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AGE PROGRESSIVE VOLCANISM IN THE NEW ENGLAND SEAMOUNTS AND THE OPENING OF THE CENTRAL ATLANTIC OCEAN

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Abstract. Radiometric ages (K-Ar and ^{40}Ar-^{39}Ar methods) have been determined on dredged volcanic rocks from seven of the New England Seamounts, a prominent northwest-southeast trending volcanic lineament in the northwestern Atlantic Ocean. The ^{40}Ar-^{39}Ar total fusion and incremental heating ages show an increase in seamount construction age from southeast to northwest that is consistent with northwestward motion of the North American plate over a New England hot spot between 103 and 82 Ma. A linear volcano migration rate of 4.7 cm/yr fits the seamount age distribution. These ages fall within a longer age progression from the Corner Seamounts (70 to 75 Ma), at the eastern end of the New England Seamounts, to the youngest phase of volcanism in the White Mountain Igneous Province, New England (100 to 124 Ma). The New England hot spot, estimated from the new radiometric ages and motion of North America in the hot spot reference frame to be near 28°N, 33°W, probably generated a short line of mid to late-Tertiary age seamounts on the African plate but appears to be presently inactive. The hot spot reference frame is used to calculate the motion of the North American plate away from the African plate from early Cretaceous time to the present. Prominent magnetic anomalies recorded in the central Atlantic seafloor give the positions of the spreading ridge for a range of known ages. Hot spots that now underlie the African plate in the eastern central Atlantic (New England, Canary, Madeira, Cape Verde, Azores) could have produced Cretaceous seamount and island chains on the North American plate during the early opening of the central Atlantic. Each of these hot spots has been overridden by spreading ridges at predictable times. Some of these hot spot crossings are expressed as geochemical anomalies in the oceanic crust now far removed from spreading ridges.

1. Introduction

The quest for a frame of reference for determining plate motions and reconstructions has commanded much attention in plate tectonic research. Paleomagnetic and paleoclimatic data estimate plate motions with respect to the earth spin axis but do not give information about longitudinal motion. The pattern of magnetic anomalies and transform faults in ocean basins is used to reconstruct plate positions back to ancient spreading ridges. With the evidence for asymmetric spreading, propagating fractures, and ridge jumps, however, spreading ridges are seen as transient features that allow calculations of relative motions only.

The possibility that plate motions may be recorded by lines of islands and seamounts in the ocean basins is attractive in this regard. If, as the Carey-Wilson-Morgan model [Carey, 1958; Wilson, 1963; Morgan, 1971] proposes, sublithospheric, thermal anomalies called hot spots are active and fixed with respect to one another in the earth's upper mantle, they would then constitute a reference frame for directly and precisely measuring plate motions. Ancient longitudes as well as latitudes would be determined from volcano construction ages along the tracks left by hot spots and, providing relative plate motions are also known, quantitative estimates of convergent plate motions can be calculated [Engebretson and Cox, 1982; Jurdy, 1982; Duncan and Hargraves, 1984]. As more detailed information about the distribution of ages along prominent oceanic volcanic lineaments accrues, it is evident that hot spots move extremely slowly (<5 mm/yr) if at all [Morgan, 1981; Duncan, 1981] and so provide a useful measure of lithospheric plate motion with respect to the mantle.

The New England Seamounts form a northwest-southeast trending volcanic lineament in the western central Atlantic (Figure 1). One of the postulated origins for these seamounts is that they were formed by hot spot activity during the early opening of the central Atlantic [Coney, 1971; Morgan, 1972, 1981; Vogt, 1973]. If this is the case, the New England Seamounts offer one of the few possible hot spot tracks for connecting the North American plate motion with the hot spot reference frame. This volcanic lineament has also figured prominently in Tom Crough's models of hot spot epeirogeny [Crough, 1979, 1981; Crough et al., 1980]. Crough [1981] proposed that Cretaceous to early Tertiary uplift in southeastern Canada and the northern Appalachians resulted from the thermal swell left by northwesterly passage of North America over a hot spot. This hot spot subsequently generated the New England Seamounts during seafloor spreading in the central Atlantic.

This paper reports radiometric age determinations on dredged volcanic rocks from seven volcanoes in the New England Seamount chain that exhibit a clear progression of increasing ages from southeast to northwest. This age distribution supports a hot spot origin as well as the genetic relationship proposed by Crough [1981] between uplift and volcanism in the northern Appalachians and the linear volcanism that produced the New England Seamounts. Following this evidence, the position of the central Atlantic spreading ridge from early Cretaceous time to the present is reconstructed in the hot spot reference frame to examine when the ridge crossed over presently active hot spots. Such crossings should leave geochemical anomalies (higher con-

