Introduction: Active Margins in Transition—Magmatism and Tectonics through Time: An Issue in Honor of Arthur W. Snoke

Allen J. McGrew* and Joshua J. Schwartz†

*Department of Geology and Environmental Geoscience, University of Dayton, 300 College Park, Dayton, Ohio 45469-2364, USA
†Department of Geological Sciences, California State University, Northridge, Northridge, California 91330-8266, USA

ABSTRACT

The evolution of active margins through time is the record of plate tectonics as inscribed on the continents. This themed issue honors the eclectic contributions of Arthur W. Snoke (Fig. 1) to the study of active margins with a series of papers that amply demonstrate the broad scope of active margin tectonics and the diverse methods that tectonic geologists employ to decipher their histories. Taken together, this set of papers illustrates the diversity of boundary conditions that guide the development of active margins and the key parameters that regulate their evolution in time and space.

INTRODUCTION

Among the key questions directing the scientific investigation of active margin tectonics and addressed in this issue are the following:

1. What are the fundamental boundary conditions that constrain the tectonic evolution of active margins?
2. To what extent can common threads be discerned linking the evolution of diverse types of margins? Conversely, to what extent must each margin be treated individually? Do active margins follow a few basic evolutionary paths, or is each case unique?
3. What are the key parameters regulating the evolution of active margins? For example, what is the role of tectonic heredity as expressed through initial crustal thickness, crustal age, compositional structure, evolving thermal structure, and (as a product of all of these) the evolution of crustal rheology?

Over an eclectic career spanning more than 40 years, few workers have contributed more to the collective enterprise of understanding the anatomy and evolutionary patterns of active margins than Arthur W. Snoke, the honoree for this issue.

THE CAREER AND INFLUENCE OF ARTHUR W. SNOKE

Art Snoke’s contributions to structural geology and tectonics span a geographically and intellectually impressive range, evincing the hallmarks of a sweeping curiosity and a master collaborator. Art’s contributions weave together a diversity of techniques to unravel regional tectonic histories—igneous and metamorphic petrology, petrofabric analysis, geochemistry, geochronology, and stratigraphic analysis—all informed by his encyclopedic familiarity with the broad diversity of Earth’s tectonic environments. For Art, however, it always begins with careful, keen-eyed, detailed field observation.

Art’s major conceptual contributions focus on three key areas, all of which are intrinsic to understanding the form and evolution of active margins at various scales in both space and time.

1. The interplay between magmatism and deformation in island arcs and Cordilleran terranes—for example, Tobago (Snoke et al., 2001a), the Blue Mountains terrane of eastern Oregon, USA (Schwartz et al., 2010, 2011), and his doctoral thesis area, the Klamath Mountains Province of California and Oregon (Snoke, 1977; Snoke and Barnes, 2006).
2. The tectonic significance and evolution of metamorphic core complexes and their role in the transition of active margins from tectonic thickening to crustal thinning and extension (e.g., Snoke, 1980; Dallmeyer et al., 1986; Snoke et al., 1990; MacCready et al., 1997).
3. The role of shear zones and mylonitic rocks in understanding deep-crustal deformation and the rheological transition from deep-crustal to upper-crustal environments (e.g., Lister and Snoke, 1984; Snoke et al., 1998, 1999).
In addition to his own direct contributions, many of Art’s 35 M.S. and 9 Ph.D. students, not to mention myriads of undergraduates, have themselves gone on to make their own contributions to an impressive range of subfields of structural geology, tectonics, and geology in general. Even a cursory tally of his former students would reveal significant contributions in areas such as arc and accretionary tectonics, metamorphic core complex geology and extensional tectonics, deep-crustal tectonics, neotectonics, and salt tectonics. All of them would cite Art’s lasting influence on the way they approach science, and even the way they approach life.

