

Orographic precipitation, erosional unloading, and tectonic style

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ABSTRACT

Comparative tectonics of the Thelon (1.97 Ga) and Wopmay (1.88 Ga) orogens of north-west Canada and the Grenville (1.1 Ga) and Alleghany (0.3 Ga) orogens of eastern North America support geophysical models linking orographic precipitation and erosion to tectonic style. Paleomagnetic data imply that the Thelon and Grenville orogenic fronts were favorably situated to face trade winds and experience monsoonal precipitation. High rates of uplift could have been balanced by erosional unloading. Consequently, the orogenic fronts are deeply eroded and lack thin-skinned foreland thrust-and-fold belts. Tectonic progradation was achieved instead by thermal activation of the orogenic footwall. Foreland basins, where preserved, are overfilled with sediments that are dominantly fluvial to shallow marine, compositionally mature, and progradationally stacked. The Wopmay and Alleghany orogenic fronts developed in rain shadows. Erosional unloading could not offset even modest rates of tectonically driven uplift, resulting in mass flow onto the foreland manifested by thin-skinned thrust-and-fold belts and associated foreland basins. Foreland basins are underfilled and well preserved, containing sediments that are dominantly deep water, compositionally immature, and aggradationally stacked. The nature of the Mauritanide orogenic front is consistent with it being the windward complement of the Alleghany front.

INTRODUCTION

Contractional orogens and related sedimentary basins are stylistically diverse. The two largest orogens in eastern North America have the same overall tectonic polarity and association with supercontinental fusion, but they are stylistic opposites. The Grenville orogen is deeply eroded, has steep frontal metamorphic gradients, extensive footwall reactivation, and virtually no thin-skinned thrust-and-fold belt or foreland basin. The converse is true of the Alleghany orogen. This is not simply a function of age: many orogens older than the Grenville (e.g., the 1.9 Ga Wopmay and New Quebec orogens in Canada) more closely resemble the Alleghany in tectonic style.

It has become customary to attribute such stylistic differences to variable tectonic histories or processes (e.g., Royden and Burchfiel, 1989). Here we consider a neglected factor—that erosional unloading governed by orographic precipitation modulates the material flux within orogens in ways reflected in the resulting tectonic style. Inspired by the New Zealand Alpine orogen, Koons (1989) and Beaumont et al. (1991) investigated this factor in geophysical models that coupled crustal deformation with surface processes. Our purpose is to show how the orographic erosion factor could explain two pairs of ancient orogenic fronts having common subduction polarities but contrasting tectonic

styles. The explanations are compatible with independent paleoclimatic inferences. We do not claim that inherent tectonic factors are unimportant but that, in certain situations, they may be strongly modulated by exogenic forcing.

GEOPHYSICAL MODELING

Beaumont et al. (1991) ran finite-element models of the plane-strain velocity field developed during the deformation of a viscous-plastic region of the crust as it is compressed against a rigid footwall ramp (continental margin). Their models incorporate the effects of erosion and sediment transport controlled by orographic precipitation according to a surface process model developed by Koons (1989) and Chase (1992). Adiabatic decompression of air masses that cross the region results in a windward area of high precipitation and a leeward rain shadow.

Surface processes influence tectonics because the gravitational component of stress distribution within the orogen is a function of the mass flux induced by erosion (Beaumont et al., 1990). In effect, uplift trajectories are drawn toward areas of maximum erosional unloading. At windward orogenic fronts, large amounts of uplift are possible because of sustained high rates of erosion. The resulting thermal anomalies conductively soften the footwall, leading to its involvement in the deformation. At leeward fronts,

uplift is inhibited and the frontal metamorphic gradient and extent of footwall reactivation are reduced. The models predict that a dynamically steady-state mass balance can be achieved at windward fronts in which the tectonic mass flux is balanced by erosional denudation. At leeward fronts, erosion is insufficient to balance the tectonic mass flux, resulting in the tectonic progradation of a thin-skinned thrust-and-fold belt into the foreland.

