Foreland-forearc collisional granitoid and mafic magmatism caused by lower-plate lithospheric slab breakoff: The Acadian of Maine, and other orogens

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ABSTRACT

During collisional convergence, failure in extension of the lithosphere of the lower plate due to slab pull will reduce the thickness or completely remove lower-plate lithosphere and cause decompression melting of the asthenospheric mantle; magmas from this source may subsequently provide enough heat for substantial partial melting of crustal rocks under or beyond the toe of the collisional accretionary system. In central Maine, United States, this type of magmatism is first apparent in the Early Devonian West Branch Volcanics and equivalent mafic volcanics, in the slightly younger voluminous mafic/silicic magmatic event of the Moxie Gabbro–Katahdin batholith and related ignimbrite volcanism, and in other Early Devonian granitic plutons. Similar lower-plate collisional sequences with mafic and related silicic magmatism probably caused by slab breakoff are seen in the Miocene–Holocene Papuan orogen, and the Hercynian–Alleghenian belt. Magmatism of this type is significant because it gives evidence in those examples of whole-lithosphere extension. We infer that normal fault systems in outer trench slopes of collisional orogens in general, and possibly those of oceanic subduction zones, may not be primarily due to flexural bending, but are also driven by whole-lithosphere extension due to slab pull. The Maine Acadian example suggests that slab failure and this type of magmatism may be promoted by preexisting large margin-parallel faults in the lower plate.

Keywords: Acadian orogeny, lithospheric slab breakoff, foredeep magmatism, outer trench slope normal faults, Papuan orogeny.

INTRODUCTION

Hoffman (1987) first called attention to the phenomenon that he termed foredeep magmatism. He cited several examples from the Proterozoic of Laurentia in which mafic magmas were emplaced on the lower plate of a collision zone in the proximal or distal foreland. Foreland magmatism during the Phanerozoic has not been widely reported; in this paper we review and present additional evidence to explain extensive foreland magmatism present as a prominent regional belt of granitoid rocks in the Silurian–Devonian of the northern Appalachians (United States), in the Neogene of Papua New Guinea, and in the Hercynian orogen.

The Acadian orogeny of the northern Appalachians is a Late Silurian–Devonian collision zone (e.g., Robinson et al., 1998). In Maine, it is interpreted as the result of collision between the outboard Avalon terrane and the Taconic-modified passive margin of Laurentia and was markedly protracted, beginning in the Late Silurian in outboard locations and ending in the Late Devonian at the northwestern side of the orogen (Bradley et al., 2000).

Robinson (1993), following Nelson (1992), proposed a model of subcontinental lithospheric detachment of the lower plate as the Laurentian margin entered a southeast-dipping subduction zone. Consequent high heat flow and melting of the mantle and lower crust was suggested to explain magmatism in the Medial New England Belt during the Acadian orogeny, west of the subduction-related coastal volcanic belt. This model (Fig. 1) was elaborated on in Bradley et al. (1996), Robinson et al. (1998), Bradley and Tucker (2002), and Begeal et al. (2004). Similarly, Sacks and Secor (1990) suggested lithospheric necking to explain early granitic magmatism in the lower plate of the southern Appalachian system during the Alleghenian orogeny. These models propose detachment of sections of the underthrust lower plate during the early orogenic stages of the subduction of a passive margin, rather than later, as proposed by Bird (1978) for the Himalaya, when significant lithospheric thickening and overthrusting has occurred.

ACADIAN OF CENTRAL MAINE—GEOLOGY OF THE CHESUNCOOK DOME

The Chesuncook Dome of north-central Maine is near the inboard margin of the Central Maine Basin, the deformed vestige of the deep-water basin that closed during Acadian collision (e.g., Bradley et al., 2000). Two events of near-trench magmatism are recorded in the Early Devonian geology of the Chesuncook Dome and are the initial focus of this paper. Significant aspects of the geology of the dome (Griscom, 1976; Kusky et al., 1994; Begeal et al., 2004) are summarized here and in Figure 2.

