Mesozoic hotspot epeirogeny in eastern North America

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ABSTRACT

Geologic data, especially conodont paleotemperatures, imply that southeastern Canada and New England have been elevated at least 4 km relative to the central Appalachian region. Apatite fission-track ages suggest that the uplift and consequent erosion occurred in Cretaceous–early Tertiary time, consistent with the formation of a broad swell as North America moved northwestward over the Great Meteor hotspot.

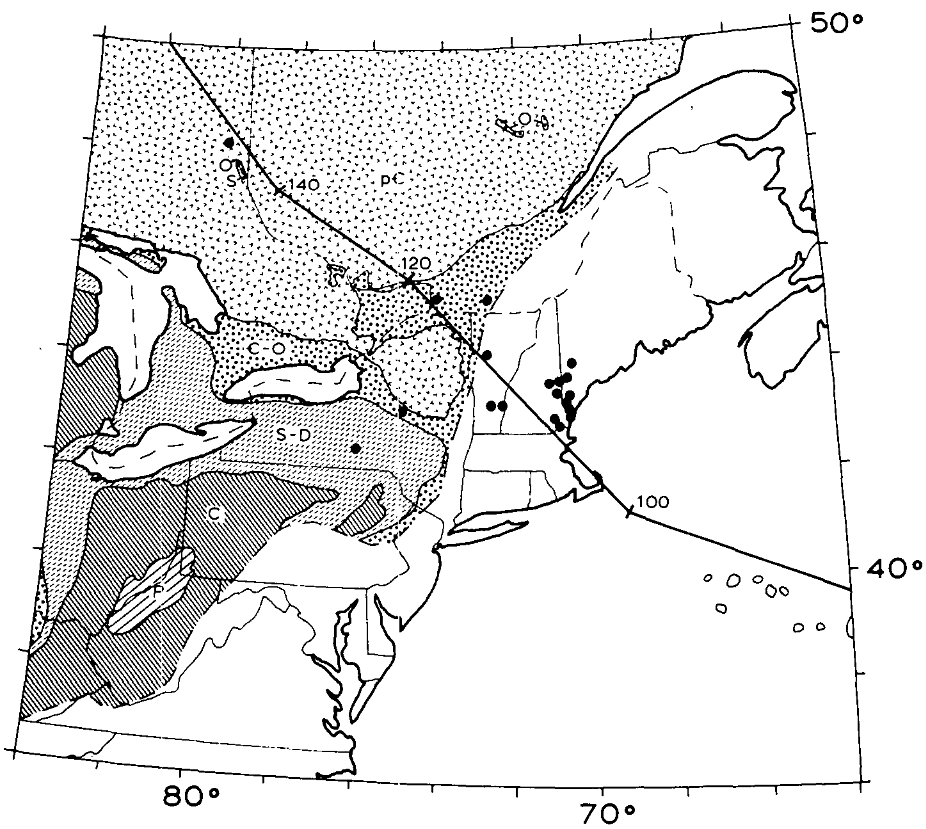

Figure 1. Predicted track of Great Meteor hotspot from about 160 to 80 m.y. B.P., superposed on generalized geologic map of craton in eastern North America. Solid dots are radiometrically dated igneous intrusions which track explains (see text). Trace marks southern limit of Canadian Shield, suggesting that hotspot swell caused present structural relief.

INTRODUCTION

Mapping of residual depths throughout the world's oceans (Cochran and Talwani, 1977) has revealed that broad topographic swells formed over mantle hotspots are the major departures from the expected age-depth relation. Hotspots swells are thus the most significant form of sea-floor epeirogeny, apart from the normal subsidence of the sea floor as it ages. These swells are apparently caused by a reheating of the lithosphere (Detrick and Crough, 1978) and should form on continental lithosphere as well as on oceanic lithosphere. Continental swells now over hotspots may include the Hoggar and Tibesti Massifs in central Africa, the Ethiopian and East African Plateaus, and the Colorado Plateau (Le Bas, 1971; Burke and Wilson, 1972; Suppe and others, 1975; Gass and others, 1978). Typical oceanic swells are 1,200 km wide and 1 km high (Crough, 1978); these continental swells have comparable dimensions.

Plausibility arguments suggest that hotspot epeirogeny has had a major influence on continental evolution, perhaps controlling the elevation, thermal history, and sedimentary patterns of cratons (Crough, 1979). This concept can be tested by examining continental-hotspot tracks for evidence of hotspot uplift.

