original location of the escarpment, we feel obliged to respond to Sheridan's other comments.

Our discussion of the semicircular shape of the buried bench around the Blake Nose is a direct argument against the fault on the seaward side of these buried benches, which were described by Sheridan and others (1979) as being half-graben structures. Obviously, the detailed shape of the benches is irrelevant if the benches are sedimentary features that may or may not have a buried basement block as a base.

Arguments concerning deep crustal control are based on magnetic anomaly data and gravity models. Figure 1 here is taken from Klitgord and Behrendt's (1977) magnetic anomaly map, the most complete and up-to-date anomaly map available. Sheridan and others (1979) used the 200-nT contour map of Taylor and others (1968), which is not adequate for evaluating the amplitudes of anomalies in the region. On the 50-nT contour map (Fig. 1), a magnetic anomaly high is associated with the Blake Nose, and another linear anomaly is associated with the escarpment south of Great Abaco Canyon (Klitgord and Behrendt, 1977). The 250-km segment of the escarpment between these two regions has relatively small magnetic anomalies, suggesting that no major crustal block is in that area. Shallow blocks could be present at both ends of this section, serving as localizing agents.

We agree that if the gravity model to which Sheridan refers is correct, a crustal juncture must exist nearby. The rather large correction factors associated with such a large escarpment mean that locating the juncture accurately is difficult. The gravity data do not require a crustal block at the benches (for example, Fig. 2, Sheridan and others, 1979) or disprove our erosion hypothesis. Moreover, in his Comment, Sheridan suggests that strata from the Blake Plateau project into the buried benches. If strata from the Blake Plateau do project into the buried benches, as we think horizon $J_2$ does, then we have no apparent structural control for the detailed location of the Blake Escarpment.

We thank Sheridan for identifying the erroneous subsidence-rate units (intended to be metres per $10^6$ yr). He is correct that the new dates invalidate this argument. However, the inverse of this argument does not imply that these buried benches are in fact reefs, only that the two-point subsidence "curve" has the proper sense of curvature.

We also thank Sheridan for pointing out the drafting error in our (1980) Figure 6, a cartoon illustrating the amount of material removed by erosion. Incidentally, we did these calculations on depth sections.

Sheridan agrees that extensive erosional retreat of the escarpment has taken place. Apparently we disagree only about the extent; he thinks that the horizontal retreat is limited to a few kilometres. A consequence of a few kilometres or more of erosional retreat would be the formation of an unconformity that truncates the toe of the former escarpment or rise, as, for example, the Miocene strata are truncated at the sea floor where profile TD-5 was collected. The only features that help define the extent of the pre-Miocene escarpment are the buried benches, which enable us to conclude that the erosion retreat was as great as 15 km; thus, the benches must have originated during erosional retreat.

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# Comment and Reply on 'Mesozoic hotspot epeirogeny in eastern North America'

## COMMENT

**J. Gregory McHone**, *Department of Geology, Indiana University–Purdue University at Indianapolis, Indianapolis, Indiana 46202*

The New England region and the adjacent Atlantic Ocean basin contain a series of igneous intrusions that several authors suggest were generated by movement of the North American plate over a "hotspot" or thermal plume during the Mesozoic Era (Coney, 1971; Morgan, 1971; Rhodes, 1971; McGregor and Krause, 1972). Crough (1981) offered a version of this model in which an Early Cretaceous position over the plume also led to regional uplift in New England, causing extensive erosion (at least 4 km), and the creation of the present northern Appalachian map patterns.

Crough's (1981) use of conodont, fission-track, radiometric, and tectonic data is an admirable example of a multidisciplinary approach to a complex subject. Some of the problems with the New England hotspot model are resolved by Crough's modifications, although one must refer to his other papers for a more complete discussion (Crough, 1979; Crough and others, 1980). However, another model has also been proposed for the generation of the New England intrusions and seamounts, calling upon the development of intraplate fracture zones activated by plate movements (Foland and Faul, 1977). Lucid discussions of this mechanism have been published by Marsh (1973) and Shaw (1980); both authors used other examples for the fracture model. Crough's hotspot model has both weak and strong points, some of which were not brought out in his 1981 paper, but none of the points rules out the fracture model as an alternative explanation.

Most of Crough's (1981) radiometric

data are from igneous provinces of the White Mountain Magma Series of north-central New England and the Monteregian Hills series of adjacent Quebec. On the basis of petrology, radiometry, and other distinctions, there are actually three magma groups in the region, because there are also many examples of rift-related dolerite dikes that belong to the extensive eastern North American swarms (McHone, 1978). Of the other two groups, one consists of granitoids and syenitoids of Early Jurassic age and is located mainly in northern New Hampshire, whereas the last is a much more extensive group of alkalic plutons and dikes, of Early Cretaceous age, forming what I call the New England–Quebec magma province. This province is bounded on the southeast by the Atlantic Ocean, but it is about 300 km by 400 km in size, or nearly the same as the area covered by the more recent volcanic activity of the Hawaiian Islands—the most widely quoted example of hotspot magmatism.