Shallow-marine sedimentation was established in the region from the Middle to latest Silurian. Close to the Silurian-Devonian boundary, this is interrupted by a significant erosional disconformity and covered by a rapidly deepening sedimentary section, with successive deposition of quartzite, limestone, limestone breccia, and silt/mud contourites/pelagics. Begeal et al. (2004) interpreted this to be the result of uplift over a flexural forebulge followed by subsidence down the outer trench slope, and suggested that the breccia was provided by normal fault scarps formed during this process. Within the deeper-water deposits of the outer trench slope, the West Branch Volcanics erupted, forming a unit of laterally variable thickness (from 200 to more than 1000 m over a few kilometers distance, possibly also normal fault controlled). This

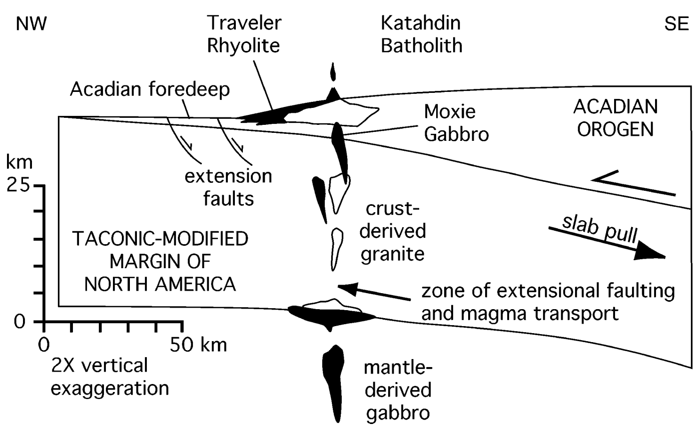

Figure 1. Schematic cross section of Chesuncook Dome–Katahdin area showing relationship of mafic and granitic magmas to upper and lower plates of Acadian orogen. Modified from Bradley and Tucker (2002).

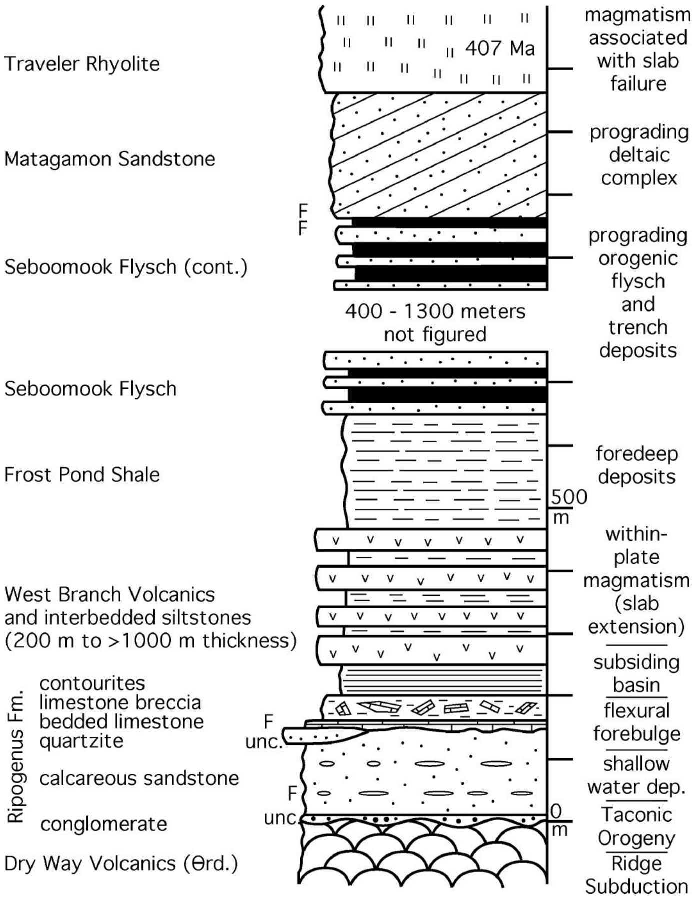

Figure 2. Silurian–Devonian stratigraphic section from Chesuncook Dome, Ripogenus Dam area. Bedded limestone of Ripogenus Formation is exaggerated for clarity. Based on geology of Griscom (1976) and Begeal et al. (2004). F—fossil; unc.—unconformity.

volcanism occurred in the foreland when the Acadian deformation front was 90 km or more to the southeast (Bradley et al., 2000).