Art exemplifies the saying that “the best geologist is the one who has seen the most rocks.” To peruse his publication list is to survey a broad spectrum of Earth’s major active margin tectonic environments. Included among these are: island arcs, arc-continent collision zones, accreted terranes, forearc tectonics, Precambrian tectonics and the primordial origins of plate tectonic behavior, “thick-skinned” Laramide tectonics (exemplified by his work on the geology of his adopted home state of Wyoming), collisional orogenic belts (the southern Appalachian Piedmont, the Tunisian Atlas, and the Ivrea-Verbano zone), deep-crustal tectonics, crustal cross sections, deep-crustal shear zones (the Ivrea-Verbano Zone, the Klamath Mountains, and the Ruby Mountains–East Humboldt metamorphic core complex), and his pioneering work on metamorphic core complex evolution and extensional tectonics (again, the Ruby Mountains–East Humboldt metamorphic core complex). Art’s passion for field geology is documented by multiple detailed, high-quality geologic maps of dauntingly complex regions. His efforts in this regard range from his award-winning map of Tobago (Snoke et al., 2001b) to multiple quadrangle maps submitted, in press, or already published by him and/or his students in the vicinity of the Ruby Mountains–East Humboldt Range–Wood Hills metamorphic core complex.

Despite the scope and quality of Art’s contributions to field-based science, the broad intellectual compass of Art’s conceptual contributions will be his most lasting legacy. This collection of papers aptly reflects Art’s legacy in another crucial way: Art has played a critical role as a convenor of the structural geology and tectonics community and a consummate, if ever-modest and self-effacing, leader and organizer. His service to the structural geology and tectonics community encompasses leading multiple truly outstanding field trips (an under-appreciated but important service to the community); organizing field conferences (e.g., the groundbreaking 1981 Penrose Conference on the Significance and Petrogenesis of Mylonitic Rocks, the 1987 Penrose Conference on Metamorphic Core Complexes Revisited, and the 1989 Conference on Caribbean Geology); and organizing important edited book projects that serve to synthesize broad domains of knowledge. The book projects in particular serve to reprise the broad compass and importance of Art’s contributions to the geological community, as illustrated by a simple listing of their titles: Geology of Wyoming (Snoke et al., 1993); Fault-Related Rocks: A Photographic Atlas (Snoke et al., 1998); Geologic Studies in the Klamath Mountains Province, California and Oregon—A Volume in Honor of William R. Irwin (Snoke and Barnes, 2006); and Crustal Cross-Sections from the Western North American Cordillera and Elsewhere: Implications for Tectonic and Petrologic Processes (Miller and Snoke, 2009).

Art has led a career predicated on the premise that science is fundamentally a social enterprise—a great chain of discovery through which we each pay tribute to our mentors through the service that we offer to those who follow. Art’s service to the structural geology and tectonics community was acknowledged through the Geological Society of America’s Career Contribution Award in Structural Geology and Tectonics in 2017. Many of the papers in this volume come from Art’s coworkers and colleagues, who would freely acknowledge the foundations that he laid for their own work.

VOLUME CONTRIBUTIONS

The wide variety of papers in this themed issue aptly honors the diversity and significance of Art’s own contributions. Taken together, the papers represent the broad scope of active margin evolution through geologic time from the Neoarchean (Frost et al., 2018; Swapp et al., 2018) to the Miocene (LaForge et al., 2017). Geographically, most papers focus on diverse aspects of the long time-scale tectonic evolution of the Cordilleran margin of western North America. However, a more global perspective is provided by examples of active margin tectonics in the Karoo Basin of South Africa (McKay et al., 2016); extensional orogenic collapse along the active margin of Zealandia (Schwartz et al., 2016); a record of terrane accretion in the northeastern USA (Kruckenberg et al., 2019); and an investigation into the role of slab pull and self-lubricating lithospheric weak zones in regulating plate motions and Gondwanan tectonics (Vizán et al., 2017).

Thematically, these papers investigate diverse tectonic settings and processes, including terrane accretion, continental collision, large-scale magmatism, transform tectonics (including both transpressive and transtensional regimes), intra-arc and backarc tectonics, and orogenic collapse and continental extension. Several papers investigate transitions between more than one regime and the trigger mechanisms or evolving boundary conditions that drive such changes.

Finally, the papers also illustrate the wide diversity of tools employed by contemporary geoscientists to explore the tectonic evolution of active margins. Many of these techniques have also figured prominently in Art Snoke’s own key career contributions—high-precision isotope geochronology and thermochronology, geochemical analysis, thermobarometric investigation, quantitative microstructural analysis, geophysical investigation, tectonostratigraphic analysis, and—the perennial touchstone of Art’s career—classic, field-based observation.

Below, we offer brief synopses of the key findings reported in each paper in order of publication.