In Figure 2 of his 1981 paper, Crough plotted radiometric ages of some of the New England–Quebec intrusions and fission-track ages of regional apatites, all transposed up to 300 km to plot along the proposed hotspot trace as located in a separate study by Crough and others (1980). In addition, he plotted a single kimberlite date from a location 520 km to the northwest of the New England–Quebec province and two dates for the New England Seamounts more than 1,000 km to the southeast. The outer points and a few of the New England–Quebec points appear to show a progression toward younger ages from northwest to southeast, and Crough overlapped a curve that he related to the rate of motion of the plate over the hotspot in Mesozoic time.

There are, however, many other Mesozoic intrusions in eastern North America, most of which are not easily related to a hotspot trace. Also, the New England–Quebec province appears to have definite boundaries (McHone, 1978), leaving large gaps along the hotspot trace between the province and both the kimberlite and seamounts. I have replotted the New England–Quebec part of Crough's (1981) Figure 2 to provide more detail of the age-distance fit along his hotspot trace (Fig. 1 here). As Crough pointed out, the older group of White Mountain Magma Series intrusions is not explained by the same hotspot trace used for the younger New England–Quebec intrusions. The younger group ranges between 95 and 136 m.y. in age but shows little evidence of any systematic change across 400 km of the province. However, because of the low slope of the hotspot line (due to rapid plate motion), and the relative uncertainties of K-Ar dates, Crough's model could fit the data.

If a hotspot trace is the correct model for the Cretaceous epeirogeny and New England–Quebec magmatism, I would suggest that the plume started under New England, well after Early Jurassic time when the central Atlantic opened, but significantly near the time when the initial separation of Newfoundland from Iberia opened the northern Atlantic Ocean (Wilson, 1975). The older White Mountain Magma Series might then be related to a geographically coincidental mantle plume that was active during the central Atlantic opening but left little trace of its presence outside of New Hampshire. Was there also epeirogeny during this event? We may speculate that the later magmatism has thermally reset the evidence, because fission tracks in apatite are healed at relatively low temperatures.

If, on the other hand, the older White Mountain Magma Series intrusions and the New England–Quebec magmas were initiated and emplaced along the same "weak zone" of deep-seated fractures, their overlap is explained. Both episodes may be related to stresses produced by the opening of first the central Atlantic and later the northern Atlantic, with magmatism diminishing after each event in accord with gradual strain accommodations along the zone. The regional uplift may be due mainly to the transfer of heat into the lithosphere by the intrusions themselves. Perhaps epeirogeny is not dependent upon the mechanism that generates the magmas.

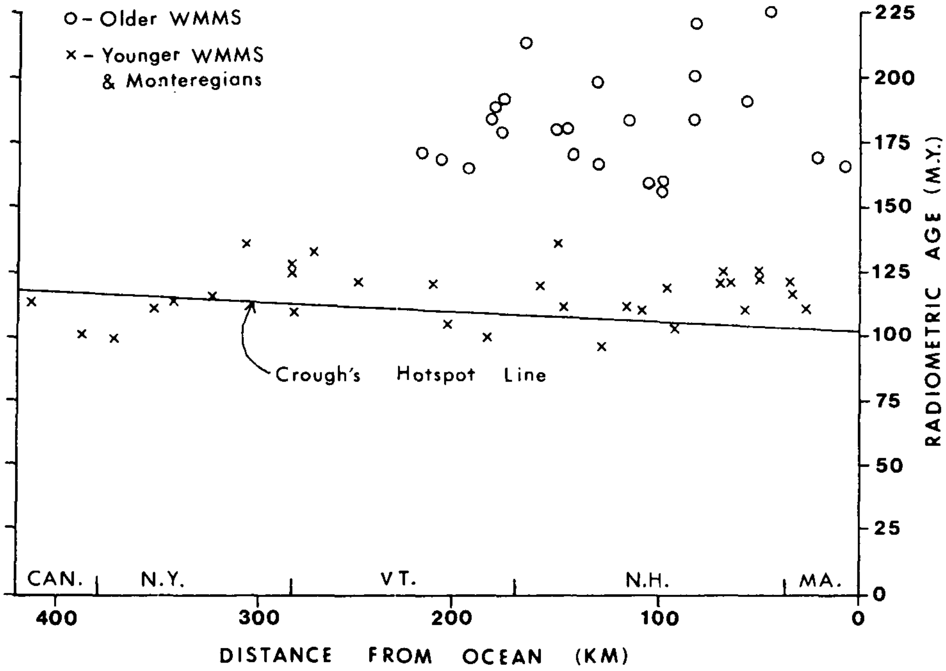

**Figure 1. Age versus distance relationships of New England Mesozoic intrusions along Crough's (1981) hotspot trace. Radiometric data are from Foland and Faul (1977), Weston Geophysical Research (1977), McHone (1978), and McHone and Corneille (1980). WMMS = White Mountain Magma Series.**