The conformably overlying Seboomook Flysch (~2+ km thick; Hall et al., 1976) and Matagamon Sandstone represent trench-filling turbidite and succeeding shallow-marine sediments, both derived from the Acadian orogenic highlands to the southeast (Pollock et al., 1988; Bradley and Hanson, 2002). The Matagamon Sandstone is conformably overlain by the Traveler Rhyolite, as much as 3200 m of ash-flow tuffs with a U/Pb zircon age of 407 Ma (Rankin and Hon, 1987; Rankin and Tucker, 1995). Field relations, geochemistry, and a precise isotopic age on the granite (407 ± 0.4 Ma) show that the Traveler Rhyolite is the extrusive equivalent of, and local carapace to, the Katahdin Granite, an exceptionally large pluton, ~60 by 35 km (Hon, 1980; Rankin and Hon, 1987; Rankin, 1994; Rankin and Tucker, 1995; Bradley and Tucker, 2002).

WEST BRANCH VOLCANICS—GEOCHEMICAL AFFINITIES

The West Branch Volcanics are mostly basalts with a few basalt andesites. Geochemical studies by Fitzgerald (1991), Hon et al. (1992), and Schoonmaker and Kidd (2003) show that they are strongly enriched in the light rare earth elements (LREEs), have a strong negative slope on mid-oceanic-ridge basalt (MORB)-normalized diagrams (Fig. 3), and have high Ti/Y ratios characteristic of within-plate basalts. Samples plot within, or define a trend that originates from, the within-plate field in the Ti-Zr-Y diagram of Pearce and Cann (1973). However, on MORB-normalized diagrams thorium is strongly enriched (and cerium to a lesser extent), and a prominent negative Ta-Nb anomaly is

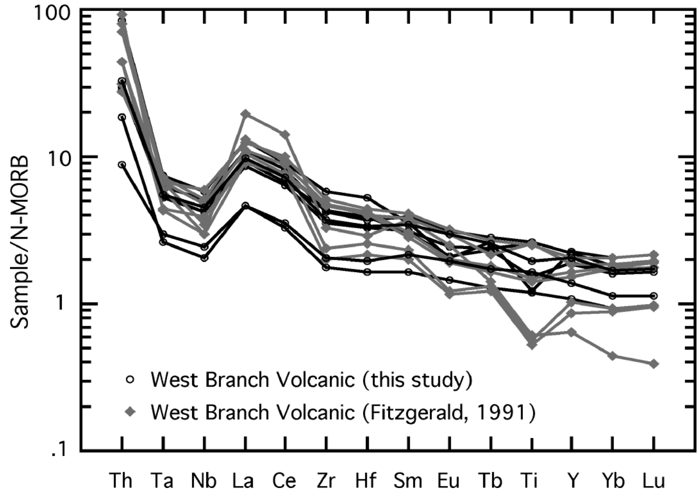

Figure 3. Mid-oceanic-ridge basalt–normalized (N-MORB) spider diagram of West Branch Volcanics. Normalization values are from Sun and McDonough (1989).

present (Fig. 3). At least one of the few samples that are basalt andesite in composition contains both mafic and silicic inclusions, indicating the incorporation of preexisting crustal rocks into the magma. Additionally, the spread in the geochemical composition of the West Branch Volcanics trends toward an upper-crustal composition on geochemical tectonic discrimination diagrams (Ti-Zr-Y, Hf-Th-Nb, Th/Yb-Ta/Yb, Ce/Nb-Th/Nb; Schoonmaker and Kidd, 2003). We agree with Fitzgerald (1991) and Hon et al. (1992) that the thorium enrichment is the result of incorporated crustal material, and the Ta-Nb anomaly results from the partial melting of a previously subduction-modified, subcontinental lithosphere rather than from a highly enriched plume source. Similar within-plate–like chemistries are seen in time-equivalent volcanics in other parts of Maine (Spider Lake, Hedgehog, Edmunds Hill, and Five Mile Brook Formations; Hon et al., 1992; Keppie and Dostal, 1994) and New Brunswick (Tobique Belt, Dalhousie Group, and Chaleur; Dostal et al., 1989; Keppie and Dostal, 1994), suggesting that this is regionally significant.