The modeling implies that erosion rates at windward fronts may be sufficient to significantly reduce the topographic loads that contribute to lithospheric flexure (excluded in the model formulation). Hence, lithospheric flexure is reduced despite greater sediment supply, resulting in overfilled foreland basins. Conversely, at leeward fronts, low rates of erosion lead to enhanced topographic loads. Lithospheric flexure is increased despite reduced sediment supply, producing underfilled foreland basins. It follows that windward foreland basins should be poorly developed and dominantly progradational; leeward foreland basins should be well developed and dominantly aggradational (Burbank and Beck, 1991). Also, windward fronts should produce compositionally more mature detritus than leeward fronts because chemical weathering is linked to precipitation. These differences are summarized in Table 1.

TABLE 1. STYLISTIC SPECTRUM OF OROGENIC FRONTS
RELATED TO RATES OF PRECIPITATION AND EROSION

	HIGH RATES	LOW RATES
Overall depth of erosion	Deep	Shallow
Frontal metamorphic gradient	Steep	Gentle
Footwall reactivation	Extensive	Restricted
Thin-skinned thrust-fold belt	Narrow	Broad
Synorogenic detritus	Compositionally mature	Compositionally immature
Foreland basin	Poorly preserved, overfilled, fluvial to shallow marine deposits dominant; progradational stacking	Well-preserved, underfilled, submarine fan deposits dominant; aggradational stacking

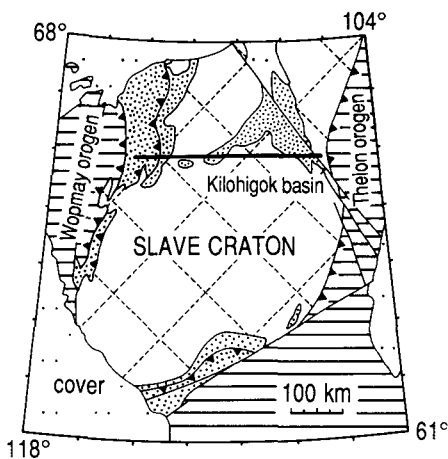


Figure 1. Tectonic setting of Slave craton and sedimentary rocks (dotted) related to collisions with microcontinents (ruled) in Wopmay and Thelon orogens. Bar gives line of section in Figure 2.

THELON AND WOPMAY OROGENS

The Thelon and Wopmay orogens face each other across the 500-km-wide Archean Slave craton (Fig. 1) in the northwest corner of the Canadian Shield. Collisions between the passive margins of the craton and other microcontinents occurred at 1.97 Ga on the east side and 1.88 Ga on the west side (Bowring and Grotzinger, 1992). Remnants of the related sedimentary basins are preserved across much of the intervening craton (Fig. 2).

Paleomagnetic data indicate that the foreland basins evolved at paleolatitudes of 10°–30° (McGlynn and Irving, 1981; Evans and Hoye, 1981). Paleopoles, corrected for probable tectonic rotations about local vertical axes, cluster in northern South America. Prevailing southwesterly (present coordinates) winds were inferred, independent of the present argument, from the rimmed car-

bonate platform and condensed carbonate foreslope facies of the Wopmay orogen passive margin, combined with strongly oblique, northeast-southwest, azimuthal elongation of the shelf-edge stromatolites (analogous to spur-and-groove structure of modern reefs) (Grotzinger, 1986). The inference is compatible with a northern hemisphere location only (Fig. 3a): northeasterly trade winds would have blown from the southwest (in present coordinates), and the coast would have been moistened by tropical ocean currents deflected by the >3000-km-long active continental margin (e.g., modern Philippines). Were it antipodean (Fig. 3b), trade winds would have been offshore southeasterlies, and the coast would have been desiccated by the warming of polar ocean currents along its (present) western margin (e.g., modern Atacama and Namib deserts).