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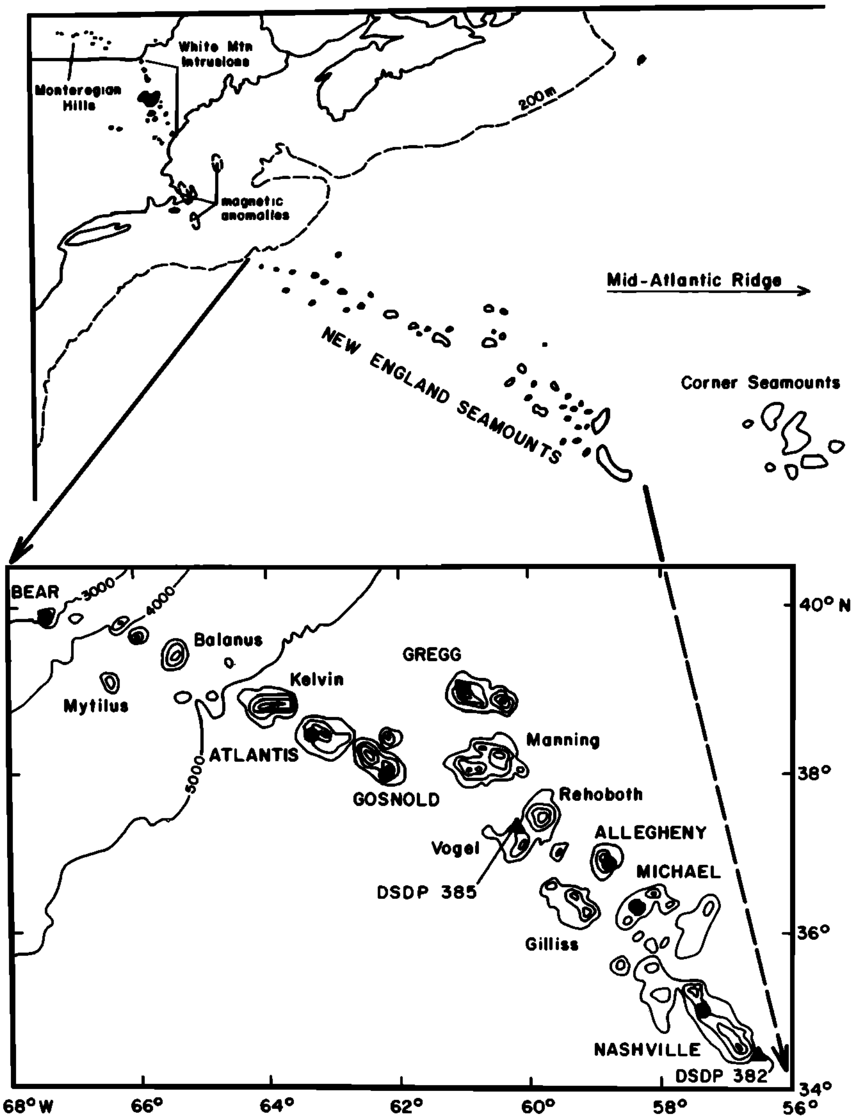

Fig. 1. The New England Seamounts form a 1200-km chain of over 30 volcanoes (bathymetry in 1000-m contour intervals). Individual seamounts rise up to 4000 m above the western Atlantic abyssal plain. A hot spot origin has been proposed for this lineament, linking it with the Monteregian Hills, the White Mountain intrusives, and the Corner Seamounts. Bold names are those seamounts from which radiometric ages were determined. Locations of dated samples are solid circles. DSDP sites are solid triangles.

centrations of incompatible trace elements, distinct isotopic ratios) in the oceanic crust.

2. Debated Origins for the New England Seamount Chain

The New England (or Kelvin) Seamounts extend 1200 km from the Georges Bank (upper continental rise) off the northeastern United States southeastward to the Corner Seamounts, in the direction of the Mid-Atlantic Ridge. The volcanic lineament comprises over 30 seamounts, which range in height from less than 400 m to over 4000 m above the abyssal ocean floor [Uchupi et al., 1970]. Most are steep sided (>10° slopes), many exhibit multiple peaks, and some have flat tops (e.g., Rehoboth Seamount [Vogt and Tucholke, 1978]). Only a thin sedimentary cover is present at most seamounts. Shallow-water fossils, vesicular volcanic breccias, and flat-topped topography argue for subaerial to shallow eruptions at some volcanoes [Tucholke et al., 1978].

The earliest ideas regarding the origin of the New England Seamounts related this lineament to volcanic eruptions along a major transform fault, resulting either as a seaward extension of Paleozoic Appalachian structural trends [Drake et al., 1968; Uchupi et al., 1970] or during the Jurassic opening of the central Atlantic [Le Pichon and Fox, 1971]. The absence of any offset in magnetic anomalies north and south of the New England Seamounts shows that no significant transform motion has occurred along the lineament [Vogt, 1973]. Later suggestions have involved an origin by hot spot activity [Morgan, 1971, 1981; Coney, 1971; McGregor and Krause, 1972; Vogt, 1973; Crough, 1981]. There has been no unanimity, however, as to the present position of the culpable hot spot for New England Seamount volcanoes because the lineament stops abruptly with the Corner Seamounts and there is no continuity to presently active volcanism.

Morgan [1971] and Coney [1971] have proposed the Azores hot spot, which influenced continental break-up and then maintained its position on the spreading ridge. Vogt [1973], however, argued that the seamounts are much too tall to have been created at the Jurassic Mid-Atlantic Ridge. Backtracking oceanic lithosphere subsidence curves places the seamounts near sea level in mid to late-Cretaceous time, in agreement with the oldest sediments recovered from them [Uchupi et al., 1970; Tucholke et al., 1978]. The volcanoes would then be much younger than the crust on which they sit (late Jurassic to early Cretaceous). Morgan [1983] and Crough [1981] have concurred in postulating a hot spot near Great Meteor Seamount in the eastern central Atlantic which was overridden (and hence separated from its track on the North American plate) by the Mid-Atlantic Ridge soon after formation of the Corner Seamounts.

All proponents of the hot spot origin have connected New England Seamount volcanism with earlier uplift and igneous activity in New England (the White Mountain Igneous Province) and later eruption of the Corner Seamounts (Figure 1). Radiometric ages from the continental volcanic centers do not appear to support the hot spot model. Foland and Faul [1977] reported that K-Ar age determinations, corroborated by Rb-Sr and U-Pb age estimates, from the White Mountain intrusive centers fall into three groups: the oldest near 230 Ma, another 200 to 156 Ma, and the youngest 124 to 100 Ma. Further to the northeast, the Monteregian Hills in Quebec exhibit ages in the range 125 to 100 Ma [Gold, 1967]. There is no clear age progression along the continental lineaments and Foland and Faul [1977] and McHone [1981] preferred to relate volcanic and plutonic activity in the White Mountains and Monteregian Hills to transform faulting which responded at various times in the Mesozoic to plate tectonic changes in the Atlantic Ocean.