MOXIE-KATAHDIN-TRAVELER MAGMATIC SUITE

An early Emsian (ca. 404–408 Ma), largely granitoid magmatic belt extends along strike several hundred kilometers from Massachusetts to Maine (Bradley et al., 2000), and similarly aged plutons and volcanics extend into New Brunswick and the Gaspé Peninsula (Tobique Volcanic Belt), an overall extent of nearly 1000 km (Fig. 4). In the Chesuncook Dome area, rocks of this belt include the Moxie pluton

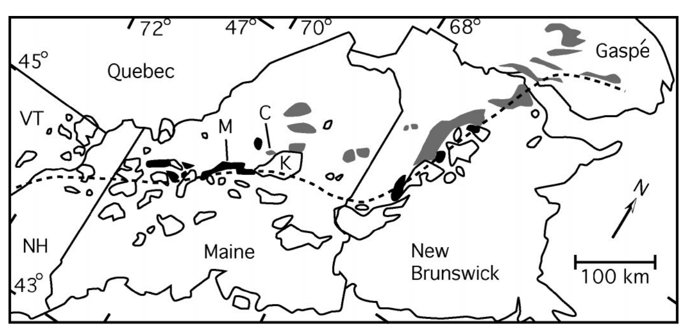

Figure 4. Regional map showing distribution of Silurian–Devonian magmatism. Open fields—granitoid plutons; black—mafic plutons; gray—volcanics, mainly basaltic and andesitic; K—Katahdin batholith; M—Moxie pluton; C—Chesuncook Dome. Dashed line is general trace of magmatism. Adapted from Williams (1978); Dostal et al. (1979), and Bradley et al. (2000).

(a large strike-parallel gabbroic dike, 80 km long by 1–3 km wide, dated as 406.3 ± 3.8 Ma; Bradley et al., 2000), the granitic Katahdin batholith, and the Traveler Rhyolite. We suggest that extension of the downgoing plate, which initially manifested in Lockhovian time (ca. 417 Ma) by normal faulting associated with a change in sedimentation from shallow to deep water and by West Branch volcanism, recurred ca. 407 Ma with the much larger volume magmatism of the coeval Moxie pluton and Katahdin-Traveler suite. By then, the Acadian deformation front had migrated into this area, and the magmatism as a result intruded, and was locally deposited on, the trench-fill sediments.

We interpret the source of the Moxie pluton to have been upwelling mantle resulting from lithospheric slab breakoff, and that the strike-parallel form of the intrusion was controlled and localized by the break-off fault zone in the lower plate. The mafic compositions of the Moxie pluton contrast with the felsic nature of the Katahdin-Traveler suite and other large granitoid plutons of the Greenville Plutonic Belt. Intermediate Pb isotopic signatures ($^{206}Pb/^{204}P = 18.20$–18.40, $^{207}Pb/^{204}Pb = 15.56$–$15.60$), and intermediate Sr isotope values of 0.7041–0.7083 (Ayuso, 1986) for Central Maine granites, including the Katahdin Granite, suggest a mixing of mantle-derived mafic magmas (Moxie like) with continental crust–derived granitic partial melts, a conclusion also proposed by Hon (1980) for the Katahdin-Traveler suite. Bradley and Tucker (2002) suggested that heat from Moxie-like plutons may have contributed to partial melting of continental crust, both in the downgoing plate and in the growing forearc region of the overriding plate.

Emplacement of the Katahdin Granite is likely syntectonic (Bradley and Tucker, 2002), but this should be seen as located near the active deformation front (near trench) in the context of the northwestward migration of the Acadian foreland and deformation front across Maine over a period of at least 40 m.y. (423–383 Ma) documented by Bradley et al. (2000). Localization of other younger Acadian granitoid intrusions in similar spatial relation to the advancing trench-deformation front (Bradley et al., 2000) suggests that one or more additional (partial?) slab break-off magmatic events may have occurred.

It is notable that the Katahdin Granite and other plutons of similar age (Hubacher and Lux, 1987; Bradley et al., 2000) within and along strike of the Greenville Plutonic Belt intrude lowest greenschist facies metamorphic rocks (indicating shallow-level intrusion) but were not subsequently stripped away by uplift and erosion. The preservation of the upper part of the Katahdin magma chamber and the carapace of the Traveler ash flows erupted from it is also evidence that the Chesuncook region and along-strike correlatives were not areas of great crustal thickening during the Early to Middle Devonian event. In the Acadian orogen, exhumed high-pressure rocks are not present. This is also consistent with early detachment of the oceanic lithosphere limiting the subduction of buoyant continental material.