The contrasting tectonic styles of the two orogens are consistent with the expected high rates of precipitation and erosional unroofing of the Thelon orogen relative to the Wopmay orogen (Table 1). Regional metamorphic grade of the overriding plate is granulite facies in the Thelon (Thompson, 1989) and greenschist facies in the Wopmay (St-Onge, 1985). The cratonic footwall of the Thelon was tectonically thickened and unroofed, such that Paleoproterozoic sedimentary cover was preserved no closer than 50 km horizontally (prior to younger transcurrent faulting) from the leading edge of the overriding plate (Fig. 1). The intervening

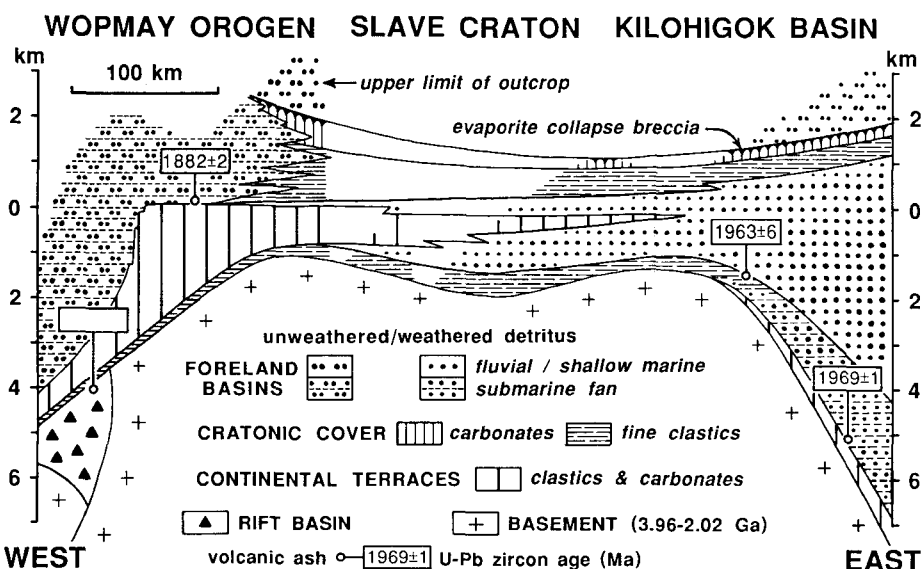


Figure 2. Tectonostratigraphic relations and chronostratigraphic data for sequences related to Wopmay and Thelon orogens (see Fig. 1 for location).

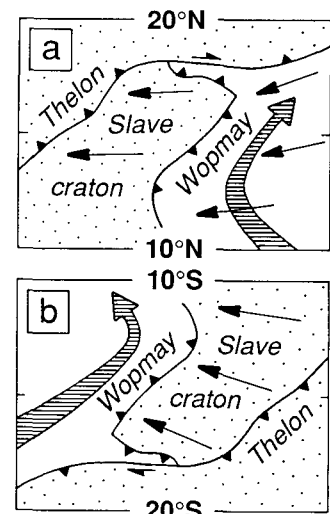


Figure 3. Northern (a) and Southern (b) Hemisphere paleogeographies compatible with existing paleomagnetic data, showing inferred trade winds (solid arrows) and ocean currents (ruled arrows). Only (a) is compatible with geologic observations (see text).

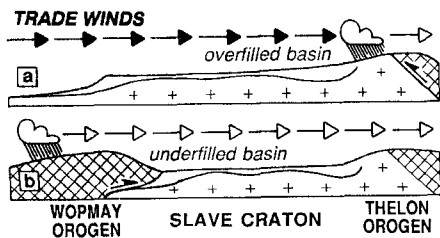


Figure 4. Cartoon of orographic precipitation, topography, and sedimentary basins on Slave craton at (a) 1.95–1.90 Ga and (b) 1.88–1.86 Ga, assuming easterly trade winds and a 15°N line of section (Fig. 3a). Sections are oriented to be consistent with Figure 2.

