZ—northern and southern marginal zones of Limpopo metamorphic complex, respectively.

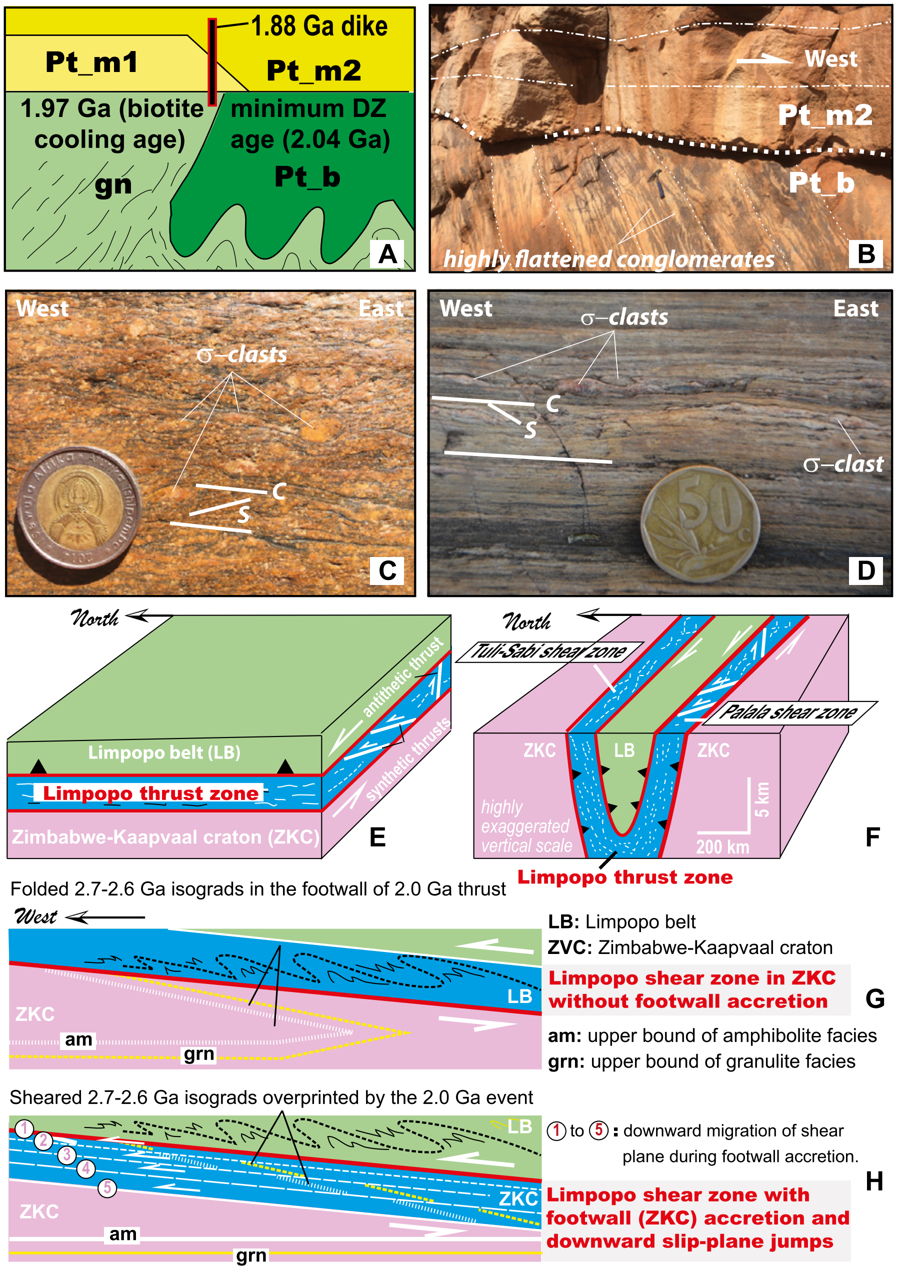

Figure 3. (A) Folded Blouberg Formation below the flat-lying Waterberg Group (southern Africa), with geology from Bumby et al. (2001) and age constraints from Schaller et al. (1999; ca. 1.97 Ga cooling age), Corcoran et al. (2013; ca. 2.04 Ga minimum detrital zircon [DZ] age), and Hanson et al. (2004; ca. 1.88 Ga mafic dike age). Note highly flattened boulder-size clasts in the tilted beds due to intense shortening. Map symbols: gn—Limpopo metamorphic rocks; Pt_b—Paleoproterozoic Blouberg Formation; Pt_m1 and Pt_m2—lower and upper, respectively, Mogalakwena Formation of the Waterberg Group. (B) Field picture of the folded Blouberg Formation (Pt_b) below Waterberg strata (Pt_m2) at 23°09′26.1″S, 29°42′05.6″E. See Figure 2 for general location. Rock hammer for scale is ~70 cm long. (C) Field picture of the Tuli-Sabi shear zone at 21°37′18.8″S, 28°10′49.8″E. See Figure 2 for general location. (D) Field picture of the Palala shear zone at 23°25′00.5″S, 28°12′47.6″E. See Figure 2 for general location. (E) Restored subhorizontal Limpopo thrust zone with synthetic and antithetic shear bands. (F) Folded shear zone displaying opposite senses of shear at local and regional scales. (G) Inverted metamorphism due to footwall folding. (H) Inverted metamorphism due to footwall accretion.