Morgan [1983] and Crough [1981], however, have offered a hot spot solution. They proposed that the distinct groups of igneous ages within the White Mountains are due to passage of North America over separate hot spots--the younger two age groups created by the Cape Verde and New England hot spots in Jurassic and Cretaceous time, respectively. According to this model, only the latest phase of volcanic activity in the White Mountains is related to Monteregian Hills volcanism and the construction of the New England Seamounts.

Previously available data do not clearly favor one origin over another but do constrain the age range of volcanic activity in the New England Seamounts. DSDP drilling (Leg 43 [Tucholke et al., 1978]) recovered volcaniclastic breccias from two seamounts (Nashville and Vogel) but did not reach the constructional shield-building lavas. The oldest sediments at Nashville Seamount (site 382) were early Campanian (78-83 Ma), while at Vogel Seamount (site 385) mid-Maestrichtian (66-70 Ma) were the oldest positively identified fauna, over 100 m above the breccias, while possible Coniacian-Santonian (83-88 Ma) fauna exist just above the breccias [Tucholke et al., 1978].

Houghton et al. [1978] reported radiometric age determinations (K-Ar) on basaltic clasts and hornblendes separated from the breccias at both seamounts. At site 382 measured ages range from 79 ± 4 Ma to 88 ± 6 Ma, while at site 385 ages vary from 38 ± 15 Ma to 91 ± 3 Ma. Because seawater alteration tends to lower measured K-Ar ages [Dalrymple and Clague, 1976], the maximum ages at each volcano are considered more reliable. These are also in reasonable agreement with the ages of oldest sediments at each site. It appears that at least two of the New England Seamounts were active at about 80 to 90 Ma. Because of the large uncertainty in the age estimates and dates from only two seamounts, it has been impossible to distinguish an age-progressive trend from coeval volcanism along this lineament.

3. Sample Description, Methods, and Results

Additional samples for this study come from the extensive collection of dredged volcanic rocks at the Woods Hole Oceanographic Institution (courtesy of G. Thompson). These samples, from 12 separate volcanoes, cover the entire geographical extent of the New England Seamounts, from Bear Seamount to Nashville Seamount, and provide the maximum potential age range. The rocks examined were holocrystalline alkalic basalts, containing olivine and often porphyritic plagioclase. Many samples contained fresh amphibole which could be separated for dating. All samples exhibited some degree of low-temperature seawater alteration--mainly of the matrix to green-brown smectites, with calcite and zeolites filling veins and vesicles. Detailed petrological and geochemical studies of these samples are in progress (G. Thompson, personal communication, 1983).

Samples from seven of the New England Seamounts were found suitable for dating. This material includes nine of the freshest basalts (whole-rock samples) and fresh amphiboles separated from an additional five altered basalts. Four basalts were initially analyzed by the conventional K-Ar dating method (Table 1). High proportions of radiogenic argon were measured, which led to precise age determinations. Duplicate analyses of two samples, however, showed that these age determinations were not reproducible. In view of the scattered ages and petrographic evidence of Ar loss and K addition with clay and zeolite formation, it appears that K-Ar age determinations on these samples are all minimum estimates. The K-Ar ages reported here (Table 1), together with previous results [Houghton et al., 1978], show no clear pattern (Figure 2) and cannot be used to assess the various origins proposed for the New England Seamounts.

In contrast, ^{40}Ar-^{39}Ar total fusion and incremental heating ages determined on the same and additional samples (Tables 2 and 3) are consistent and show a systematic distribution within the New England Seamount lineament (Figure 2).

TABLE 1. K-Ar Age Determinations for Dredged Volcanic Rocks From the New England Seamounts

Sample	Location	Percent K	Radiogenic ^{40}Ar, x10^{-5} cm^3/g	Percent Radiogenic ^{40}Ar	Age* ± 1σ, x10^6 years
		Bear Seamount Whole Rock			
AII 85-1-47	39°49'N, 67°26'W	1.678	0.5586	91.2	83.7 ± 0.9
			0.5930	92.5	88.8 ± 1.0
AII 85-1-54	39°49'N, 67°26'W	1.398	0.4662	90.6	83.9 ± 0.9
		Atlantis II Seamount Whole Rock			
AII 85-12-2	38°25'N, 63°15'W	1.579	0.5089	91.5	81.1 ± 0.9
			0.5416	73.9	86.2 ± 1.0
		Gregg Seamount Whole Rock			
KNR 61-24-8	38°54'N, 60°59'W	0.511	0.0834	64.2	41.6 ± 0.5

*Ages calculated from the following decay and abundance constants: $\lambda_\varepsilon = 0.581 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; ^{40}K/K = 1.167×10^{-4} mol/mol.

