Downloaded from geology.gsapubs.org on June 20, 2014

Geology

Hot orogens, tectonic switching, and creation of continental crust

W.J. Collins

Geology 2002;30;535-538
doi: 10.1130/0091-7613(2002)030<0535:HOTSAC>2.0.CO;2

Email alerting services click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article

Subscribe click www.gsapubs.org/subscriptions/ to subscribe to Geology

Permission request click http://www.geosociety.org/pubs/copyrt.htm#gsa to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes

Geological Society of America

Downloaded from geology.gsapubs.org on June 20, 2014

Hot orogens, tectonic switching, and creation of continental crust

W.J. Collins* Department of Geology, School of Geosciences, University of Newcastle, Newcastle, New South Wales 2308, Australia

ABSTRACT

Many granulite terrains were too hot to have formed during continental collision. Rather, along with many high-grade metamorphic terrains that typify continental crust, most formed in accretionary orogens during tectonic switching, when prolonged lithospheric extension was interrupted by intermittent, transient contraction. Based on modern and ancient examples, tectonic switching occurs when slab retreat induces upper plate extension, causing arc splitting, formation of microcontinent slivers, and backarc basins; then intermittent arrival of buoyant oceanic plateaus induces transient flat subduction (or slab flip) and crustal thickening. During slab retreat, basaltic magmas produced from decompressed asthenosphere advect into the extending orogen, causing granulite facies metamorphism and granite generation, but subsequent thickening during flat subduction cools the region. Thickening is focused in the thermally softened backarc region and, if sediment filled, a hot, short-lived (~10 m.y.), narrow (50–100 km) orogenic belt forms. Such thickening is often misleadingly ascribed to arc or microcontinent collision. Once slab-retreat mode is reestablished, lithospheric extension recommences and a new arc-backarc system forms, generally outboard. Arrival of another plateau will reverse the procedure, and another short-lived, hot orogen will form within the orogenic system. Cycles of tectonic switching efficiently produce continental crust.

Keywords: continental accretion, crustal thickening, extension, granulites, tectonics.

*E-mail: Bill.Collins@newcastle.edu.au.

INTRODUCTION

Although granulite terrains are commonly considered to be dominantly supracrustal rocks buried during continental collision, typical peak equilibration temperatures cannot be simulated by conventional collision models (Fig. 1). Amphibolite facies metamorphism can barely be attained if more realistic thermo-mechanical models are applied (Jamieson et al., 1998). Furthermore, peak metamorphic assemblages are commonly synchronous with thickening-related foliations, yet conventional models require postcollisional peak conductive heating ~50–100 m.y. after cessation of thickening (e.g., Thompson and Connolly, 1995). Regional high-grade metamorphic terrains, including the vast Precambrian shield regions of cratonic blocks, represent thickened hot orogens that generally formed in another tectonic setting.

Granulites and other high-grade metamorphic rocks may form narrow linear belts in continental arcs beneath Cordilleran batholiths, but the deep crust should be dominantly mafic, consistent with xenolith studies (Rudnick, 1992) and exposed lower crustal sections (Percival et al., 1992). However, many granulite terrains are dominated by evolved supracrustal rocks and granites, not gabbros and diorites. Furthermore, arcs are dominantly extensional environments (Garfunkel et

