Subduction, asthenospheric flow, and the evolution of foreland thrust-and-fold belts: Insights from the southern Canadian Cordillera

Raymond A. Price, Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, ON, K7L3N6, price@geol.queensu.ca

The Cordillera of North and South America, the archetypical, asymmetrical, bivergent, continental-margin orogen, displays conspicuous contrasts between the retrograde-vergent back-arc foreland thrust-and-fold belt that occupies the continental margin of the orogen and the prograde-vergent fore arc thrust-and-fold belt that occurs locally along the oceanic margin. The back-arc belt is continuous for the length of the orogen, although variable in width and structure. It generally comprises supracrustal rocks that were scraped off the under-riding crystalline basement of the continental margin by the over-riding volcanic arc and back-arc basin rocks of the interior of the orogen; but locally it involves thrusting and related folding of the brittle upper part of the continental crust. The retrograde-vergent thrusting and folding has generally been viewed as a second-order effect of the subduction of oceanic lithosphere; it has been ascribed to crustal thickening during convergence between the interior of the continent and an adjacent continental-margin subduction zone, and to the ensuing lateral gravitational spreading of the thickened crust as a critical-taper thrust-and-fold wedge with an associated foreland basin. The fore arc belt, which is a first-order effect of the subduction, can be distinguished from the back-arc belt because it comprises material scraped off the under-riding oceanic lithosphere by the over-riding continent; moreover, it is commonly discontinuous, because the subduction zone is commonly a zone of tectonic erosion and removal of continental material rather than accretion and addition of oceanic material.

Continental collision orogens develop where a plate of continental crust is drawn into a continental margin subduction zone by the negative buoyancy of the attached oceanic lithosphere that is sinking into the mantle. Although continental collision orogens commonly involve the development of a prograde-vergent foreland thrust-and-fold belt comprising supracrustal rocks that are scraped off the under-riding continent by the over-riding continent, these can be distinguished from continental margin, retrograde-vergent, thrust-and-fold belts because they include a subduction scar comprising the fault zone that separates and juxtaposes rocks that came from two different continents.

The prevailing interpretation of the nature and tectonic significance of the foreland thrust-and-fold belt of the North American Cordillera as a second-order effect of the crustal thickening generated by subduction has recently been challenged with conjectures[1, 2] about the former existence of a "ribbon continent" located outboard of the North American continental margin, and separated from it by an ocean basin, and about the subduction, under this "ribbon continent", of both the conjectural intervening ocean basin and the western continental margin of North America. These conjectures, which imply that the Cordilleran foreland thrust-and-fold belt is a prograde-vergent, first-order expression of the subduction of oceanic lithosphere, require that a previously (and still) unidentified plate-tectonic suture (subduction scar) occurs within the eastern part of the North American Cordillera, and that it extends from east-central Alaska to northwestern Mexico, separating North American supracrustal strata from supracrustal strata on a "ribbon continent" that originated elsewhere.

The basic tenets of the "ribbon continent" conjecture are incompatible with what is known about the geology of much of the North American Cordillera. For example, in the southeastern Canadian Cordillera: (1.) The integrity and continuity of the Crowsnest Pass cross-strike discontinuity (CPCD), a set of transverse, northeast-trending structures that extends across the foreland thrust-and-fold belt from southwestern Alberta to the Cordilleran accreted oceanic terranes of northeastern Washington and south-central British Columbia, precludes the existence of the subduction scar that is required by the "ribbon continent" conjecture. The CPCD, which is aligned with the Vulcan low, a northeast-trending Paleoproterozoic crustal suture that marks the northern limit of the Archean Medicine Hat domain in the basement of the Western Canada sedimentary basin southeast of Calgary, comprises a set of faults that were reactivated and influenced basin subsidence and basin-margin uplift and erosion during the formation of the Mesoproterozoic Belt-Purcell basin, the Neoproterozoic Windermere basin, and the Paleozoic Cordilleran miogeocline continental shelf basin. Reactivation of these basin margin faults during Jurassic to Paleocene thrusting and folding influenced the location and orientation of the structural culminations that dominate the structure of the foreland thrust-and-fold belt. (2.) Furthermore, stratigraphic analysis of the undisturbed strata in the western Canada sedimentary basin and adjacent parts of the eastern Cordillera demonstrates that a distinctive sequence of tectonostratigraphic units, bounded by distinctive erosional surfaces, can be confidently correlated through the thrust-and-fold belt and into the interior of the southern Canadian Cordillera, where these North American rocks are in fault contact with accreted oceanic-volcanic-arc and ocean-floor rocks of Quesnel, and Slide Mountain terranes. (3.) Moreover, Archean and Paleoproterozoic crystalline basement rocks that are exposed beneath Eocene extensional detachment faults in the interior of the Cordillera can be correlated with tectonic domains in the subsurface of the Western Canada sedimentary basin that contain rocks of the same type and age. (4.) In addition, stratigraphic relationships among the accreted ocean-basin and oceanic volcanic-arc terranes, and between them and the North American supracrustal indicate that they formed above an east-dipping subduction zone and in a related back-arc basin, and that during Early Jurassic collapse of the back-arc basin, subduction generated arc magmatism migrated eastward into the North American supracrustal rocks. If a conjectural "ribbon continent" and a west-dipping subduction zone do not provide a viable tectonic process model for the origin of the Cordilleran foreland thrust-and-fold belt, what does?

