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Unroofing Maine: Relating pressure of crystallization, thermochronological data, tectonics, and topography

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ABSTRACT

We gathered data on the age and depth of crystallization of mid-Paleozoic igneous and metamorphic rocks from 64 sites in and near Maine and also a time series of rock temperatures from the Casco Bay area of Maine. By fitting a trend surface to some of our geobarometric data, we estimated total erosion at the Casco Bay site in the last 284 m.y. and thus the geothermal gradient at that time. The temperatures could thus be converted to a time-series of erosion. Assuming Airy isostasy, we then obtained a time series of the mean height of the land surface above present sea level, represented by *H*.

Of four erosion laws fit to the latter, a power law, $E = \nu_p H^u$ where E is the erosion rate, and ν_p and u are fitting parameters, provides the best fit without excessive mathematical complexity. However, the exponent, u, is (unexpectedly) < 1. We attribute this to crustal thickening at a restraining bend in the Norumbega fault zone. In addition, data from opposite sides of the fault suggest that dip-slip motion has been significantly > 6 km and that it likely began in the late middle Paleozoic, thus extending earlier estimates of this component of displacement backward in time and upward in magnitude. A decrease in denudation rate in the early Mesozoic is interpreted as reflecting suturing of Gondwana and Laurentia to form Pangea; the denudation rate increased again following Mesozoic rifting. This latter increase occurs later to the northwest, suggesting retreat of a rift-flank escarpment at a rate of a few tenths of a millimeter per year.

Using our full geobarometric data set, we calculated an average value of u of 1.2. We then generated topographic maps of the state at 380, 320, and 200 Ma. At 380 Ma, the mountains of western Maine were likely somewhat higher than today's Rocky Mountains. Drainage then was to the northeast, contributing sediment to the Maritimes Basin. The Alleghanian collision at ~320 Ma raised comparable mountains somewhat nearer the present coast in western Maine. Following Mesozoic rifting drainage was also to the southeast, into rift basins bordering the opening Atlantic Ocean. Since the Devonian, an average of >9 km of rock have been eroded from Maine.

1. Introduction

When we admire the rounded hills and low mountains characteristic of much of Maine today, we rarely think of the rugged peaks that once were here or of the immense thickness of rock that has been eroded away to produce the present topography. To explore the character of this ancient topography and its evolution, we collected published data on cooling ages and equilibration pressures of plutons and metamorphic assemblages, now exposed at the surface, from 64 sites in Maine, New Hampshire, and New Brunswick. Then, using an average crustal density, we converted these pressures to depths and, assuming Airy isostasy, to mean heights of the local topography relative to present sea level.

We also used the pressure data to estimate the Paleozoic geothermal gradient in the Casco Bay area of Maine, where West et al. (1993) and West and Roden-Tice (2003) obtained mineral and apatite fission track ages. Their data, hereinafter referred to as the Casco Bay thermochronological data set (or CBT), provide temperatures, at several times in the past, of rocks presently exposed at the surface. Using our Paleozoic geothermal gradient, we transformed these data into a time series of mean topographic elevations. This led us to insights into likely topographic and tectonic history.

We begin by summarizing relevant aspects of Maine's geologic history.

2. Geology of Maine

2.1. Formation of peri-Gondwanan terranes

In the early Paleozoic the core of present-day Maine lay somewhat south of the equator on the margin of Laurentia. The coast faced

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southward toward an ocean, on the opposite side of which lay Gondwana (e.g., Hatcher, 2010, Fig. 4). The ocean was complex. Within it were arc systems as well as several microterranes rifted from Gondwana. Collectively, these are referred to as peri-Gondwanan terranes (Hatcher, 2010). Throughout the early to mid-Paleozoic, in a series of transpressional collisions, these exotic terranes converged with and were accreted to the Laurentian margin (e.g., Hogan and Sinha, 1989, p. 24; van Staal et al., 2009; Hatcher, 2010; Hibbard et al., 2010).

2.2. Acadian orogeny

In Maine, the first of these collisions resulted in the Ordovician Taconic orogeny, recorded in rocks in the northwestern part of the state. Our earliest geobarometric data, however, are from the Late Silurian and Devonian (420–380 Ma) Acadian orogeny. The Acadian involved tectonism and broad-scale regional metamorphism, most intense in western Maine and diminishing in intensity to the east and northeast (De Yoreo et al., 1989, p. 172).

Recognizing that some details of the Acadian are debated, particularly the nature of the subduction between the last colliding microcontinent and Laurentia (Bird and Dewey, 1970, Fig. 9B; Osberg, 1978; Bradley, 1983; Eusden et al., 2000; van Staal et al., 2009; Hibbard et al., 2010), Bradley (1983, p. 391, Fig. 6) and Bradley et al. (2000) suggested the following sequence of events: (i) At ~420 Ma, deformation peaked along the present Maine coast. Simultaneously, structures along the northwestern edge of the Merrimack trough (Fig. 1) and sporadic volcanism in the Piscataquis volcanic arc indicate the beginning of northwest-dipping subduction beneath Laurentia. (ii) Somewhat later, structures along the southeastern margin of the Merrimack trough suggest the initiation of southeastward subduction (Fig. 2). Magma rising above this down-plunging plate resulted in syntectonic plutons, dating from 420 to 400 Ma, in (present-day) coastal Cambro-Ordovician rocks. (iii) The deformation front migrated northwestward across Maine over the next 40 m.y. (Fig. 1, thin lines with ages in italics), affecting sediments in the Merrimack trough and resulting in extensive plutonism in the Piscataquis volcanic arc between 407 and 397 Ma. (4) The front finally died out in southeastern Quebec at ~380 Ma (Bradley and Tucker, 2002, p. 484, Fig. 2).