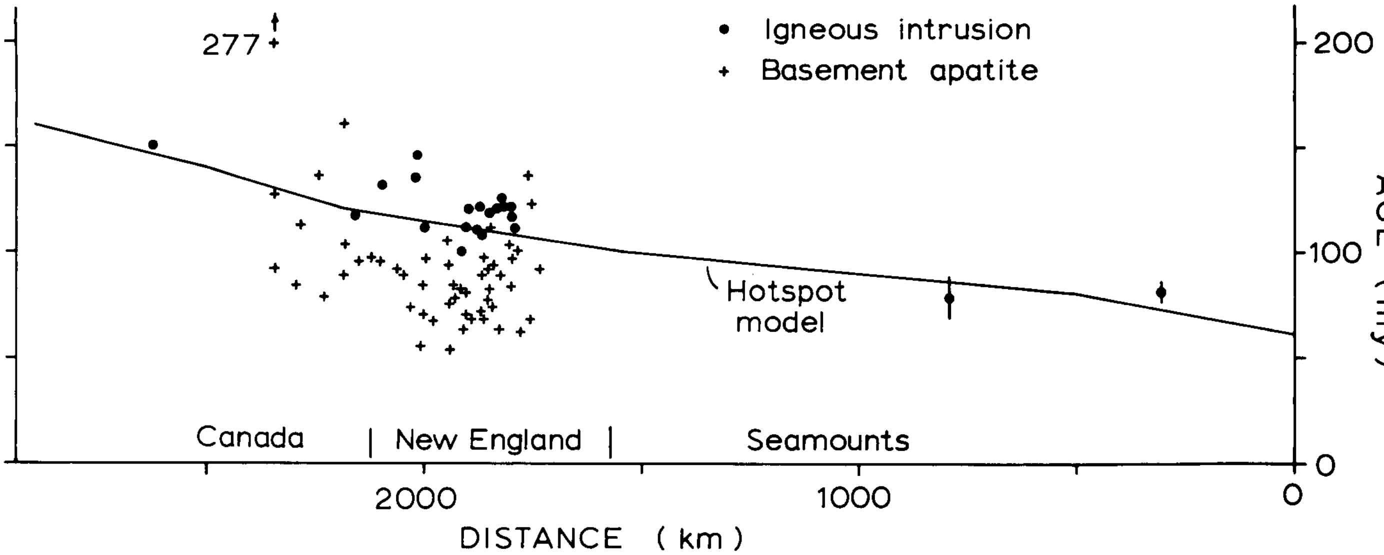

Figure 2. Predicted and observed age-distance relations along hotspot trace for igneous rocks in Figure 1 and apatite fission-track ages of basement (Zimmerman, 1977). Intrusion ages are scattered about hotspot model indicated by solid line, but have predicted trend. Apatite dates record uplift and erosion of this region. If hotspot swell caused uplift, apatite ages should be equal to or slightly younger than hotspot track.

HOTSPOT TRACK AND SURFACE GEOLOGY

North America moved northwestward over the Great Meteor hotspot in Jurassic-Cretaceous time (Fig. 1). The absolute plate motions used to reconstruct this traverse were calculated to fit the volcanic data on this and two other traces on two other plates, assuming a uniform motion of Africa (Crough and others, 1980). More detailed computations could improve the fit but would not change the conclusion that motion over a hotspot now near Great Meteor Seamount in the eastern Atlantic explains the locations and ages of the New England Seamounts offshore (Vogt and Tucholke, 1979) and the kimberlites (Zartman and others, 1967; Poole and others, 1970) and Cretaceous alkalic complexes (Macintyre, 1971; Foland and Faul, 1977) farther inland (Figs. 1, 2).

This hotspot track follows the approximate northern limit of the present Paleozoic platform cover in eastern North America (Fig. 1). My suggested explanation of this occurrence is that (1) at the end of Paleozoic time, the Appalachian basin extended farther to the north through southern Canada, covering parts of the now-exposed shield, and (2) in Mesozoic time, movement over the Great Meteor hotspot created an elongate swell that shifted slowly from northwest to southeast. Maximum uplift and erosion occurred along the axis of the hotspot trace, and lesser uplift and erosion occurred toward the margins. Consistent with the large size of known swells, the southern limit of uplift was approximately at lat 38°N where the most complete Paleozoic section remains.

This explanation differs from that of Dewey and Kidd (1974) and others who have assumed that the present variations along the Appalachians are due to processes occurring at the time of orogeny. Although original tectonic variations are undoubtedly important, the data now suggest that posttectonic differential uplift has controlled much of the present structure. My interpretation is very similar to that of Isachsen (1975), who proposed that the regional outcrop pattern reflects a recent uplift of the Adirondack Dome in New York. However, I think the Adirondack Dome is merely part of the broader uplift of the entire New England–southern Canada region.