McKay et al. (2016): Petrogenesis and Provenance of Distal Volcanic Tuffs from the Permian–Triassic Karoo Basin, South Africa: A Window into a Dissected Magmatic Province

McKay et al. (2016) explore the ages and geochemistry of zircons in volcanic tuffs in the Karoo Supergroup, South Africa, to understand magmatism in southern Gondwana in the Permian. Their
data document a period of subduction-related magmatism in the early to middle Permian and a transition to shallow, intra-plate magmatism after ca. 265 Ma. Based on zircon geochemistry, they suggest that magmatism shifted from an arc environment in the early Permian to an extensional setting in the late Permian. This shift may be associated with development of a backarc magmatic system adjacent to western Antarctica that predates known extensional volcanism elsewhere in Gondwana.

Schwartz et al. (2016): Thermochronology of Extensive Orogenic Collapse in the Deep Crust of Zealandia

Schwartz et al. (2016) use thermochronologic data from metamorphic zircon and titanite to document the tempo and thermal evolution of the lower crust during the tectonic transition from arc construction and crustal thickening to extensional collapse. They find that garnet granite metamorphism and partial melting of the lower crust temporarily overlapped with batholith construction and lasted for several million years afterwards. They document that metamorphic titanites display complex chemical and temporal variations that cannot easily be attributed to thermally activated volume diffusion or simple core-rim crystallization. They therefore interpret the ages of metamorphic titanites as recording protracted growth and/or complex chemical and temporal variations that cannot easily be attributed to thermally activated volume diffusion or simple core-rim crystallization. They propose that thermal weakening of the lower crust due to magmatism and high heat flow was a key factor controlling the transition from crustal thickening to crustal thinning and extensional orogenic collapse of the Zealandia Cordillera.

Ma et al. (2016): Detrital-Zircon Geochronology of the Sawtooth Metamorphic Complex, Idaho: Evidence for Metamorphosed Lower Paleozoic Shelf Strata within the Idaho Batholith

Ma et al. (2016) examine detrital zircons from metasedimentary rocks of the Sawtooth metamorphic complex as evidence for a stratigraphic age of metamorphosed strata within the Idaho batholith. They find that the medium- to high-grade quartzites and quartzofeldspathic metasedimentary rocks contain two distinctive age spectra consisting of primary 2900–2510 Ma and 1990–1760 Ma zircons for one group, and 1870–1670 Ma, 1490–1330 Ma, and 1220–1020 Ma zircons for the other group. Lesser abundant Cambrian and Neoproterozoic ages are also present in the two groups. Based on statistical and visual comparisons of age spectra from Proterozoic and Paleozoic strata deposited on the western passive margin of Laurentia, they suggest that metasedimentary rocks of the Sawtooth metamorphic complex were deposited in the Cambrian and Middle Ordovician. They conclude that the Cordilleran passive margin sequence was continuous along the western margin of Laurentia, including the area occupied by the Idaho batholith.

Ernst et al. (2016): Zircon U-Pb Ages and Petrologic Evolution of the English Peak Granitic Pluton: Jurassic Crustal Growth in Northwestern California

Ernst et al. (2016) document the emplacement of the English Peak plutonic complex in the central Klamath Mountains with new U-Pb zircon ages. The English Peak plutonic complex is a calc-alkaline igneous complex composed of two small, 1–2-km-diameter, satellite plutons and a much larger, 10–15-km-diameter zoned granitic pluton. Satellite plutons give weighted-mean zircon ages of 172.3 ± 2.0 Ma and 166.9 ± 1.6 Ma, respectively. The main pluton, the English Peak pluton, consists of gabbro-tonalite with ages of 160.4 ± 1.1 Ma, 158.1 ± 1.1 Ma, and 158.0 ± 1.2 Ma. Two samples from late-stage, tonalite-granodiorite-granite give younger ages of 156.3 ± 1.3 [3.1] Ma and 155.3 ± 1.2 [3.0] Ma. They suggest through geochronologic correlation with other Klamath terranes that accreted ophiolitic basement terranes were modified and incorporated into the evolving Jurassic continental crust prior to the earliest Cretaceous onset of westward transport of the stack of Klamath allochthons relative to the active Jura-Cretaceous Sierran calc-alkaline arc.