OTHER EXAMPLES OF GRANITOID COLLISIONAL FORELAND MAGMATISM

A present-day example of collisional foreland magmatism occurs where the northern margin of the Indo-Australian plate is involved with the Papuan New Guinea orogen. North-directed subduction of the Indo-Australian plate since the late Oligocene–early Miocene has resulted in a change from passive margin–type sedimentation to foreland and overlying orogenic clastic sediments, which onlap southward away from the Central orogenic belt (Pigram and Symonds, 1991). Analysis of the Papuan Basin shows significant subsidence of the Indo-Australian plate starting ca. 25 Ma (Haddad and Watts, 1999). South of the implied suture zone, there are a series of mafic to intermediate Quaternary volcanoes (Mackenzie, 1976) as well as a belt of late Miocene and younger granitoids (Griffin, 1983) that intrude the foreland and/or the overthrust Australian passive margin sediments. Although some (e.g., Hill and Raza, 1999) have suggested that these magmatic rocks represent an episode of southward subduction, we think the evidence for this interpretation is weak, and the foreland depositional and subsidence history shows no evidence for it. Klootwijk et al. (2003) proposed an origin by collisional crustal/lithospheric thickening, but this does not explain the position of some magmatic centers near the foreland basin margin. We propose that the late Miocene–Holocene magmatism in Papua New Guinea is, like the Maine Acadian, caused by slab-pull extension of the underthrust plate, and by emplacement of the resulting mantle-derived decompression melts into the upper plate.

The Hercynian orogenic belt in England contains granitoid rocks emplaced into low-grade sediments of an accretionary thrust belt (Shackleton et al., 1982), which we suggest resulted from slab breakoff late during southeast-directed collisional subduction. Broadly synkinematic and widespread granitoid magmatism in the lower plates of Archean greenstone belts might also have originated by the same slab-break-off mechanism.

POSSIBLE MECHANISM FOR SLAB FAILURE

The distinctive characteristic of the orogenic segments described here is that mafic and/or felsic magmatism occurred in the active foredeep region and into, or through, the lower plate. Presumably, most continental margin subduction events are eventually terminated by slab breakoff at depth. However, in the case of the Acadian orogeny, slab failure appears to have initiated when the leading edge of the subducting continental margin was still in the far foreland or outer trench position. One possible explanation is that a significant structural weakness was present in the lower plate at or near the continental-oceanic boundary. We interpret the pre-Silurian geology of the Chesuncook region to indicate that it was affected by an Ordovician ridge-subduction event (Schoonmaker and Kidd, 2003), similar to the development of the San Andreas transform boundary (Atwater, 1970). We think that this event formed a mechanically weak pseudo-passive margin containing large strike-parallel faults, which subsequently failed in extension during Acadian underthrusting.

Based on gravimetric analysis of the northern Australian craton, Haddad and Watts (1999) interpreted a zone of lithospheric weakness that corresponds to the region of Quaternary volcanism discussed here. Their preferred explanation is a weakening of the lithosphere due to heating during magmatism. However, we prefer the explanation that the weakness originated from Mesozoic rifting and/or transform faults (Pigram and Symonds, 1991) associated with opening of the Coral Sea (Late Cretaceous), or earlier Mesozoic rifting of the craton, specifically faulting along the Bosavi transfer zone (Early to Middle Jurassic).

CONCLUSIONS AND IMPLICATIONS

We emphasize that foreland collisional magmatism can create large and regionally significant granitoid magmatic belts and is not restricted to small-volume mafic events, or to the Precambrian. The examples discussed suggest that it is more common than previously recognized. Collisional orogens like the Maine Acadian, characterized by magmatism in the outer forearc and near-trench region of the lower plate, may be the result of particular inherited presubduction structures in the lower plate, while others lacking this kind of magmatism may have simpler histories without such structures, for example, the rifted margin of Laurentia in the Taconic orogen.

Magmatism of this type is significant because it gives evidence of whole-lithosphere extension. It implies that normal fault systems in outer trench slopes of collisional orogens, and possibly oceanic subduction zones as well, do not develop exclusively from flexural bending, but may originate, or grow, by whole-lithosphere extension due to slab pull, even where extension is insufficient to cause surface magmatism. The uneven development of outer trench slope normal faulting near trenches in the present oceans and its active development in a position where flexural angles are never more than a few degrees are both features more easily reconciled with a primary origin from whole-lithosphere extension rather than mild flexural bending.

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