EVIDENCE OF UPLIFT

The former northward extent, age, and thickness of the platform cover may never be known exactly, but a variety of evidence indicates that southeastern Canada was once covered by a sedimentary wedge similar to that in the central Appalachian basin. First, sediments of Late Ordovician and younger age in the basin are mostly foreland clastic deposits derived from Paleozoic mountains to the east. The Paleozoic mountain building that occurred in New England and Canada would have provided ample sediment to bury the craton to the west. The Andes may offer a present analogue of this situation—a foreland basin fringes the entire length of the range.

Second, outliers of Paleozoic sediment throughout the southeastern Canadian Shield provide direct evidence that the cover was once more extensive. Ordovician deposits in the Ottawa-Bonnechere graben, Ordovician and Silurian deposits at Lake Timiskaming, and Devonian blocks in an igneous pipe near Montreal (Williams, 1910) suggest that the shield was mantled by sediments at least until Devonian time (Kay, 1942).

Third, isopach maps of the remaining sediments in the Appalachian basin imply that the deposits originally extended farther to the north. As an example, the thicknesses of Middle Devonian sediments are shown in Figure 3. The contours roughly parallel the trend of the Appalachians, with no evidence of thinning to the north. These relations are clearest in the thick Devonian section, but all the Paleozoic sequences appear to have had a greater northward distribution.

Fourth, lithofacies relations indicate that the present northern margin of the basin is defined by postdepositional erosion. For example, the clastic ratio of Middle Devonian deposits decreases from east to west across the basin but does not change appreciably along the strike of the isopachs (Fig. 3). Thus, there is no evidence for a clastic source along the present northern edge. Mississippian deposits do have a higher clastic ratio to the north (Sloss and others, 1960), but this probably reflects greater uplift and erosion in the northern Appalachians following the Acadian orogeny. In the northern part of the present Appalachian basin, paleocurrent indicators from Late Devonian through Early Pennsylvanian time show sediment transport toward the northwest and west (Pelletier, 1958), rather than toward the south as expected for a northern shield source. Exceptions to this generalization occur in Ohio and western Pennsylvania, where the Berea Sandstone (de Witt, 1951) and Sharon Conglomerate (Fuller, 1955; Meckel, 1967) indicate a northern source during intervals of Mississippian and Pennsylvanian time.

Finally, conodont geothermometry establishes that the lower Paleozoic sediments now exposed in southern Canada and northern New York were once deeply buried (Epstein and others, 1977). The color alteration index of Ordovician conodonts increases from west to east in the present Appalachian basin, implying that thermal alteration is controlled by maximum depth of burial (Fig. 4). The isograds show little change along the strike of the Appalachians. Making the reasonable assumption that the basin's geothermal gradient never had substantial lateral variation, these results indicate that the Ordovician sediments near the Adirondacks were probably once buried as deeply as those in the central Appalachian basin. Alteration values of 4 or greater occur in thrust sheets and may only indicate the prethrusting burial depths in the region to the east of their present location. The values of 3 or less occur in autochthonous units and, by comparison with similar values farther south, suggest a former overburden thickness of about 4 km.