et al., 2019) favor an intracontinental origin for the Limpopo thrust.

We note that the duration (~40 m.y.), slip magnitude (>600 km), slip rate (>15 mm/yr), tectonic setting (intracontinental), and widespread anatexis are all similar to those of the Cenozoic Himalayan orogen (e.g., Yin, 2006). This comparison inspires a Himalayan-style model for the development of the Limpopo belt. During the initial stage (ca. 2.2–2.1 Ga; Fig. 4A), the oceanic domain of the ZKC plate was subducting eastward (present coordinates) below an outboard craton (OC), along which a magmatic arc was constructed. The OC could have been the Congo craton, which exposes a 2.24–2.00 Ga plutonic belt (Fig. 1; McCourt et al., 2013). The ZKC-OC collision closed the intervening ocean and initiated the Limpopo thrust as a new convergence boundary within the ZKC (Fig. 4B). Subsequent rifting, expressed by Paleoproterozoic Blouberg and lower Waterberg deposition, may have been associated with rifting along the ZKC-OC suture (Bumby et al., 2001), leading to OC departure together with the pre-Limpopo arc from the ZKC. The start of this extensional event marked the end of the collision-induced Limpopo thrusting (Fig. 4C). Post-Limpopo collision along the Magondi belt at ca. 1.98 Ga (Fig. 1; Hanson, 2003) reactivated the 2.7–2.6 Ga magmatic belt, which was expressed by crustal-scale folding of the older Limpopo belt (Fig. 4D). Renewed extension across the folded Limpopo belt and its neighboring regions resulted in Paleoproterozoic upper Waterberg Group deposition at ca. 1.93–1.88 Ga (Fig. 4E; Dorland et al., 2006).

DISCUSSION AND CONCLUSIONS

Our Himalayan-style model requires the Limpopo thrust to have acted as an intracontinental plate-convergence boundary. Because intracontinental plate boundaries (e.g., the Himalayan thrust, the Dead Sea fault, and the San Andreas fault) and large-scale crustal motion with magnitudes greater than the thickness of the lithosphere are key expressions of modern plate tectonics (e.g., Cawood et al., 2018), the development of the Limpopo belt requires the operation of modern plate-tectonic processes, expressed as relative motion of rigid lithospheric blocks at ca. 2.0 Ga on Earth.

Our Himalayan-style model explains the location and timing of the observed inverted granulite- to amphibolite-facies metamorphism across the Limpopo marginal zones. In the Himalaya, the apparent inverted metamorphism was created by (1) footwall folding and/or simple shear of preexisting isograds (Fig. 3G; e.g., Hubbard, 1996), and (2) footwall accretion through downward incremental jumps of active slip planes (Fig. 3H; Harrison et al., 1998). The first process predicts prethrusting metamorphism (Fig. 3G), whereas the second requires synthrusting metamorphism. Here, we suggest that the inverted metamorphism in the southern marginal zone was induced by footwall overturned folding of the earlier 2.7–2.6 Ga isograds during the 2.0 Ga Limpopo thrusting (Fig. 3G). In contrast, the inverted metamorphism in the northern marginal zone may have resulted from the 2.0 Ga Limpopo thrusting via footwall accretion (Fig. 3H). We also interpret the widespread ca. 2.0 Ga Rb-Sr biotite and feldspar cooling ages across the northern and southern marginal zones and the Limpopo belt itself (van Breemen and Dodson, 1972; Kramers and Mouri,