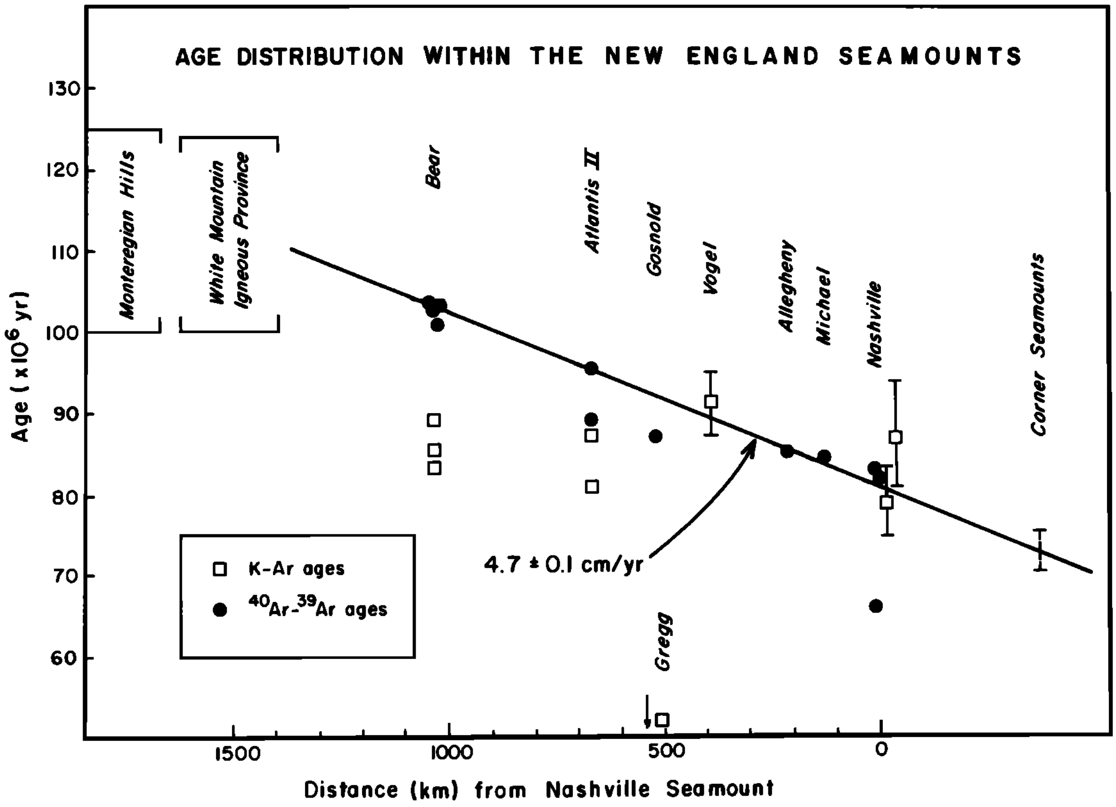

Fig. 2. K-Ar and ^{40}Ar-^{39}Ar age determinations on dredged and drilled volcanic rocks from the New England Seamounts. (Vertical lines show 1 σ errors--most are within the size of the symbols.) K-Ar ages have been affected by seawater alteration, but ^{40}Ar-^{39}Ar ages are consistent and show increasing volcano construction ages from southeast to northwest along the chain. These ages lie between the age ranges of the youngest phase of volcanism in the White Mountain intrusives and age estimates for the Corner Seamounts (dashed line gives age range), and support a hot spot origin. A linear rate of migration of volcanism of 4.7 ± 0.1 cm/yr best fits the reliable ^{40}Ar-^{39}Ar ages.

TABLE 2. ^{40}Ar-^{39}Ar Total Fusion Age Determinations for Dredged Volcanic Rocks From the New England Seamounts

Sample	Location	^{40}Ar/^{36}Ar	^{40}Ar/^{39}Ar	^{37}Ar/^{40}Ar*	Percent Radiogenic ^{40}Ar	Age ± 1σ, x10^{6} years
		Bear Seamount Whole Rock				
AII-85-1-47	39°49'N, 67°26'W	1886.9	34.74	0.1597	85.1	98.8 ± 1.1
AII-85-1-54	39°49'N, 67°26'W	4970.9	78.21	0.1178	94.3	100.7 ± 0.8
AII-85-1-11	39°49'N, 67°26'W	4763.6	80.17	0.1047	94.1	103.1 ± 0.8
AII-85-1-23	39°49'N, 67°26'W	5946.9	79.38	0.1107	95.3	103.4 ± 0.8
		Atlantis II Seamount Amphibole				
AII 85-13-54	38°26'N, 63°14'W	347.2	214.8	3.1884	22.4	88.9 ± 2.5
		Allegheny Seamount Whole Rock				
AII 85-16-5	36°50'N, 58°49'W	3547.3	68.72	0.1616	92.2	83.8 ± 1.0
		Michael Seamount Amphibole				
KNR 61-18-34	36°19'N, 58°18'W	425.3	208.1	0.4225	33.0	83.5 ± 1.3
		Nashville Seamount Amphibole				
KNR 61-12-1	35°19'N, 57°32'W	778.9	76.70	0.4592	64.0	65.9 ± 0.8
KNR 61-12-X	35°19'N, 57°32'W	1136.6	73.81	0.9655	79.5	81.9 ± 1.3

*Corrected for ^{37}Ar decay.

Multiple samples yield consistent ages at Bear, Atlantis II, and Nashville seamounts. (A single exception is an amphibole sample from Nashville Seamount that gave an anomalously young age.) Together with single age determinations at Gosnold, Allegheny, and Michael seamounts, a clear pattern of decreasing volcano age from northwest to southeast develops.

Recent geochronological work on seawater-altered basalts from seamount chains [Dalrymple and Clague, 1976; Duncan, 1978, 1982; Dalrymple et al., 1981] has shown that ^{40}Ar-^{39}Ar methods generally give reproducible ages that are closer estimates of crystallization age than the K-Ar ages disturbed by Ar loss and K addition. In the ^{40}Ar-^{39}Ar experiments, less of the age signal from the alteration phases is recovered, so that the argon analyzed comes predominantly from the primary crystalline phases. The four whole-rock samples from Bear Seamount give extremely consistent results. Two ^{40}Ar-^{39}Ar total fusion ages (Table 2) and the recalculated total fusion age from the incremental heating experiment (Table 3) agree within experimental error at 103 Ma. The two additional ages are only slightly younger.

The ^{40}Ar-^{39}Ar incremental heating experiments on the three whole rock samples did not develop especially convincing age plateaus. While these basalts were holocrystalline, the matrix was fine grained, and it is probable that some redistribution of ^{39}Ar from K-rich to K-poor phases occurred during irradiation [Turner and Cadogan, 1974]. This would produce the decreasing ages with increasing temperature observed in each experiment. Plateau ages can be chosen that comprise more than 50% of the total gas evolved, and isochron ages and intercepts can be calculated with removal of anomalously high- or low-age fractions. If the hypothesized ^{39}Ar redistribution has occurred, however, these calculated ages are not geologically meaningful. Hence the ^{40}Ar-^{39}Ar total fusion ages, determined by adding together all gas fractions for a given incremental heating experiment, are probably the only useful data from the whole-rock samples. The amphibole sample from Nashville Seamount, being monomineralic, would not have been affected by ^{39}Ar redistribution and exhibits a good plateau (82.7 ± 1.1 Ma) and isochron (81.5 ± 1.2 Ma), which match the total fusion age (82.9 ± 1.0 Ma).