Along the (present-day) coast, additional plutonism occurred between 370 and 390 Ma, thus postdating the Acadian deformation peak there (Fig. 2) (Holdaway et al., 1982, 1988; Hogan and Sinha, 1989, p. 22; Holdaway, 2004). Hibbard et al. (2010) referred to this as the Famennian event and suspected that it is related to dextral transpression and docking of a later terrane, the Meguma terrane. Contact metamorphism is associated with these plutons. Many of our pressure data come from this period (Fig. 3).

2.3. Norumbega fault zone

During the Late Paleozoic, continued oblique convergence of previously accreted terranes produced a series of NE-trending, dextral transcurrent faults and shear zones that, in Maine, have been collectively referred to as the Norumbega fault zone (Ludman and West, 1999). The Norumbega is a major transpressive structural feature, 25 to 40 km wide and extending at least 400 km from central New Brunswick to southwestern Maine. It may be connected with other faults reaching as far north as St. Lawrence Bay and as far south as southeastern Connecticut (Ludman and West, 1999). Although roughly coincident with the suture between Laurentia and Avalonia, its role as a major terrane boundary is unclear (Ludman and West, 1999).

Little evidence has been found for activity on the Norumbega before ~384 Ma, the age of the Deblois pluton in eastern Maine that is offset by it (Ludman et al., 1999). Most of the possibly 100–150 km (Ludman et al., 1999; Swanson, 1999) of dextral displacement on it appears to have occurred between ~384 and ~360 Ma (Ludman et al., 1999; West, 1999), although recent analyses suggest that some localized

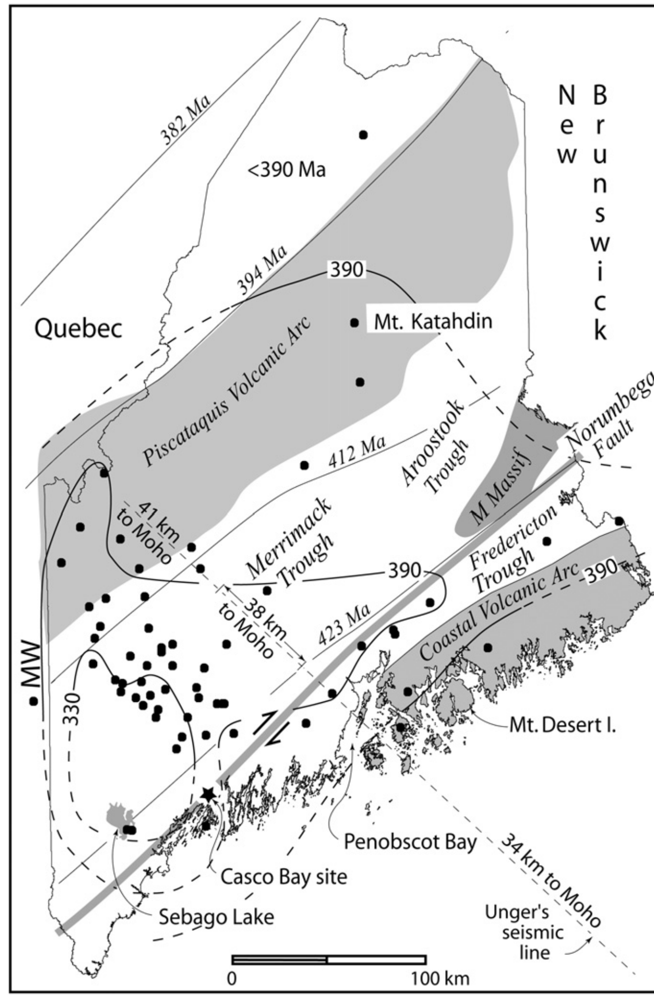

Fig. 1. Map of Maine showing locations of mineral assemblages used to estimate pressures (dots). Also shown are times of crystallization (contours labeled 330 and 390) and of passage of the Acadian deformation front (thin solid lines, italic ages), the location of West's Casco Bay site, and the approximate location of the seismic line discussed by Unger et al. (1987) and Stewart (1989). M = Miramichi. MW = Mt. Washington. Deformation front data are from Bradley et al. (2000, Fig. 10). Terrane subdivisions are from Bradley (1983, Fig. 2).

dextral shearing continued up to the early Mesozoic (M. Swanson, University of Southern Maine, written communication, 2012). West et al. (1993) and West and Roden-Tice (2003) have argued for significant Mesozoic dip-slip reactivation on it in the Casco Bay region. We expand upon this hypothesis below.

2.4. Alleghanian orogeny

At ~320 Ma, Gondwana began to encounter the amalgamated peri-Gondwanan/Laurentian terrane of Maine and Nova Scotia, resulting in the Alleghanian orogeny (Lux and Guidotti, 1985; Culshaw and Liesa, 1997; Hatcher, 2002). Contact first occurred in the north and then, as Gondwana rotated clockwise relative to Laurentia, progressed southward, resulting in dextral shear throughout the Appalachians. The merged continents formed the supercontinent, Pangaea. The Alleghanian appears to have been little more than a gentle bump in Nova Scotia (Murphy and Collins, 2008), but its intensity increases southward; it may have been responsible for thrust nappes in Connecticut (Wintsch et al., 2003), and it resulted in extensive folding and overthrust faulting in the central and southern Appalachians.

In Maine, the Alleghanian is represented by a number of plutons and associated deep-seated metamorphism in the southwestern part of the