Reports

Sources of Continental Crust: Neodymium Isotope Evidence from the Sierra Nevada and Peninsular Ranges

Abstract. *Granitic rocks from batholiths of the Sierra Nevada and Peninsular Ranges exhibit initial* $^{143}Nd/^{144}Nd$ *ratios that vary over a large range and correlate with* $^{87}Sr/^{86}Sr$ *ratios. The data suggest that the batholiths represent mixtures of materials derived from (i) chemically depleted mantle identical to the source of island arcs and (ii) old continental crust, probably sediments or metasediments with a provenance age of* $\sim 1.6 \times 10^9$ *years. These conclusions are consistent with a model for continental growth whereby new crustal additions are repeatedly extracted from the same limited volume of the upper mantle, which has consequently become depleted in elements that are enriched in the crust. There is little evidence that hydrothermally altered, subducted oceanic crust is a primary source of the magmas.*

Neodymium isotopic variations in granitic rocks from batholiths of the Sierra Nevada and Peninsular Ranges have been studied to determine the sources of a large volume of continental crust that was added to the western margin of the North American continent during Phanerozoic time and to identify the processes that are associated with the production of new sialic crust. Batholiths of the Sierra Nevada and Peninsular Ranges consist mainly of silica-rich plutonic rocks and form a linear belt about 100 km wide which extends semicontinuously for 2000 km from northern California to the southern tip of Baja California (*1, 2*). The batholiths lie west of the western limit of known Precambrian rocks (Fig. 1) (*3, 4*). The Sierra Nevada plutonic rocks occupy the axial zone of a large synform consisting of a thick section of Paleozoic eugeoclinal sediments overlain by Mesozoic stratified rocks dominated by volcanics (*5*). The batholith of the Peninsular Ranges is intruded into a predominantly lower Mesozoic section of sediments and volcanics (*6*). In both batholiths the volcanic rocks are similar to island arc rocks. The nonvolcanogenic sediments were apparently eroded from the Precambrian crust to the east (*7*).

These large batholith belts combine many of the properties of island arcs, which are considered to be the sites of production of new crust (*8*), and the older stable regions of the continental crust. They are similar to island arcs in that they are linear belts of igneous rock, often gently arcuate, and apparently formed above subduction zones. They are associated with metamorphosed volcanic rocks which are in composition broadly compatible with an island arc-type setting (*1, 2, 6, 9*). On the other hand, they also resemble older regions of the continental crust in that they are predominantly plutonic and are rich in silica. These traits, and the fact that these batholiths lie west of the limit of Precambrian basement (Fig. 1), suggest that they may represent the genetic link between island arcs and stabilized continental crust. However, earlier isotopic studies of the Sierra Nevada in which the Rb-Sr method was used have failed to satisfactorily confirm the link between island arcs and the batholith (*10, 11*). In the Peninsular Ranges, O and Sr isotopic data more strongly suggest the presence of a mantle-derived component and therefore are supportive of the island arc model (*12*). In this study, the systematics of Sr and Nd isotope variations (*13*) are used to investigate the sources of the batholith rocks. The Sierra Nevada batholith (SNB) samples were analyzed for Rb-Sr isotopes by Kistler and Peterman (*10, 11*) (Table 1). Sample locations are given in Fig. 1. Samples were selected on the basis of location, $^{87}Sr/^{86}Sr$ composition, and other compositional features (*10, 11, 14*). They represent a range of geochemically distinct rock types from both the extreme east and west sides of the batholith and from the north and south.

The Peninsular Ranges batholith (PRB) samples represent a more restricted sampling. Samples SM, WM, and RL (Fig. 1) are from the type localities of San Marcos gabbro, Woodson Mountain granodiorite, and Rubidoux leucogranite (*1, 2*). They are all from the northern part of the batholith and are close to the western edge. Samples 800 and 805 are from the San Telmo pluton (*15, 16*). These samples have been analyzed for major and trace elements (*16*) and O isotopes (*17*). Sample 805 exhibits petrographic and O isotope evidence for hydrothermal alteration after emplacement and contrasts with sample 800, which is from the same pluton but is petrographically pristine.

Sample PC-30a is a Precambrian schist from east of the present boundaries of the SNB proper (*10, 11, 18*). Sample FD33 is a composite of metavolcanic rocks from the central-western Sierra Nevada (*10, 11*).

The analytical techniques are described in (*19–21*). The plutonic rocks analyzed contain more than 62 percent SiO_2 (by weight), except gabbro sample PRB-SM-1. Isotopic data are listed in Table 1 and plotted on a graph of ϵ_{Nd} versus ϵ_{Sr} in Fig. 2 (*22–25*). The measured ϵ_{Nd} values span a huge range, from +8 to −8, and lie on both sides of the bulk-earth value $\epsilon_{Nd} = 0$. The ϵ_{Nd} and ϵ_{Sr} values are correlated, with more positive ϵ_{Nd} values corresponding to more negative ϵ_{Sr} and vice versa. The samples can be separated into two groups. One group, composed of samples with positive ϵ_{Nd} and negative ϵ_{Sr}, falls on or close to the oceanic basalt correlation line.