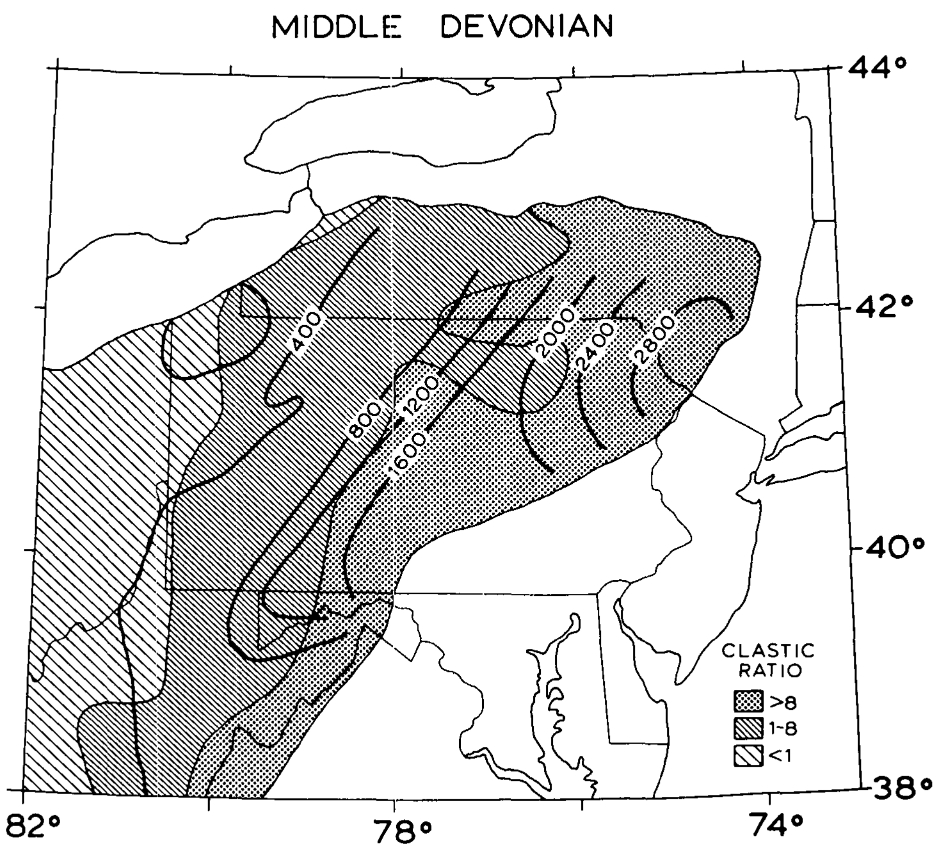

Figure 3. Isopach and lithofacies relations for Middle Devonian sediments in Appalachian basin south of hotspot track (from Sloss and others, 1960). Contours of sediment thickness (in feet) are not drawn where Middle Devonian sediments are exposed at surface and eroded. Patterns indicate ratio of clastic to nonclastic sediments. These deposits once extended farther north, and there is no indication of northern cratonic source area.

TIMING OF UPLIFT

The date of the Canada-New England uplift can be estimated from existing geologic data. First, the distribution of sediments in the Appalachian basin suggests that the uplift occurred in post-Paleozoic time. As can be seen in Figure 1, from West Virginia northward, none of the younger systems unconformably overlaps the eroded edge of older systems. Thus, the most significant regional warping and erosion probably postdate the youngest (Early Permian) unit.

Second, experimental results suggest that the surface of New Hampshire has been eroded by many kilometres since Jurassic time. Phase relations among feldspars in exposed plutons dated at about 180 m.y. B.P. (Foland and Faul, 1977) imply that these rocks originally crystallized at a depth of 5.7 to 7.6 km (Wilson, 1969).

Third, the Devonian clasts that were preserved by falling into an igneous pipe near Montreal indicate that at least 800 to 1,200 m of erosion has occurred there since Early Cretaceous time. At present, the youngest in situ sediments are Ordovician, so the minimum level of erosion is based on the estimated thickness of the missing Silurian and Devonian sections that presumably once covered the area (Kay, 1942). The breccia pipes have not been dated radiometrically, but they yield reliable paleomagnetic poles, matching those in the Monteregian plutons and consistent with the plutons' age of 120 m.y. (Foster and Symons, 1979). Therefore, the missing sediments were present when the region moved onto the hotspot and were eroded later.

Finally, apatite fission-track ages (Zimmerman and others, 1975; Zimmerman, 1977) indicate that the uplift was probably contemporaneous with the passage of the Great Meteor hotspot. To a good approximation, apatite acts as a maximum recording thermometer, with its fission-track age yielding the time since the mineral last cooled below 100 °C.

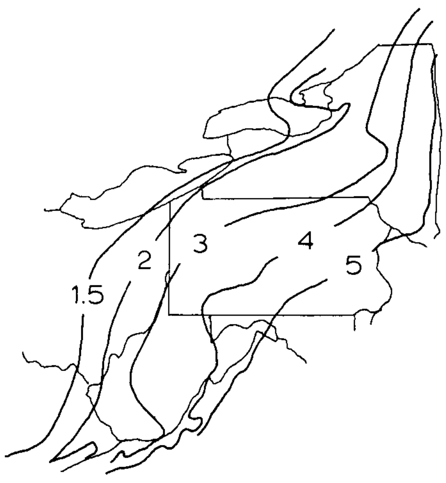

Figure 4. Contours of conodont color alteration index in Ordovician sediments in eastern North America (from Epstein and others, 1977). Values 1 to 5 range from unaltered samples to those that have been heated to more than 250 °C. Because temperature is controlled by burial depth, contours imply that northern New York and southern Canada were once covered by clastic wedge similar in thickness to that in central Appalachian basin.

Because conodont geothermometry indicates that the Lower Ordovician sediments in Ontario were probably buried deeply enough to attain this temperature (Epstein and others, 1977; C. R. Barnes, 1979, written commun.), the basement apatite ages should record the time the Paleozoic cover was removed.