A linear rate of migration of volcanism of 4.7 ± 0.1 cm/yr best fits the ^{40}Ar-^{39}Ar total fusion ages and volcano distribution. (Three age determinations were omitted from the regression because they fall significantly below this fitted line, Figure 2.) The progressive decrease in volcano construction ages supports the proposed hot spot origin for the New England Seamounts. This rate is, accordingly, the velocity of the North American plate in the hot spot reference frame between 103 and 82 Ma. The age range also falls neatly between the estimated age of the Corner Seamounts (70 to 75 Ma [Peterson et al., 1970]) and the youngest phase of igneous activity in the White Mountains (100 to 124 Ma [Foland and Faul, 1977]). The suggestion that these colinear igneous provinces were produced by North American plate motion over a common hot spot from early to late Cretaceous time is now well supported by the age-space relationship of the volcanism.

We may now backtrack any of the new ages using the North American plate motion proposed by Morgan [1981] to determine the present position of the New England hot spot. Using the age and position of Bear Seamount, this hot spot is at 28°N, 33°W, some 500 km southwest of Great Meteor Seamount (29.7°N, 28.3°W) and close to the position proposed by Morgan [1983]. There is presently no active volcanism here, the closest seamounts being Great Meteor and neighboring

TABLE 3. ^{40}Ar-^{39}Ar Incremental Heating Age data for Dredged Volcanic Rocks From the New England Seamounts

Increment	^{40}Ar/^{36}Ar	^{40}Ar/^{39}Ar	^{37}Ar/^{40}Ar*	^{39}Ar (Percent of Total)	Percent Radiogenic ^{40}Ar	Age ± 1σ, x10^{6} years
	AII 85-1-47 Bear Seamount (39°49'N, 67°26'W) Whole Rock					
1	3102.1	94.17	0.0164	13.7	90.6	(115.7 ± 0.9)†
2	3687.6	85.90	0.0167	36.8	92.0	106.2 ± 0.8
3	4953.2	79.39	0.0199	22.6	94.1	101.7 ± 0.8
4	3187.7	82.84	0.0198	8.4	90.0	102.4 ± 0.8
5	1775.5	84.74	0.0253	5.8	83.6	96.5 ± 0.8
6	2196.4	64.89	0.5459	12.7	87.8	(78.8 ± 0.6)
Recalculated total fusion age						102.6 ± 0.8
Plateau age (steps 1, 6 omitted)						104.3 ± 1.1
Isochron age and intercept						103.3 ± 2.2 130 ±36
	AII 85-12-2 Atlantis II Seamount (38°25'N, 63°15'W) Whole Rock					
1	1248.3	95.80	0.0116	15.3	76.6	99.9 ± 0.8
2	2264.9	83.79	0.0144	18.5	87.1	99.4 ± 0.8
3	5453.5	78.47	0.0165	14.4	94.7	101.1 ± 0.8
4	6203.4	75.39	0.0154	9.4	95.3	97.9 ± 0.8
5	3926.2	72.08	0.0575	6.3	92.6	(91.2 ± 0.8)
6	9306.4	66.81	0.2289	35.9	97.3	(89.1 ± 0.7)
Recalculated total fusion age						95.4 ± 0.9
Plateau age						99.5 ± 1.0
Isochron age and intercept						93.1 ± 1.7 302 ±17
	AII 85-14-31 Gosnold Seamount (38°05'N, 62°12'W) Whole Rock					
1	5404.8	78.21	0.0356	18.8	94.6	(98.3 ± 0.8)
2	17962.8	67.78	0.0426	35.9	98.4	91.1 ± 0.7
3	12157.9	67.72	0.0446	21.6	97.7	90.4 ± 0.9
4	5215.7	50.85	0.5311	23.8	95.3	(67.1 ± 0.6)
Recalculated total fusion age						86.7 ± 0.7
Plateau age						90.8 ± 0.8
Isochron age and intercept						90.9 -29
	KNR 61-14-1 Nashville Seamount (35°18'N, 57°33'W) Amphibole					
1	425.2	235.0	0.0029	1.7	31.9	98.4 ± 1.6
2	607.7	120.4	0.0046	1.6	52.3	83.0 ± 1.3
3	1298.2	75.40	0.0238	2.1	77.7	77.4 ± 1.0
4	8674.9	64.97	0.0564	33.7	96.8	83.0 ± 0.9
5	8091.8	64.72	0.1207	60.9	96.7	82.8 ± 0.8
Recalculated total fusion age						82.9 ± 1.0
Plateau age						82.7 ± 1.1
Isochron age and intercept						81.5 ± 1.2 293 ± 7

*Corrected for ^{37}Ar decay.

†Not used in plateau or isochron calculations.

Cruiser, Hyer, Plato, and Atlantis seamounts, which form an arcuate, north-northwesterly trend toward the Mid-Atlantic Ridge. Dredged alkalic basalts from Great Meteor Seamount have been dated (K-Ar) at 11 to 16 Ma [Wendt et al., 1976]. While these should be considered minimum ages, limestones of Miocene to Pliocene age recovered from this seamount also indicate a late Tertiary age, which is compatible with the inferred position of the New England hot spot. African plate motion, determined from hot spot tracks in the eastern-central and southern Atlantic Ocean basins [Morgan, 1981; Duncan, 1981] predicts a track left by the New England hot spot that follows very closely the trend of seamounts ending with Great Meteor Seamount. This model also predicts that these seamounts get older toward the Mid-Atlantic Ridge, which should be easily tested by dating volcanic rocks dredged from these volcanoes.