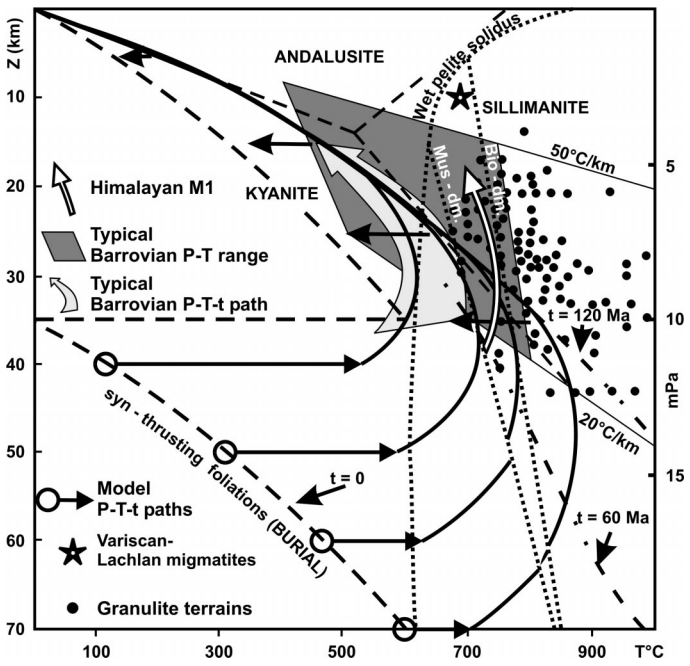


Figure 1. Pressure-temperature-time (*P-T-t*) loops modeled for continental collision (Thompson and Connolly, 1995) show that temperatures do not generally reach typical granulite facies conditions (data points from Harley, 1989). Barrovian metamorphic array and *P-T-t* paths are from Jamieson et al. (1998). Mus-dm and Bio-dm are muscovite and biotite dehydration melting curves.

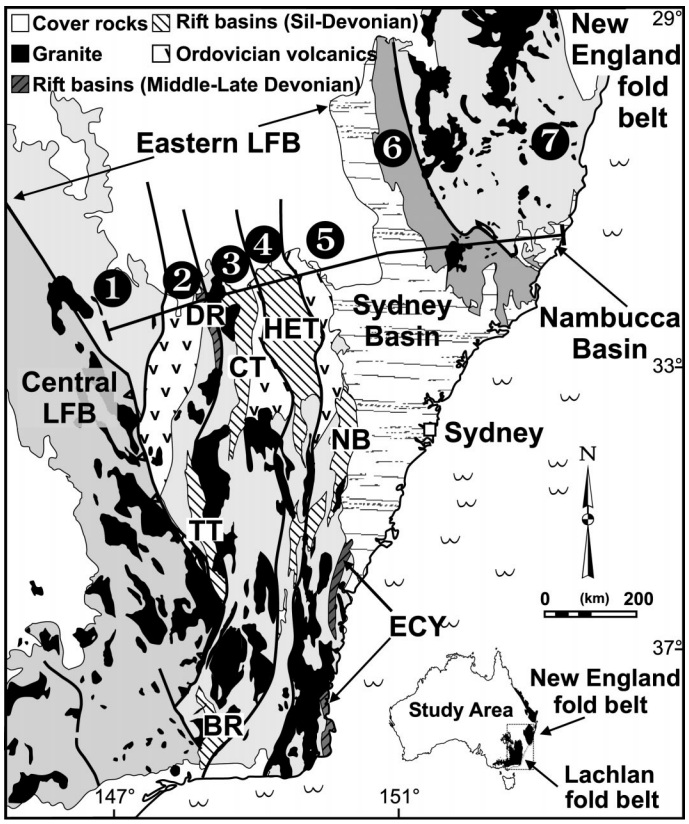


Figure 2. Geological map of east-central Lachlan and New England orogens showing distribution of major magmatic units and structural zones. Basement is low-grade Ordovician turbidite broadly correlatable over entire region. Structural zones of eastern Lachlan: 1—Girilambone; 2—Parkes/Tumut; 3—Molong-Deddick; 4—Hill End–Kuark; 5—Mallacoota-Capertee; 6—Tamworth; 7—Tablelands (see Fig. 3). LFB—Lachlan fold belt; DR—Dulladerry Rift; CT—Cowra Trough; HET—Hill End Trough; NB—Ngunawal Basin; TT—Tumut Trough; BR—Buchan Rift; ECY—Eden-Comerong-Yalwal Rift.

© 2002 Geological Society of America. For permission to copy, contact Copyright Permissions, GSA, or editing@geosociety.org.