Archean basement was reactivated under intermediate-pressure metamorphic conditions (Thompson, 1989). In the Wopmay orogen, Paleoproterozoic sedimentary cover is still preserved adjacent to the leading edge of the overriding plate, and exposures of reactivated basement are limited to structural culminations related to postcollisional cross folding (Hoffman et al., 1988). The widths of the thin-skinned thrust-and-fold belts, defined as the transverse horizontal distance from the top of the crustal-scale footwall ramp to the preserved leading edge of the allochthon, are 60 km in the Thelon orogen (Tirrul and Grotzinger, 1990) and 140 km (corrected for younger transcurrent faulting) in the Wopmay orogen (Hoffman et al., 1988).

Contrasting climatic conditions at the two orogenic fronts (Fig. 4) are also reflected in the respective foreland basins (Table 1). The Kilohigok basin (Thelon orogen) is dominated by a braided alluvial wedge (Fig. 2) up to 300 km wide parallel to the uniform west-northwesterly paleoslope. The alluvium prograded well beyond the limit of flexurally driven subsidence (Grotzinger and McCormick, 1988; McCormick and Grotzinger, 1992). The extent of uniformly sandy facies, lacking interbedded mud or silt, and the absence of eolian facies suggest that humid climate and perennial flow conditions existed in the source area (McCormick and Grotzinger, 1992). This is consistent with the remarkable compositional maturity (for a foreland basin) of the sands, which contain only 2%–10% labile components. In contrast, the Wopmay foreland basin is dominated by submarine fan sands fed by south-directed turbidity flows (Hoffman, 1987a). The overlying fluvial deposits are relatively muddy, and paleocurrent directions are highly variable, consistent with aggradation, but the ultimate extent and nature of the fluvial wedge have been lost to erosion. The extreme compositional immaturity of both the submarine and fluvial sands (>30% labile components) implies an arid source area undergoing minimal

chemical weathering, consistent with the former presence of evaporites in the transition zone (Jackson, 1989).

The rain shadow from the Wopmay orogen was also felt in the Thelon orogen (Fig. 4). The main fluvial wedge in Kilohigok basin is overlain by fine-grained marine deposits, indicating a marked decline in clastic input despite continued subsidence (Fig. 2). In both foreland basins, progressively more evaporitic conditions are indicated by marine shales overlain sequentially by marlstone, limestone, dolomite, and a stratiform redbed-carbonate megabreccia. The megabreccias contain gypsum and halite pseudomorphs and are ascribed to solution collapse in evaporite deposits. By 1.87 Ga, the craton across which rivers had recently surged was a vast salt pan ringed by ranges.

GRENVILLE AND APPALACHIAN OROGENS

The Grenville (1.1 Ga) and Alleghanian Appalachian (0.3 Ga) orogens are parallel, northwest-facing collision belts pivotal to the fusion of the supercontinents Rodinia and Pangea, respectively. Both involved the closure of broad oceans with many island arcs, and both had the same dominant subduction polarity with respect to Laurentia. Why then do they look so different? The Grenville has the attributes of a windward orogenic front (Beaumont et al., 1990). Mesoproterozoic arc terranes were compressed against a southeast-dipping, crustal-scale footwall ramp (Green et al., 1988). The zone of footwall reactivation is 200 km wide (Rivers et al., 1989), and it underwent 25–30 km of Grenvillian denudation (Anovitz and Essene, 1990). The Grenville front coincides with a steep metamorphic gradient (>20 °C/km) and a narrow (<10 km) foreland thrust-and-fold belt. As exposed in the Canadian Shield, the orogen has no foreland basin, nor are sediments preserved within or structurally beneath the thrust belt. However, relatively undisturbed 2.4–1.7 Ga sedimentary cover is locally preserved on the foreland up to the front, suggesting that the absence of a Grenvillian foreland basin is not simply due to subsequent erosion. Detritus derived from the orogen is present 3000 km away—in the Cordillera, the western Arctic, and northeast Greenland—implying Amazon-type drainage from the orogen across the continent (Rainbird et al., 1992). A windward Grenville front is consistent with the deposition of evaporites in the hinterland (Whelan et al., 1990) and their absence from the broadly coeval Midcontinent rift system of the foreland.