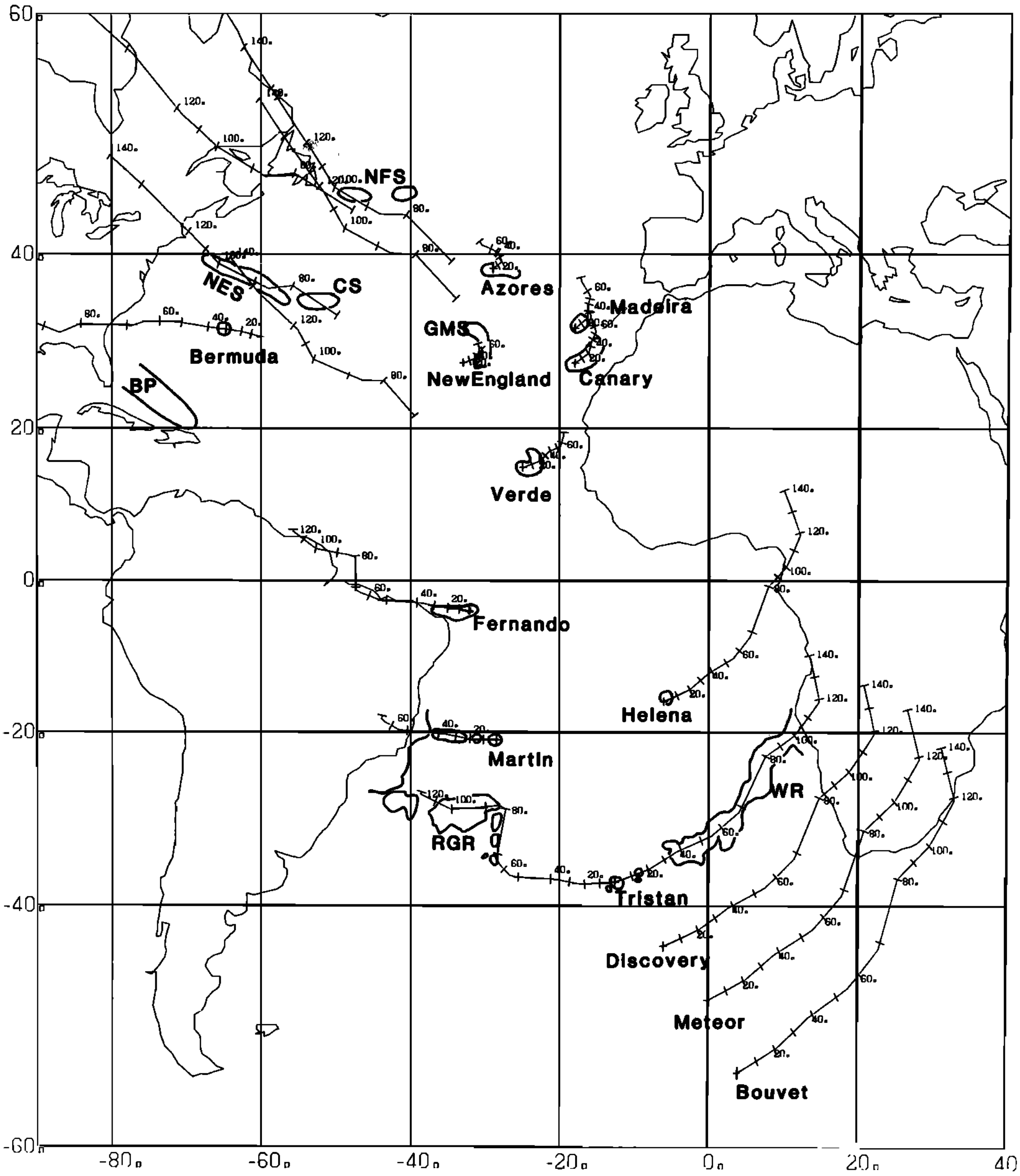

Fig. 3. Predicted hot spot tracks (from plate motions, Table 4) on plates bordering the central and south Atlantic Ocean match observed bathymetry and ages quite well, indicating stationary hot spots (see text for discussion). New ages in the New England Seamounts can be backtracked to determine the position of the New England hot spot, near 28°N, 33°W. Individual seamount chains are New England Seamounts (NES), Corner Seamounts (CS), Newfoundland Seamounts (NFS), Great Meteor to Atlantis Seamounts (GMS), Bahama Platform (BP), Rio Grande Rise (RGR), and Walvis Ridge (WR).

4. Central Atlantic Opening in the Hot Spot Reference Frame

The geometry of volcanic lineaments in the southeastern Atlantic Ocean together with dated sites along them have been used to calculate the motion of the African plate with respect to the fixed hot spot reference frame [Morgan, 1981; Duncan, 1981]. By adding the relative motion between Africa and North America deduced from magnetic anomalies and transform faults on central Atlantic Ocean crust [Pindell and Dewey, 1982] to African plate motion, the motion of the North American plate with respect to the fixed hot spots is predicted. In Figure 3 we compare the hypothetical hot spot paths left on the North American plate since the beginning of Cretaceous time with known volcanic ridges and seamount chains. (A similar exercise gives the predicted tracks on the South American plate.)