Downloaded from geology.gsapubs.org on June 20, 2014

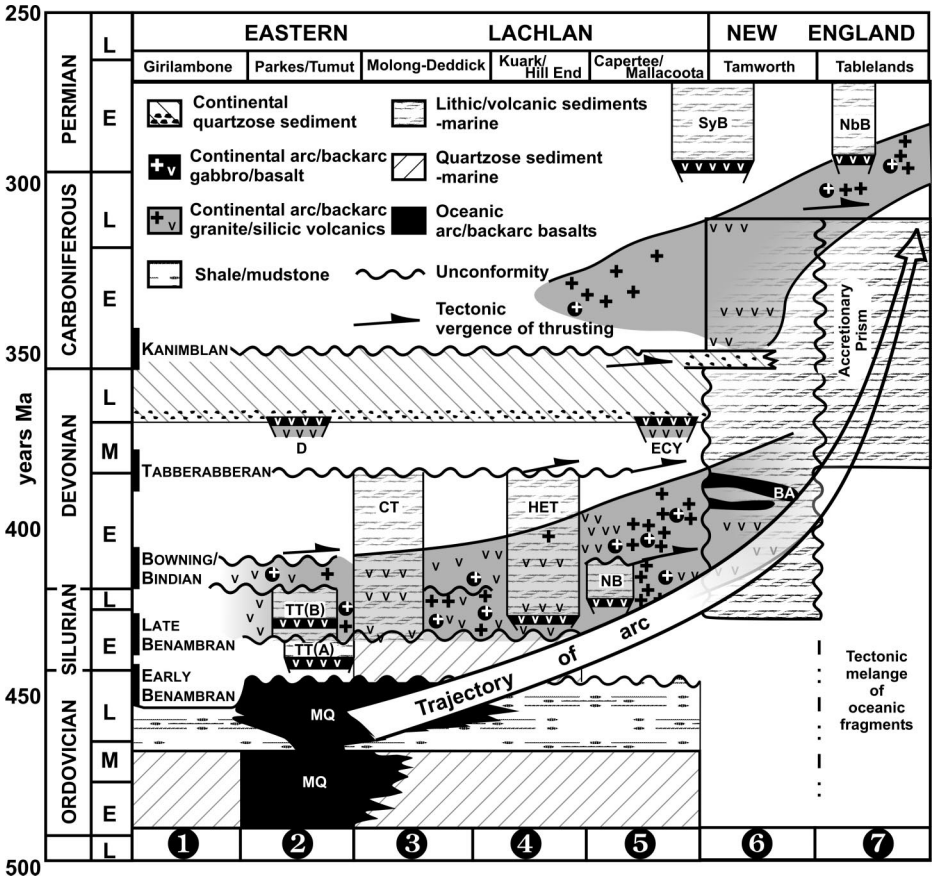


Figure 3. Time-space plot of eastern Lachlan and New England orogens showing evidence for tectonic switching and outboard migration of arc and/or backarc magmatism (shaded region). Extension events are marked by troughs and basins, contraction events are marked by unconformities. See text for discussion. BA—Baldwin Arc; CT—Cowra Trough; D—Dulladerry Rift; ECY—Eden-Comerong-Yalwal Rift; HET—Hill End Trough; MQ—Macquarie Arc; NB—Ngunawal Basin; NbB—Nambucca Basin; SyB—Sydney Basin; TT—Tumut Trough (A and B are rift packages of Stuart-Smith et al., 1992). Defined contractional events are also shown (e.g., Kanimblan; see text).

al., 1986), consistent with the little-appreciated fact that generation of most basaltic magmas, even in arcs, requires high degrees of lithospheric stretching to decompress and melt the asthenosphere (e.g., Pearce and Parkinson, 1993). Lithospheric extension is considered a necessity for granulite facies metamorphism (Sandiford and Powell, 1986), but the deep-crustal rocks of narrow continental arcs are not representative of regional granulite terrains, and the general mode of deformation involves crustal thinning, not thickening.