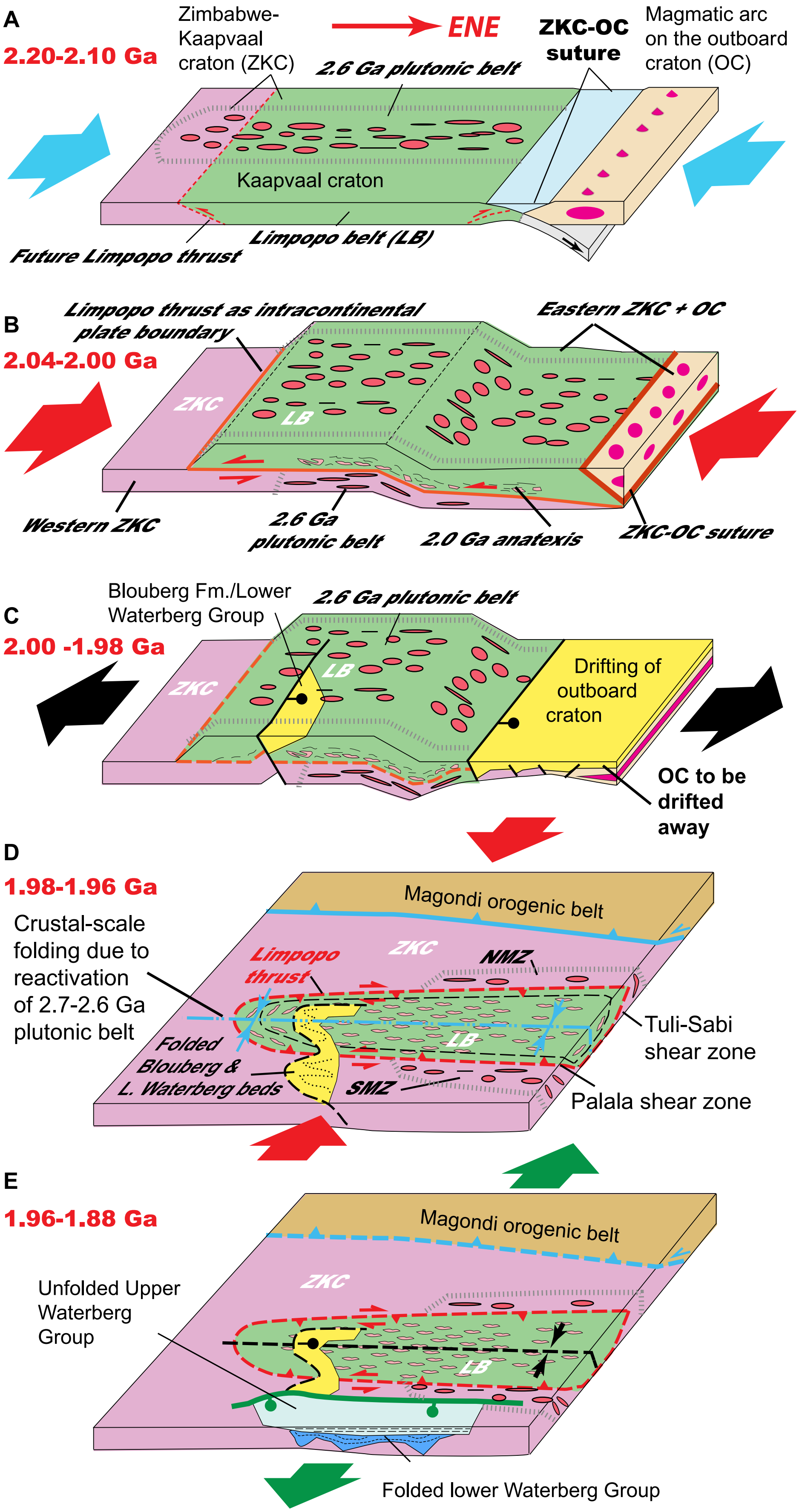

Figure 4. Tectonic model for the evolution of the Limpopo orogenic belt (southern Africa). NMZ and SMZ—northern and southern, respectively, marginal zones of the Limpopo metamorphic complex.

2011) to be the results of footwall refrigeration and hanging-wall erosion during the Limpopo thrusting. This interpretation is consistent with the preservation of older 2.7–2.6 Ga Rb-Sr biotite ages obtained from the ZKC rocks located outside the marginal zones farther away from the Limpopo belt (van Breemen and Dodson, 1972).

Although the exposure of the folded Blouberg and lower Waterberg strata is much smaller than the overall Limpopo belt (Fig. 2), the post-orogenic folding effect was not considered in any of the earlier tectonic models. Our hypothesis is testable in that it predicts a faster and earlier onset of cooling in the core of the orogen during folding, the presence of fold structures of the same age and same trend north and south of the Limpopo belt, and a single larger Archean craton (ZKC) in southern Africa.

ACKNOWLEDGMENTS

An Yin thanks Jan Kramers, Wilbert Kehelpannala, Dirk van Reenen, and Andre Smit for leading informative field trips; and Andrew Zuza, Peter Haproff, Nicole Jewell, and Abijah Simon for field assistance. We appreciate constructive comments by Peter Cawood, Dirk van Reenen, and an anonymous reviewer. This research was partially supported by a faculty research grant from the University of California–Los Angeles.

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