The New England hot spot track passes through the Corner Seamounts between 70 and 75 Ma and follows the New England Seamounts between 80 and 110 Ma. Between 130 and 120 Ma the track passes through New England, beneath the White Mountain intrusive centers. The fact that the hot spot track passes over Bear Seamount at 103 Ma is no surprise, since it was used to determine the hot

TABLE 4. Rotation Poles for Central Atlantic Plate Motions in the Hot Spot Reference Frame, 140 Ma to Present

Time, Ma	Latitude, °N	Longitude, °E	Angle, deg counter clockwise
African Plate Over Hot Spot Reference Frame			
21 - 0	51.0	-45.0	4.0
38 - 0	42.0	-45.0	7.5
55 - 0	40.0	-40.0	11.8
69 - 0	35.0	-40.0	16.3
80 - 0	31.0	-49.0	23.2
100 - 0	30.0	-45.0	28.0
119 - 0	28.0	-44.0	34.0
140 - 0	22.1	-48.5	38.9
North American Plate Over Hot Spot Reference Frame			
21 - 0	61.8	85.7	-2.5
38 - 0	57.2	96.8	-5.6
55 - 0	60.1	94.9	-10.3
69 - 0	54.2	103.4	-14.9
80 - 0	41.7	102.8	-21.4
100 - 0	51.4	93.6	-29.3
119 - 0	46.3	91.3	-32.3
140 - 0	47.0	76.1	-42.2

spot's location. The close match to other features--the White Mountain intrusives, the Corner Seamounts, the entire New England Seamount chain, and the Great Meteor chain of seamounts--is strong evidence, however, for hot spot volcanism which has remained fixed with respect to hot spots in the South Atlantic since at least the beginning of Cretaceous time.

Few additional seamount chains exist in the western central Atlantic. The Newfoundland Seamounts lie along the path of the Madeira hot spot. A single ^{40}Ar-^{39}Ar total fusion age of 97.7 ± 1.5 Ma has been determined on a dredged trachyte [Sullivan and Keen, 1977] which matches the predicted age (~95 Ma). Earlier activity may be manifested by alkaline intrusions along the northeast coast of Newfoundland that have ages ranging between 115 and 145 Ma [Clarke, 1977]. Muir Seamount (34°N, 62°W) and smaller neighbors lie on the path of the Cape Verde hot spot, which Morgan [1981] and Crough [1981] believe produced Jurassic igneous activity in New England. Volcanic rocks at Bermuda are 33 Ma [Reynolds and Aumento, 1974] and may have been erupted from a hot spot that earlier caused uplift across the central United States to the Cape Fear Arch [Morgan and Crough, 1979]. The Bahama Platform is thought to have a volcanic foundation beneath the carbonate platform [Dietz and Holden, 1973]. Morgan [1981] proposed that it was formed in Jurassic time as the North American plate passed over the Fernando de Noronha hot spot (Figure 3). The positions of volcanic lineaments on the South American plate are also well matched, and predicted ages are compatible with available age estimates [Morgan, 1981; Duncan, 1981].

Plate motions from earliest Cretaceous time to the present for North America and Africa are given in Table 4. With this information and the locations of identified magnetic anomalies in the central Atlantic basin [Cande and Kristofferson, 1977], we can reconstruct the position of the Mid-Atlantic Ridge relative to presently active hot spots during the opening of the central Atlantic. This is of interest with regard to the location of geochemical anomalies in central Atlantic ocean crust. With the exception of the Bermuda hot spot (now inactive), central Atlantic hot spots lie to the east of the Mid-Atlantic Ridge, beneath the African plate, yet in Cretaceous time the North American plate covered them, and at least Madeira, New England, and perhaps Cape Verde hot spots produced seamount chains in the western central Atlantic basin. Thus at certain times, spreading segments of the Mid-Atlantic Ridge must have been centered over these hot spots. During these periods the compositions of the oceanic crust produced should bear the imprint of the hot spot mantle source material, as is seen in mid-ocean ridge basalts erupted near Iceland [Schilling, 1973] and the Azores [White et al., 1976].

Basalts erupted today at spreading ridges near or astride hot spots exhibit extremely variable trace element and isotopic compositions, which reflect the mixing of distinct mantle sources. Some abyssal basalts recovered by deep-sea drilling, which are now far removed from spreading ridges and hot spots, also exhibit anomalous trace element concentrations and isotopic compositions compared with average mid-ocean ridge basalts [Bougault et al., 1983; Cande et al., 1983]. Certain of these sites lie along "flow lines" away from ridge-centered hot spots, that is, on crust that would have been generated near a hot spot if the spreading ridge maintained its position astride the hot spot. From our analysis of plate motions in the central Atlantic (Table 4), it is evident that hot spots now near the Mid-Atlantic Ridge have earlier been well to the west, and hot spots now under the eastern central Atlantic basin have earlier been near the ridge. For this reason the hot spot flow lines are considerably more complicated than for crust developed at a spreading ridge that does not move away from hot spots.

For the central Atlantic Ocean the pattern of oceanic crust generated as spreading segments of the Mid-Atlantic Ridge approached and retreated from hot spots is shown in Figure 4. Basalts from these areas should exhibit geochemical anomalies of the sort seen near hot spots today (elevated concentrations of incompatible trace elements, high ^{87}Sr/^{86}Sr and low ^{143}Nd/^{144}Nd ratios). The lateral extent of hot spot geochemical anomalies can be expected to vary among hot spots and with time around any given hot spot. Some near-ridge hot spots today appear to influence basalt compositions as far away as 300 km from the hot spot center (Iceland, Azores). The Mid-Atlantic Ridge crossed the Cape Verde hot spot shortly before magnetic anomaly M0 time, or 119 Ma (time scale of Cox [1982]). If this hot spot was active at that time, we might expect to find basalts with geochemical anomalies in two restricted areas: in the western central Atlantic north of Bermuda and south of the New England Seamounts, and in the eastern central