The granulite conundrum is a continental crust-formation problem, because granulites and related high-grade rocks are the backbones of continents. We need to reconcile the necessity for lithospheric extension with the structural evidence for crustal thickening at peak metamorphic conditions. This implies that thickening should rapidly follow thinning, while the rocks were still hot (Thompson et al., 2001). Rapid and repeated alternation from lithospheric extension to contraction is termed tectonic switching.

A mechanism for tectonic switching that can be incorporated into a tectonic model for creation of continental crust is required. I suggest that tectonic switching happens in accretionary orogens above subduction zones when the negative buoyancy of sinking oceanic lithosphere is reversed by intermittent arrival of oceanic plateaus. This changes the orogenic deformation mode from extensional to contractional, inducing closure of arcs, backarcs, and rifts. Closure of continental rifts and/or arcs during continental collision (Thompson et al., 2001) will produce hot, narrow orogens squeezed between older stabilized lithospheres, the end result being a narrow suture zone. A better continent-creation mechanism is one where protracted extension creates new crust through magmatic and sedimentary additions in and beneath extensional arcs and backarcs, and transient contraction rapidly and intermittently shortens these hot zones to normal lithospheric thicknesses. This is described in the following, using modern and ancient examples of accretionary orogens.

LARGE, ANCIENT HOT OROGEN

Most of the early-middle Paleozoic, 700-km-wide Lachlan orogen of eastern Australia (Fig. 2) is dominated by Silurian-Devonian granites that intruded through a basement of craton-derived Ordovician turbidites and underlying Cambrian-Ordovician greenstones of oceanic arc-backarc affinity (e.g., Crawford et al., 1984; Glen et al., 1998). Most granites were emplaced during peak orogenesis, when at least five major, short-lived (~10 m.y.) phases of orogenic contraction occurred (early Benambran to Kanimblan; Fig. 3). The Lachlan crust then stabilized. Most workers now consider that the orogen formed by closure of this vast arc-backarc system behind a long-lived subduction-accretion system represented by the outboard New England orogen (e.g., Collins and Vernon, 1992; Fergusson and Coney, 1992a; Foster and Gray, 2000).

The eastern and central Lachlan orogen (Foster and Gray, 2000) was hot throughout its orogenic history, where granites and related rocks compose >50% of exposure (Fig. 2). The granites were derived largely by shallow crustal melting under granulite facies conditions at 5–6 kbar (Clemens and Wall, 1981), and the thermal perturbations are reflected by regional greenschist facies metamorphism and low-pressure, high-temperature metamorphic complexes (e.g., Morand, 1990; Johnson and Vernon, 1995).