We have no independent data on Grenvillian wind directions. The paleogeographic location of the orogen is best deduced from

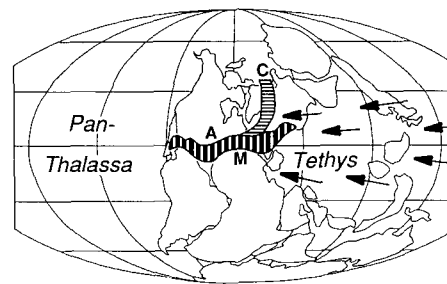


Figure 5. Middle Permian continents after Scotese (1987), showing generalized trade wind directions (arrows), Alleghany (A) and Mauritanide (M) fronts, and residual Caledonides (C).

the paleomagnetic record of the Midcontinent rift system (Palmer and Davis, 1987), which covers most of the denudational phases of the orogen. Assuming that the apparent polar wander path in the north-central Pacific represents north poles (Palmer and Davis, 1987), then the global Grenvillian orogenic system (Hoffman, 1992) would have formed an arcuate mountain chain, concave to the east, stretching from below the equator to the North Pole. The Grenville orogen of the Canadian Shield would have been situated in tropical latitudes facing easterly trade winds from 1090 Ma until after 950 Ma (Palmer and Davis, 1987). Thus, the paleomagnetic data lend credibility to the windward interpretation of the Grenville front.

The Alleghany orogen has the attributes of a leeward orogenic front: it is not deeply eroded, it has a gentle transverse metamorphic gradient, and its footwall underwent relatively little reactivation. It has a well-developed foreland basin (dominantly submarine in the Ouachitas but alluvial in the Appalachians) and a wide foreland thrust-and-fold belt. Coal deposits formed on higher aggradational plains, irrigated by glacial meltwater, but carbonate and sulfate deposition prevailed across the semiarid foreland (Witzke, 1990). The opposite side of the orogen (West African Mauritanides) has a steep transverse metamorphic gradient, a narrow thin-skinned thrust-and-fold belt, and virtually no preserved late Paleozoic foreland basin (Lécorché et al., 1991). The Mauritanide front is inferred to have experienced relatively high rates of precipitation and erosion because of its proximity to the Tethys Ocean (Fig. 5). The Alleghany front was further from Tethys, and trade winds had to cross the residual Caledonides mountains. The subduction polarity of the orogen, however, must also be a factor in its asymmetry (e.g., Willett et al., 1993).

DISCUSSION AND CONCLUSIONS

The depth of erosion of orogens has been attributed to postcollisional convergence

(e.g., the Himalaya). Accordingly, the nature of the Thelon orogen should be related to the large postcollisional convergence implied by its indentational geometry (Hoffman, 1987b). However, it is conceivable that such convergence is itself made possible by high rates of erosional unloading in the orogen. In the Himalaya, both precipitation and convergence rates increase toward the east end of the chain, whereas the mean elevation declines. The high rates of erosion in the eastern Himalaya are due mainly to the late summer monsoon. Monsoons are consequences of large high plateaus, and their erosive power depends on warm transequatorial ocean currents feeding the updrafts. In the "windward" orogenic fronts considered here (Thelon, Grenville, Mauritanides), insofar as their paleogeographies are known, monsoons fed by tropical ocean currents should have amplified the patterns of orographic precipitation imposed by trade winds.

The interpretations above are highly speculative: proper evaluation of the importance of orographic precipitation and erosion on tectonic style will depend mainly on younger orogens, where paleoclimates and tectonic chronologies are better known. Savor the irony should those orogens most alluring to hard-rock geologists owe their metamorphic muscles to the drumbeat of tiny raindrops.

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