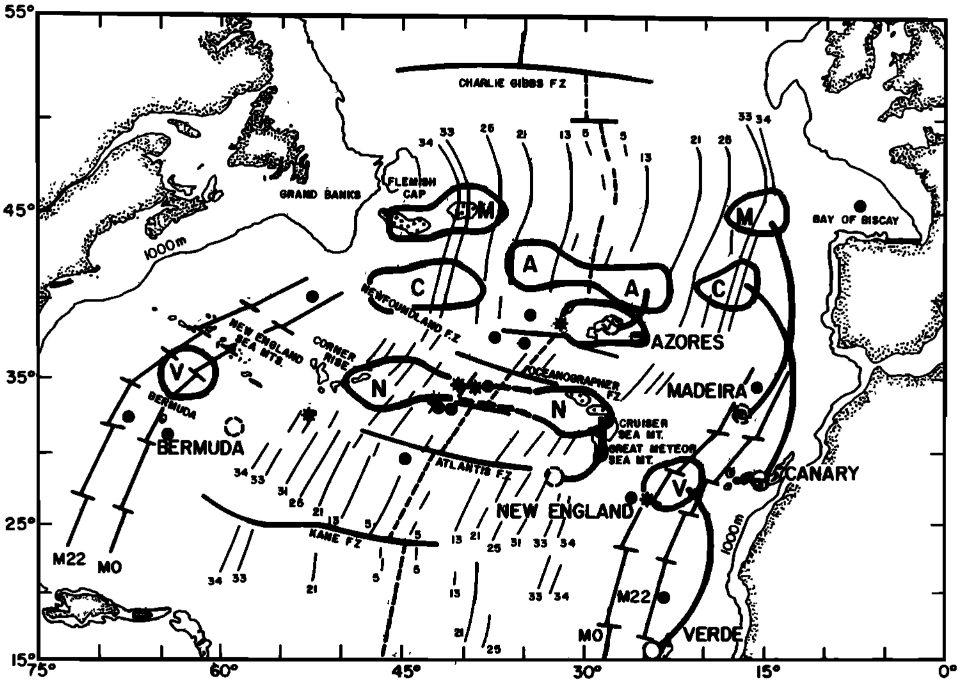

Fig. 4. As segments of the Mid-Atlantic Ridge crossed over hot spots during the opening of the central Atlantic Ocean, basalts formed at those spreading centers would be imprinted with a hot spot geochemical signature. The expected pattern of such geochemical anomalies is shown as bold lines superimposed on identified magnetic anomalies [after Cande and Kristofferson, 1977]. Dots within bathymetric highs are individual seamounts. Letters associate regions with the Madeira (M), Canary (C), Azores (A), New England (N), and Cape Verde (V) hot spots. DSDP sites that recovered basalt are shown as solid circles. Those that found enriched basalts are shown as stars.

Atlantic just to the west of the Canary Islands (Figure 4). The Canary and Madeira hot spots were close to the spreading ridge by 80 Ma (magnetic anomaly 33) and had been crossed by 57 Ma (magnetic anomaly 25). The New England hot spot was near the ridge during the formation of the Corner Seamounts (their age is approximately the age of the ocean floor on which they sit, 70 to 75 Ma) and was probably still close to the ridge until 38 Ma (magnetic anomaly 13). The Azores hot spot was overridden by a ridge segment north of its present location at about the time of magnetic anomaly 13 (38 Ma) and has remained close to the ridge since then.

Deep-sea drilling has recovered basalts from a number of sites in the central Atlantic with which the predicted patterns in Figure 4 can be compared. Prior to Leg 82, which was specifically designed to investigate mantle heterogeneities in the vicinity of the Azores hot spot, only two sites (10 and 138) produced basalts that exhibit anomalous compositions [Wright et al., 1972; Frey et al., 1974]. Site 10 lies just south of the Corner Seamounts and so may be reasonably associated with spreading near the New England hot spot. Site 138 lies in the pattern of Cape Verde hot spot influence west of the Canary Islands.

Figure 5 shows an enlarged region of the central Atlantic investigated by DSDP Leg 82 [Bougault et al., 1983]. Basalts at site 557 show the imprint of the Azores hot spot, while normal mid-ocean ridge basalts were found at site 556 (and previously drilled site 335). At site 558 both normal and enriched basalts were formed. Since this site does not lie close to any proposed hot spot, the origin of the enriched basalts remains a puzzle. Basalts from three sites drilled south of the Hayes Fracture Zone all exhibit normal compositions. The inferred crossing of the New England hot spot occurred between the Hayes Fracture Zone and the Oceanographer

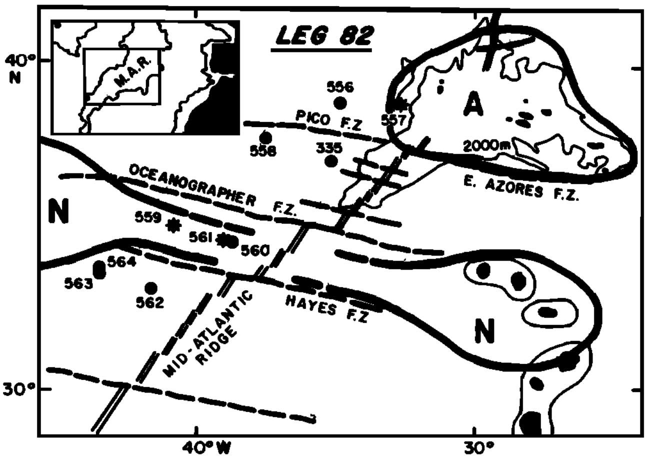

Fig. 5. An enlarged section of Figure 4, showing the drilling results of DSDP Leg 82, central Atlantic. Expected areas of enriched basalts, due to the influence of the Azores and New England hot spots, are bold lines. Enriched basalts were found at sites 557, 559, and 561. Both enriched and normal basalts were found at site 558.

Fracture Zone, where two of three sites drilled on the western flank of the Mid-Atlantic Ridge (sites 559 and 561) produced enriched basalts. The remaining site 560 basalts show normal compositions and mark the end of New England hot spot influence at this section of the Mid-Atlantic Ridge.

In general, the correlation between basaltic compositions and predicted geochemical anomalies is good. The hot spot reference frame thus provides an understanding of the location of certain mantle heterogeneities recorded in the oceanic crust. Further testing will require deep-sea drilling on older ocean floor in the central Atlantic.

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