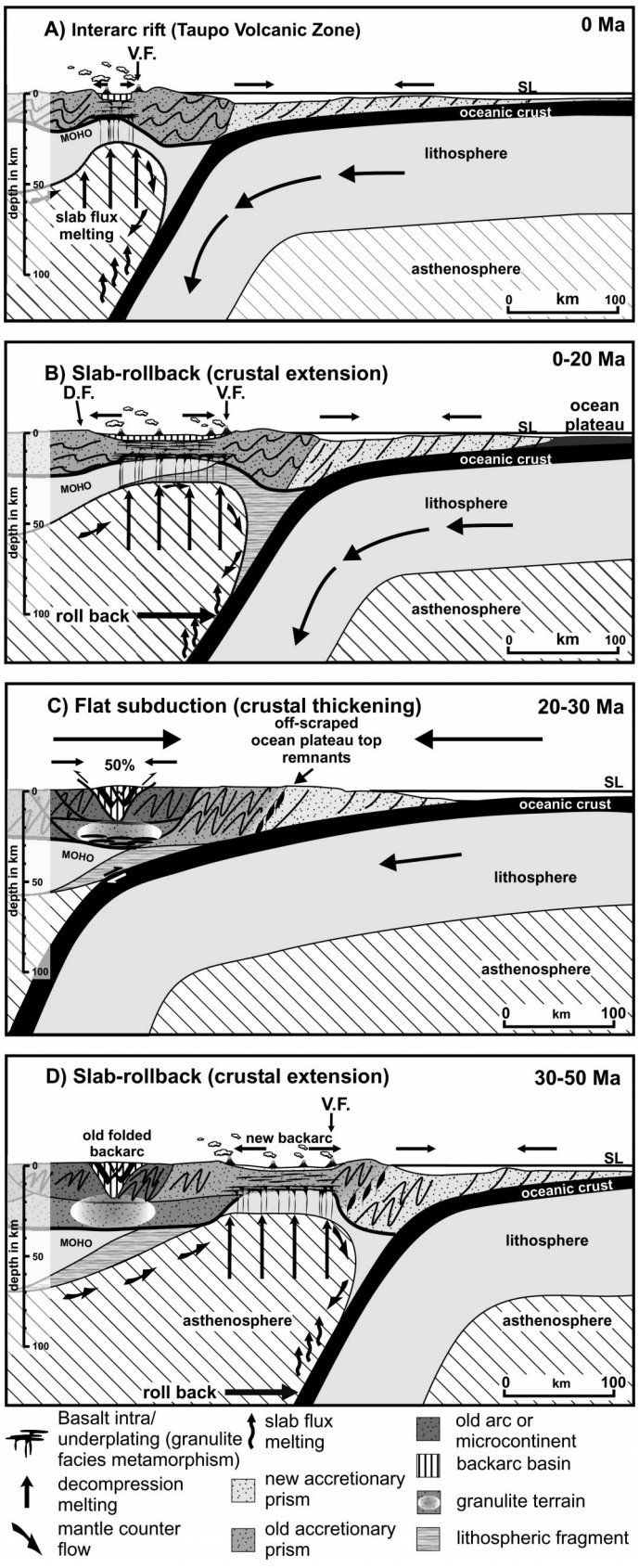
Despite repeated contraction during the orogenic history, Silurian-Devonian rift basins developed in the eastern Lachlan orogen (Fig. 3). These basins contain bimodal volcanics, the more primitive basaltic varieties of which have distinctive intraoceanic arc-backarc affinities (Collins, 2001). Primitive gabbro complexes and synplutonic mafic dikes have similar affinities. The primitive chemistry suggests an origin largely by asthenospheric decompression melting under actively thinning lithosphere (Collins, 2001).

The peak orogenic period therefore reflects tectonic switching in the eastern Lachlan orogen, when repeated extension and contraction

Downloaded from geology.gsapubs.org on June 20, 2014

events occurred behind an outboard-migrating arc (Fig. 3). Initially, the Ordovician intraoceanic arc was localized in the Parkes-Tumut zone (Glen et al., 1998), but following widespread crustal thickening ca. 450 Ma (Collins and Hobbs, 2001), it split and migrated outboard into the New England region during the Silurian-Devonian. Associated widespread rift-basin development and silicic magmatism was interrupted by periodic crustal-thickening events (Benambran to Tabberabberan) that closed and thickened the nascent backarc basins. Terminal Kanimblan deformation closed all remaining rifts and amalgamated the outboard intraoceanic New England arc and subduction complex.

A somewhat analogous modern tectonic setting is the southwest Pacific (e.g., Collins and Vernon, 1992; Collins, 2001), where arcs and backarc basins have developed progressively outboard, producing a vast area of juvenile crust the size of continental Australia in the past 100 m.y. This backarc system lacks the widespread turbidite blanket of the Lachlan orogen, of Bengal Fan proportions (Fergusson and Coney, 1992b), but it provides an important framework to develop a model for tectonic switching.



TECTONIC SWITCHING IN MODERN TECTONIC SETTINGS

Along each modern accretionary orogen, some regions are undergoing extension as others undergo contraction, such as the Andes (Gutscher et al., 2000) and New Zealand (e.g., Walcott, 1987). Zones of orogenic contraction can be correlated with flat subduction of buoyant oceanic crust in the Andes, but contractional deformation is greatly diminished or nonexistent where the slab is steep (Gutscher et al., 2000). In New Zealand, collisional orogenesis occurs in the South Island while the North Island is extending in the Taupo volcanic zone. Although variations in regional stress conditions are also affected by longer term processes, they cannot induce short-lived (~10 m.y.) extension-compression cycles associated with tectonic switching. The Andes and New Zealand show the critical control of slab buoyancy on the deformation mode of an accretionary orogen.