Žák et al. (2017): Magnetic Fabrics of Arc Plutons Reveal a Significant Late Jurassic to Early Cretaceous Change in the Relative Plate Motions of the Pacific Ocean Basin and North America

Žák et al. (2017) delineate contrasting magnetic fabrics in five successively emplaced syntectonic plutons to reveal Late Jurassic to Early Cretaceous temporal and spatial variations in tectonic strain in the oceanic terranes of the Blue Mountains province, northeastern Oregon, USA. The inferred strain regimes evolved over time: (1) thrusting and sinistral shearing at ca. 160 Ma, to (2) horizontal stretching at ca. 147 Ma in the forearc-accretionary
They attribute these progressive strain reorientations, respectively, to outboard Wallowa-Baker terrane collision, lateral extrusion, docking of the amalgamated Blue Mountains superterranne into a continental-margin reentrant, and onset of orocline bending. In addition, they argue that these changes in crustal strain directions record the transition from Late Jurassic sinistral deformation to Early Cretaceous dextral terrane translation along the paleo-Pacific margin. They also speculate that these events may have been linked along the North American Cordillera from central California to the Blue Mountains, culminating in the onset of Franciscan complex accretion and voluminous plutonism in the Sierra Nevada magmatic arc. In British Columbia, several tens of millions of years later (ca. 100 Ma), a similar plate-kinematic change suggests that these transitions may have migrated along the Cordilleran orogen through time and space.

**Link et al. (2017): U-Pb Zircon Ages of the Wildhorse Gneiss, Pioneer Mountains, South-Central Idaho, and Tectonic Implications**

Link et al. (2017) document ages and magma sources in the Pioneer Mountains, south central Idaho, USA, to understand the timing of Archean crustal growth in western North America. They find that the oldest rock in the area is a felsic gneiss in the Wildhorse gneiss with Neoarchean U-Pb magmatic zircon ages of 2.60–2.67 Ga. They interpret the orthogneiss to be part of the Grouse Creek block of the Albion Mountains to the south. Structurally above the Wildhorse gneiss is a heterogeneous paragneiss with detrital zircons as young as ca. 1460 Ma and an amphibolite with zircons dated at ca. 1850 Ma. The upper part of the Wildhorse gneiss contains metakaertzites with zircons as young as ca. 1400 Ma, and they correlate the metakaertzite with the Lemhi subbasin of the Mesoproterozoic Belt Supergroup. In the upper Wildhorse gneiss, they document the presence of a ca. 695 Ma intrusive orthogneiss that is coeval with Neoproterozoic rift-related rocks near Pocatello, House Mountain, and Edwardsburg, Idaho. Initial Hf values suggest that the granitoids had a mixed source in both continental crust and juvenile mantle.

**Litherland and Klemperer (2017): Crustal Structure of the Ruby Mountains Metamorphic Core Complex, Nevada, from Passive Seismic Imaging**

Litherland and Klemperer (2017) explore the deep structure of the Ruby Mountains metamorphic core complex, northeastern Nevada, USA, using data from a temporary passive seismic array consisting of three 100-km-long intersecting profiles collected as part of the Earthscope Flexible Array program. Common conversion point stacks of P-wave receiver functions from this data set document a mostly flat Moho at 32 ± 2 km depth throughout most of the study area but reaching 40 km depth in a narrow, north-south crustal welt 20–50 km west of the exposed Ruby Mountain core complex. Shear-wave splitting analyses show fast directions of polarization sweeping clockwise from west to east across the study area, generally paralleling regional studies and models that place the anisotropy below the lithosphere. However, because the north-south crustal welt coincides with the W-E polarizations, the observed splitting may also incorporate a component of crustal anisotropy. Integrating the new observations with older magnetotelluric and seismic-refraction and seismic-reflection data, they argue for asymmetric crustal flow during formation of the core complex at the edge of a previously formed orogenic plateau.

**Vizán et al. (2017): Paleo-Tethys Slab Pull, Self-Lubricated Weak Lithospheric Zones, Poloidal and Toroidal Plate Motions, and Gondwana Tectonics**

Vizán et al. (2017) utilize paleomagnetically constrained paleogeographic reconstructions to subdivide the Gondwana megacontinent into broad domains bounded by differential strike-slip displacements along preexisting lithospheric weak zones that were reactivated by stresses induced by slab pull at the northern subduction margin of the Paleotethys Ocean. They propose that the transcontinental extent of these self-lubricated lithospheric weak zones in tandem with the northward drift of Pangea induced a self-reinforcing system of toroidal flow in the underlying mantle. These processes occurred in conjunction with a major reorganization of mantle flow as it transitioned from the immense cold downwelling accompanying the assembly of Pangea to the hot upwelling caused by thermal energy storage beneath the supercontinent.