Southeastern Canada and New England are one of the few areas of the world which have been dated extensively by the apatite fission-track method. All these measurements, which coincidentally are located within 300 km of the hotspot track shown in Figure 1, are projected onto the track and plotted in Figure 2. The ages are almost all Cretaceous–early Tertiary, and the oldest dates are generally equal to the expected time of initial hotspot uplift. Most of the ages postdate by 30 to 40 m.y. the passage of the hotspot, but this apparent discrepancy has two possible explanations consistent with the hotspot model. First, the rate of spontaneous fission is not known precisely. Using the alternative value for this constant would increase the plotted ages by about 20% (Zimmerman, 1977). Second, uplift does not stop immediately after a continental region moves off a hotspot. As surface erosion wears down the swell, the lithosphere rises isostatically to balance the removed mass, and additional material passes through the 100 °C isotherm. The deeper the final level of erosion, the more likely that the fission-track age postdates the initial uplift. Erosion and isostatic rebound are the reasons that a swell, which originally may be only 1 km high, eventually causes several kilometres of uplift. Local variations in age may be due to variations in both the pre-uplift geotherm and the present level of erosion.

DISCUSSION

Regional uplift in Cretaceous–early Tertiary time appears to be the only reasonable explanation for the data. Weathering can lower fission-track ages by annealing tracks, but weathering changes the physical appearance of apatite grains (Gleadow and Lovering, 1974) and is known to be unimportant in the Ontario–New England samples. Near-surface reheating can reset apatite ages, but the conodont alteration contours (Fig. 4) show no evidence of a regional thermal event, and the apatite ages are not related to their distance from young intrusions (Zimmerman, 1977). Finally, it is unlikely that there is an unknown process that lowers apatite ages. Fission-track ages as old as Ordovician are measured in samples that have never been heated above 80 °C, according to the color of adjacent conodonts (Ross and others, 1976).

The remaining question is whether the Great Meteor hotspot actually caused the uplift or merely happened to be in the area when some other process was operative. Two aspects of the uplift's spatial pattern suggest a causal relation with the hotspot. First, the axis of the uplift crosscuts the Appalachian trend and the coastline but parallels the hotspot track. Second, southward from Ontario the basement elevation decreases gradually as expected for a hotspot swell. However, the hotspot-epeirogeny hypothesis also has its problems. First, from Ontario northward the shield is still above sea level, not progressively more deeply buried by sediments. Second, drilling results from Georges Bank, directly on the postulated hotspot trace, indicate no major uplift in Late Cretaceous time (Amato and Bebout, 1980). The northern exposure of the shield may possibly be explained by earlier episodes of uplift involving other hotspots. The Tertiary and Upper Cretaceous sections at Georges Bank are thinner than observed elsewhere on the eastern margin of North America, so perhaps the effect of the hotspot was to slow the shelf's subsidence rather than reverse it. Future calculations can test this suggestion.

The only way to separate causality from coincidence is to examine additional continental hotspot tracks for similar evidence of uplift. Because absolute motion reconstructions back to Triassic time suggest that eastern North America has passed over at least four additional hotspots in this time interval (Morgan, 1980; Crough and others, 1980), the present configuration of the basement should be the result of many episodes of swell formation. The most recent uplift may be along the predicted, but still undocumented, track of Bermuda across the central and southern United States. I speculate that the present relief of the Ozark Dome, southern Appalachian mountains, and Cape Fear Arch are attributable to this hotspot. In Triassic-Jurassic time, the present Canadian Shield moved over the present Canary, Madeira, and Cape Verde hotspots. The Jurassic intrusions in New Hampshire (Foland and Faul, 1977) probably mark the trace of Cape Verde. Additional apatite dating can test whether the lack of platform cover over the entire eastern shield is related to these hotspots. Indeed, so many hotspot tracks are predicted across eastern North America that preservation of cratonic sediments may be the exception rather than the rule. Perhaps significantly, no hotspot reconstruction has yet predicted a track through the central Appalachian basin.

SUMMARY AND CONCLUSIONS

A modern sedimentary analogue, outlier deposits, isopach maps, lithofacies relations, and conodont paleotemperatures imply that the foreland basin of the Appalachians once extended northward across eastern Canada. Conformable stratigraphic relations, erosion of plutons, and clasts in an igneous pipe suggest that the southern Canada–New England region was uplifted and eroded in post-Paleozoic, probably post-Jurassic, time. Apatite fission-track ages of the exposed basement indicate that the major erosion was in Cretaceous–early Tertiary time. The spatial extent and timing of this uplift seem consistent with the formation of a broad swell over the Great Meteor hotspot as the North American plate moved northwestward.

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