The Taupo volcanic zone of northern New Zealand represents a suitable analogue for the peak orogenic eastern Lachlan orogen, when tectonic switching was most prevalent, and for accretionary orogens in general (Fig. 4A). The Taupo volcanic zone contains bimodal volcanics and is exceptionally hot, with average heat flow over 13 times the crustal average (Stern, 1987). Under these conditions, granulite facies metamorphism and crustal melting is inevitable (Walcott, 1987).

MODEL FOR TECTONIC SWITCHING

Lithospheric Extension

Active crustal extension in the nascent backarc basin of the Taupo volcanic zone is related to rollback of the Pacific plate (e.g., Stern, 1987; Walcott, 1987). A conservative slab rollback rate of 5 km/m.y. is used (Fig. 4B), but is probably much higher in general. As the arc splits and migrates outboard during slab retreat, a backarc basin forms and the distal flank remains as a remnant arc (Fig. 4B). The forearc region can be a microcontinental block, preexisting arc, or accretionary prism material. In the rift, the Moho thins to <10 km, typical of backarc regions (Brooks et al., 1984), and the asthenosphere rises to <40 km. As a result, high degrees of adiabatic decompression melting of the asthenosphere in the backarc region produce juvenile basaltic crust, as seafloor and/or mafic underplate beneath thinned continental crust. The deepest parts of preexisting fertile crust will melt under granulite facies metamorphic conditions.

Figure 4. Model for tectonic switching. A, B: Slab retreat induces regional extension and formation of backarc, which fills with supracrustal material. Ocean plateau induces flat subduction and crustal thickening (C), producing localized, short-lived orogenic belt. Following plateau subduction (usually ~10 m.y.), extension mode is reestablished (D). Repeated switching efficiently produces continental crust. Note that subducting slab does not break, thereby maintaining whole-mantle convection. V.F. is volcanic front, D.F. is distal arc flank, SL is sea level.

Downloaded from geology.gsapubs.org on June 20, 2014

Extension to Contraction

Arrival of oceanic plateaus induces transient subduction flip or flat subduction. For simplicity, only the latter is described here (Fig. 4C), although the general effects are the same. Contractional deformation occurs in the upper plate (Gutscher et al., 2000), and thickening is focused in the arc-backarc region because the crust was already thermally softened during extension. Contraction immediately cools the lithosphere, because the asthenosphere is now isolated from the crust (Fig. 4C) and peak-metamorphic crustal-thickening structures are indelibly recorded in the orogen. This explains syntectonic, peak-metamorphic mineral assemblages in thickened granulites.

Preservation of the backarc during orogenic contraction will depend on the sedimentary history of the basin, which controls its intrinsic buoyancy (Cloos, 1993). If the backarc basin was sediment starved, it may be preserved as an ophiolite complex, but if it was sediment filled, its increased volume and buoyancy allow preservation as a narrow (50–100 km wide), short-lived (5–15 m.y.) fold-and-thrust belt within the greater orogen (Fig. 4C). Given the finite size of oceanic plateaus, these contractional events are likely to be diachronous across and along strike.

Backarc closure during flat subduction or slab flip causes accretion of the arc and forearc crustal fragments to the orogen, a process commonly referred to as arc or microcontinental collision. However, the term may be misleading because it implies collision induced by arrival of suspect terranes from the subducting plate. True arc-continent collision requires that the accreted terrane be exotic lower plate material rather than merely a fugitive upper plate fragment returning to its former (along strike) abode.