## REPLY

**S. Thomas Crough,** *Department of Geosciences, Purdue University, West Lafayette, Indiana 47907*

McHone presents additional radiometric ages for the New England–Quebec magma province and suggests that a reactivated fracture zone might explain the patterns of volcanism and uplift that I attributed to a mantle hotspot. I agree with him that none of the available evidence rules out the fracture model and that the hotspot model does raise some problems. Nevertheless, the following three observations indicate to me that fracture reactivation is an implausible explanation for mid-plate magmatism in general and for the New England–Quebec activity in particular.

1. There is no consistent global relation between volcanic lineaments and surficial features. The fracture mechanism is attractive for the New England magma series and seamount chain because they lie approximately parallel to transform-fault trends in the western North Atlantic. Other Atlantic lineaments such as the Madeira-Josephine trend and the Walvis Ridge, however, crosscut local transform faults at sizable angles, and most Pacific chains do the same. Perhaps there is a variety of mechanisms for forming and reopening fractures (Turcotte and Oxburgh, 1973), or perhaps some chains are caused by cracks and some by hotspots (Sykes, 1978), but the orientations of all recently formed chains are remarkably consistent with plate motions over fixed hotspots (Morgan, 1973).

2. Most dated volcanic lineaments have an age progression. The Pacific chains are the most thoroughly dated, and their Tertiary ages are in reasonable agreement with the hotspot theory (Jarrard and Clague, 1977). Coeval volcanism over large horizontal distances is often suggested as a probable consequence of fracture reactivation, but to my knowledge there is no sizable oceanic lineament that was formed simultaneously. The Ninetyeast Ridge, in the Indian Ocean, follows a transform fault and is three times longer than the New England seamount chain, making it the most likely example of a reactivated fracture. However, the ages of the ridge show a systematic decrease to the south, consistent with formation over a hotspot (Duncan, 1978). Although available data along the calculated trace of the Great Meteor hotspot are not this complete, they are sufficient to rule out coeval volcanism. The younger ages in the New England region (McHone, Comment above) can be interpreted as a single pulse of volcanism at 120 m.y. B.P. The New England Seamounts, however, are significantly younger than this and would require another pulse at 80 m.y. B.P.

3. Midplate volcanism does not usually recur along the same lineation. Igneous activity in both Jurassic and Cretaceous time (McHone, Comment above) is used as evidence for a New England zone of weakness that opens whenever plate stresses require. As a counterexample, there are also two time-separated pulses of Mesozoic volcanism in southern Brazil, but these intrusions are centered about 600 km apart (Crough and others, 1980). According to the fracture-zone model, these pulses would require two parallel zones of weakness that opened and closed at different times. Therefore, a zone of weakness would sometimes have to be a zone of strength. The reactivation model raises difficulties even in New England. Note that the continental part of the fracture, which presumably opened easily at 180 and 120 m.y. B.P., must have remained closed at 80 m.y. B.P., when the part beneath the New England Seamounts opened.

Although future work can always alter existing theories, a hotspot seems the best working hypothesis for the New England intrusions. Known plate motions over a single hotspot can explain the ages and locations of igneous events ranging from a Jurassic kimberlite in Canada to a late Tertiary–age seamount in the eastern Atlantic. The fracture hypothesis would require at least three major lithospheric faults and at least four separate periods of reactivation in order to explain these same features. Using a highly simplified model of plate and hotspot motions, the age progression across New England should be about 3.3 cm yr$^{-1}$. McHone's age data would be better matched by a slightly higher rate, which might be possible in a more refined motion model, but the dates are nevertheless consistent with rapid motion. Given the number of hotspots and the speed of plate motion, a continental area should overrun a hotspot every 600 m.y., on average (Crough, 1979). However, the probability function of encountering a hotspot is a decaying exponential of time, so the shorter time intervals between encounters should be the more frequent. It may be expected that a few areas, such as New England, underwent two episodes of midplate volcanism separated by a relatively short hiatus.

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