**LaForge et al. (2017): Synextensional Dike Emplacement across the Footwall of a Continental Core Complex, Chemehuevi Mountains, Southwestern California**

LaForge et al. (2017) use the syntectonic Miocene Chemehuevi dike swarm to characterize the timing and slip history of the Chemehuevi detachment fault system in southeastern California, USA. Detailed U-Pb geochronology documents diachronous emplacement of the dike swarm from 21.45 ± 0.19–19.21 ± 0.15 Ma adjacent to the Mohave Wash fault segment, beginning ~1.5 m.y. after the onset of regional extension. The lack of deformation of dikes at structurally shallow levels (<9 km minimum paleodepth) contrasts with the localized rotation, folding, and mylonitization of dikes at deeper structural levels, suggesting that the dikes were emplaced during processing of the detachment fault through the brittle-plastic transition. The dikes locally compose up to 25% of the footwall adjacent to the fault zone, but they probably accommodated no more than 2% of total regional extension. The dominant east-west and northeast-southwest trends of dikes within the swarm are unique to this core complex and contrast with the predicted emplacement orientation for the northeast-directed extension inferred for other core complexes in the region. The elemental geochemistry of the Chemehuevi dike swarm...
Teton Range have distinct geologic histories and are separated by a ductile deformation zone active at ca. 2.62 Ga. In the northern Teton Range, gneisses preserve evidence for 2.69–2.68 Ga high-pressure granulite-facies metamorphism (>12 kbar, 900 °C) followed by tectonic assembly at high-pressure, amphibolite-facies conditions (7 kbar, 675 °C). They interpret these features to record one of the oldest continent-continent collisional orogenies on Earth. Gneisses of the southern Teton Range contain a variety of quartzofeldspathic gneisses, including a 2.80 Ga granodioritic orthogneiss and the 2.69–268 Ga Rendezvous Gabbro. Granulite metamorphism is not observed, and instead, gneisses of the southern Teton Range have affinities with rocks elsewhere in the Wyoming Province. They propose that gneisses of the northern Teton Range formed distally and subsequently accreted from the west against the Wyoming Province at ca. 2.62 Ga. They conclude that accretion at this time was taking place along both the southern margin and western margins of the Wyoming Province.

In a companion paper to Frost et al. (2018), Swapp et al. (2018) shed new light on Archean tectonic processes and the origins of modern plate tectonic behavior by documenting a well-preserved occurrence of Neoarchean high-pressure granulite gneiss in the Teton Range of Wyoming, USA. They demonstrate that 2.70 Ga high-pressure, granulite-facies metamorphism is followed by the juxtaposition of gneisses of mixed protoliths, and then by injection of leucogranites produced by decompression melting in response to postcollisional uplift. They attribute this history to 2.70–2.68 Ga Himalayan-style orogeny, suggesting that doubling of crustal thickness by continental collision may date back to at least 2.7 Ga.

Kruckenberg et al. (2019): From Intracrystalline Distortion to Plate Motion: Unifying Structural, Kinematic, and Textural Analysis in Heterogeneous Shear Zones through Crystallographic Orientation-Dispersion Methods

Kruckenberg et al. (2019) report an innovative approach to reconstructing the angle of paleotectonic convergence between ancient plate fragments (the Nashoba and Avalon terranes) through microstructural vorticity analysis in the intervening crustal-scale mylonitic shear zone (the Burlington Mylonite Zone in eastern Massachusetts, northeastern USA). Specifically, they use lattice-scale rotation axes defined by electron backscatter diffraction to define a vorticity-normal surface that provides the frame of reference for rigid grain vorticity analysis. The mean kinematic vorticity number ($W_v$) calculated by applying rigid grain net analysis is then used to infer a sinistral reverse transpressional strain regime that operated at relatively high stress during Avalon-Nashoba plate convergence under greenschist- to amphibolite-facies conditions.

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