Reversion to Extension

Subduction of oceanic plateaus is a transient process, because the long-term plate tectonic mode is soon reestablished. Global tomographic models (e.g., van der Hilst et al., 1997) confirm that plate motion is controlled by whole-mantle convection operating on time scales of hundreds of millions of years (Davies and Richards, 1992). Plateau subduction migrates the slab hinge inboard and outboard at a scale of 100 km in several million years (Fig. 4), and only requires localized trench-parallel asthenospheric flow (Russo and Silver, 1994) to accommodate the transient change in slab trajectory. Hence, the slab is not broken and the intrinsic negative buoyancy of the sinking plate quickly reestablishes the preaccretion extension mode of the orogen. Whole mantle convection is maintained.

Plateaus subduct rapidly. The average Cenozoic rate of Pacific plate motion is ~80 km/m.y., so a 500-km-wide plateau will pass through a trench in ~6 m.y. Another 4–7 m.y. is required for the plateau to pass beneath the convergent margin. Nonetheless, plateau tops might be offscraped into the prism as greenstone mélange (Fig. 4C). Thus, short-lived (~10 m.y.) orogenic contraction events are considered a hallmark of intermittent arrival and subduction of oceanic plateaus at a retreating subduction boundary.

Following plateau subduction, the arc locates farther outboard on older arc, microcontinent, or young accretionary prism fragments (Fig. 4D). Arrival of the next plateau inverts the nascent backarc basin, but the orogen has grown outboard and contains another distinct tectonostratigraphic package of thickened backarc-related rocks and syntectonic granites. However, younger structures will reactivate older structures, so delineation of sequential orogenic belts may be difficult, arc-type rocks being superposed on one another. Regardless, tectonic switching leads to efficient continental growth in accretionary orogens by generating magmatic and sedimentary additions during extension and crustal thickening during contraction.

ACKNOWLEDGMENTS

Supported by Australian Research Council Large Grant A0001203. I thank John Ludden, Bruce Hobbs, and Ron Vernon for helpful comments and D.R. Gray and A.B. Thompson for reviews.

REFERENCES CITED

Brooks, D.A., Carlson, R.L., Harry, D.L., Melia, P.J., Moore, R.P., Rayhorn, J.E., and Tubb, S.G., 1984, Characteristics of back-arc regions: Tectonophysics, v. 102, p. 1–16.

Clemens, J.D., and Wall, V.J., 1981, Origin and crystallization of some peraluminous (S-type) granitic magmas: Canadian Mineralogist, v. 19, p. 111–131.

Cloos, M., 1993, Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts: Geological Society of America Bulletin, v. 105, p. 715–737.

Collins, W.J., 2002, Nature of extensional accretionary orogens: Tectonics (in press).

Collins, W.J., and Hobbs, B.E., 2001, What caused the Early Silurian change from mafic to silicic (S-type) magmatism in the eastern Lachlan fold belt?: Australian Journal of Earth Sciences, v. 47, p. 25–41.

Collins, W.J., and Vernon, R.H., 1992, Palaeozoic arc growth, deformation and migration across the Lachlan fold belt, southeastern Australia: Tectonophysics, v. 214, p. 381–400.

Crawford, A.J., Cameron, W.E., and Keays, R.R., 1984, The association boninite–low Ti andesite–tholeiite in the Heathcote greenstone belt, Victoria: Australian Journal Earth Sciences, v. 31, p. 161–175.

Davies, G.F., and Richards, M.A., 1992, Mantle convection: Journal of Geology, v. 100, p. 151–206.

Fergusson, C.L., and Coney, P.J., 1992a, Convergence and intraplate deformation in the Lachlan fold belt of southeastern Australia: Tectonophysics, v. 214, p. 417–439.

Fergusson, C.L., and Coney, P.J., 1992b, Implications of a Bengal Fan–type deposit in the Paleozoic Lachlan fold belt of southeastern Australia: Geology, v. 20, p. 1047–1049.

Foster, D.A., and Gray, D.R., 2000, Evolution and structure of the Lachlan fold belt (orogen) of eastern Australia: Annual Reviews of Earth and Planetary Science, v. 28, p. 47–80.

Garfunkel, Z., Anderson, C.A., and Schubert, G., 1986, Mantle circulation and the lateral migration of subducted slabs: Journal Geophysical Research, v. 91, p. 7205–7223.