The structure of the detached and displaced North American supracrustal rocks within the foreland thrust-and-fold belt in southern Canada provides unequivocal evidence for horizontal convergence (shortening) between the North American craton and the accreted terranes that varies from place to place from 100 to 300 km; it shows that some of this convergence was transformed northwestward into dextral displacements on large strike-slip faults. However, the related deformation that occurred at depth and involved both the subducting slab of oceanic lithosphere and the continental crust and mantle lithosphere from which these supracrustal strata were detached is much less clearly understood, even with the advantages of the geophysical deep imaging that has been provided by the Lithoprobe Project[3]. But the kinematics and geodynamics of this deformation are being elucidated now.

Recent discoveries about the nature and geodynamic significance of a wide zone of high heat flow and extraordinarily shallow asthenosphere above the subducting Juan de Fuca slab and in the back-arc region of the Cascade arc[4] have been extended to many other back-arc regions around the Pacific rim[5]. These discoveries help to elucidate the processes linking retrograde-vergent, critical-taper thrusting in the foreland thrust-and-fold belt to the prograde shear along the top of the subducting slab. The descending cold slab of oceanic lithosphere is a heat sink, and therefore the high temperatures documented in the back-arc mantle above the subducting slab are unexpected. The current consensus is that retrograde mantle flow (corner flow), driven by the viscous coupling between the subducting slab of oceanic lithosphere and surrounding mantle and by the thermal buoyancy of hot asthenosphere, carries heat from outside the subduction zone region into the mantle wedge[6]. This pattern of subduction related mantle flow provides the key to understanding several otherwise enigmatic aspects of the tectonic evolution of the southern Canadian Cordillera, and other continental margin orogenic belts.

In the southern Canadian Cordillera, the collapse of the Slide Mountain basin and the associated obduction of Slide Mountain terrane were followed by a minimum of between 100 and 300 km of convergence between the North American craton and Slide Mountain and Quesnel terranes. Retrograde back-arc mantle flow helps to elucidate this process and much of the ensuing tectonic evolution of the southern Canadian Cordillera: (1.) The retrograde mantle flow above the subducting slab may provide an explanation for the collapse of the Slide Mountain back-arc basin and the Early Jurassic obduction of Slide Mountain terrane over North American strata. The oceanic lithosphere that formed the floor of the Slide Mountain basin, which has disappeared, evidently became entrained with the retrograde back-arc downward flow above the subducting Cache Creek oceanic lithosphere and was returned to the mantle. The outer edge of the North American continental slope and shelf probably was drawn, by the attached sinking Slide Mountain oceanic lithosphere, into the top of the subduction zone and thus thrust under the supracrustal rocks that comprise the Slide Mountain terrane. (2.) The retrograde back-arc mantle flow may also have facilitated the delamination and removal of the oceanic crust and lithosphere of Quesnel terrane when it was detached and displaced northeastward, as a “tectonic flake”, over the thin wedge of North American basement that has been imaged by Lithoprobe under central British Columbia; (3.) Heat transported by the upwelling hot asthenosphere may have reduced lower crustal ductility and facilitated the transformation of thrust displacement into ductile crustal flow in the root zone of the foreland thrust-and-fold belt; and (4.) following the termination of the Eocene episode of dextral transtension and crustal boudinage at ~40 Ma, the mantle upwelling that sustains the abnormally high elevation of the Interior Plateau may also have dynamically sustained rock uplift and high topographic relief near the edge of the upflow in the southern Canadian Rocky Mountains and the Columbia Mountains. Patterns of mantle flow associated with the gravitational sinking of subducting slabs of oceanic lithosphere may provide important insights on many aspects of Cordilleran geodynamics.

References

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