Glen, R.A., Walshe, J.L., Barron, L.M., and Watkins, J.J., 1998, Ordovician convergent margin volcanism and tectonism in the Lachlan sector of east Gondwana: Geology, v. 26, p. 751–754.

Gutscher, M-A., Spakman, W., Bijwaard, H., and Engdahl, E.R., 2000, Geodynamics of flat subduction: Seismicity and tomographic constraints from the Andean margin: Tectonics, v. 19, p. 814–833.

Harley, S.L., 1989, The origins of granulites: A metamorphic perspective: Geology Magazine, v. 126, p. 215–247.

Jamieson, R.A., Beaumont, C., Fullsack, P., and Lee, B., 1998, Barrovian regional metamorphism: Where's the heat, *in* Treloar, P.J., and O'Brien, P.J., eds., What drives metamorphism and metamorphic reactions: Geological Society [London] Special Publication 138, p. 23–51.

Johnson, S., and Vernon, R.H., 1995, Stepping stones and pitfalls in the determination of an anticlockwise *P-T-t*-deformation path: The low-*P*, high-*T* Cooma Complex, Australia: Journal of Metamorphic Geology, v. 13, p. 165–183.

Morand, V.J., 1990, Low-pressure regional metamorphism in the Omeo Metamorphic Complex, Victoria, Australia: Journal of Metamorphic Geology, v. 8, p. 1–12.

Pearce, J.A., and Parkinson, I.J., 1993, Trace element models for mantle melting: Application to volcanic arc petrogenesis, *in* Prichard, H.M., et al., eds., Magmatic processes and plate tectonics: Geology Society [London] Special Publication 76, p. 373–403.

Percival, J.A., Fountain, D.M., and Salisbury, M.H., 1992, Exposed crustal cross sections as windows on the lower crust, *in* Fountain, D.M., et al., eds., Continental lower crust: Developments in Geotectonics 23: Amsterdam, Elsevier, p. 317–362.

Rudnick, R.L., 1992, Xenoliths—Samples of the lower continental crust, *in* Fountain, D.M., et al., eds., Continental lower crust: Developments in Geotectonics 23: Amsterdam, Elsevier, p. 269–316.

Russo, R.M., and Silver, P.G., 1994, Trench-parallel flow beneath the Nazca plate from seismic anisotropy: Science, v. 263, p. 1105–1111.

Sandiford, M., and Powell, R., 1986, Deep crustal metamorphism during continental extension: Modern and ancient examples: Earth and Planetary Science Letters, v. 79, p. 151–158.

Stern, T.A., 1987, Asymmetric back-arc spreading, heat flux and structure associated with the central volcanic region of New Zealand: Earth and Planetary Science Letters, v. 85, p. 265–276.

Stuart-Smith, P.G., Hill, R.I., Rickard, M.J., and Etheridge, M.A., 1992, The stratigraphy and deformation history of the Tumut region: Implications for the development of the Lachlan fold belt: Tectonophysics, v. 214, p. 211–238.

Thompson, A.B., and Connolly, J., 1995, Melting of the continental crust: Some thermal and petrological constraints on anatexis in continental collisional zones and other tectonic settings: Journal of Geophysical Research, v. 100, p. 15 565–15 579.

Thompson, A.B., Schulmann, K., Jezek, J., and Tolar, V., 2001, Thermally softened continental zones (arcs and rifts) as precursors to thickened orogenic belts: Tectonophysics, v. 332, p. 115–141.

van der Hilst, R.D., Widiyantoro, S., and Engdahl, E.R., 1997, Evidence of deep mantle circulation from global tomography: Nature, v. 386, p. 578–584.

Walcott, R.I., 1987, Geodetic strain and the deformation history of the North Island of New Zealand during the Cainozoic: Royal Society of London Philosophical Transactions, ser. A, v. A321, p. 163–181.

Manuscript received November 2, 2001
Revised manuscript received March 5, 2002
Manuscript accepted March 6, 2002

Printed in USA