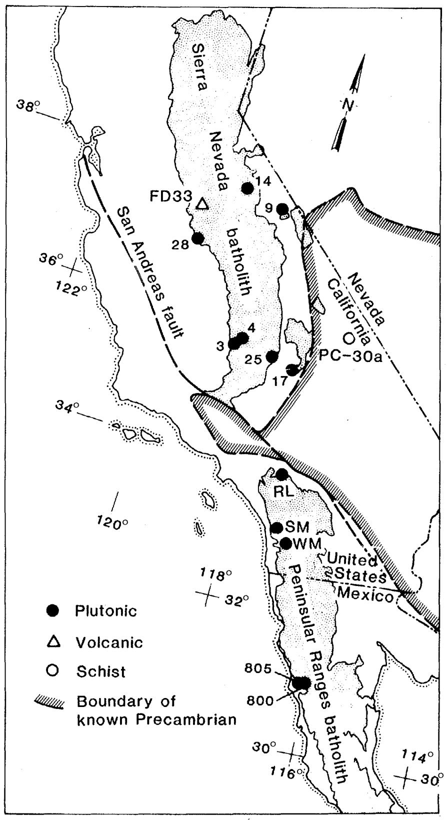

Fig. 1. Map of the batholiths of the Sierra Nevada and Peninsular Ranges, showing the locations of the rock samples analyzed. [Adapted from (*3*)]

The other group contains samples which have negative ϵ_{Nd} and positive ϵ_{Sr}, falling in the field of old crustal rocks (*13*). Sample 805 is unique in that it has positive ϵ_{Nd} and is displaced substantially to the right of the correlation trend.

All of the samples with positive ϵ_{Nd} are from the western side of the batholiths; those with the highest values are closest to the western edge. Samples with negative ϵ_{Nd} occur on both the western and the eastern sides of the SNB.

Sample FD33 also has positive ϵ_{Nd} and lies close to the oceanic correlation trend, but its ϵ_{Nd} is lower than the most positive values shown by the suite of plutonics (Table 1). Sample PC-30a has a very low ϵ_{Nd} and a large positive ϵ_{Sr} (Table 1). The model ages (*26*) calculated for this sample—T_{CHUR} for Sm-Nd ($= 1.62 \times 10^9$ years) and T_{UR} for Rb-Sr ($= 1.64 \times 10^9$ years)—are in excellent agreement. These ages are consistent with the Rb-Sr whole-rock isochron age of Lanphere *et al.* (*27*) obtained in a nearby range and confirm that the metamorphic rocks of this area are about 1.6×10^9 to 1.8×10^9 years old. The high value of ϵ_{Sr} is expected for a metasediment, as is the low Sr/Nd ratio, which was measured to be 3.5.

The correlation trend shown in Fig. 2 is thought to represent systematic variability in the isotopic composition of the upper mantle (*13, 25*). Insofar as the samples from the western side of the batholiths closely conform to the trend, it could be concluded that the magmas were derived from mantle sources with little or no contribution from old crust. However, the ϵ_{Nd} of the sources of island arc rocks is well-defined at $\epsilon_{Nd} \approx +8$ (Fig. 2). The batholith data describe an overall trend which extends from the center of the island arc field far into the range of values characteristic of old continental crust. Considering the analogies between the batholiths and island arcs, and the availability of crustal materials, the data strongly suggest that the source of the batholiths was a mixture of a mantle component identical to the sources of island arcs and a crustal component. A secondary effect, exemplified by sample 805, involves exchange of Sr between seawater and rock (*13, 24*).

A plausible crustal component for the SNB is represented by the sedimentary rocks which accumulated in the region during the Paleozoic and Mesozoic (*3, 7, 28*). The provenance of the detritus was probably the craton 1.4×10^9 to 1.8×10^9 years old underlying the southwestern United States (*27, 29*). Since sediments may accurately preserve the average ϵ_{Nd} of their source terrain (*30*), it is likely that the sedimentary section would have had an ϵ_{Nd} in the range shown in Fig. 2, especially since the sedimentation process acts to average over small-scale variations in the crystalline source rocks. The ϵ_{Sr} value in the sediments would be expected to be high, reflecting the Rb-rich nature of probable upper crustal source rocks, but variable. Sample PC-30a provides some confirmation of these inferences. The trend of the data array indicates a crustal component with large positive ϵ_{Sr}, and the inferred curvature in the trend ($d^2\epsilon_{Nd}/d\epsilon^2_{Sr} > 0$) suggests a crustal component with low Sr/Nd (*13*), both consistent with a sedimentary or metasedimentary component.

Table 1. Sample descriptions and isotopic Nd and Sr data.

Sample*	T (age × 10^6 years)	Type	K (%)	$\epsilon_{Nd}(T)$	$\epsilon_{Sr}(T)$†
SNB-73-9	210	Granodiorite	3.87	-3.5 ± 0.6	+13
SNB-73-28	126	Quartz diorite	0.60	$+6.5 \pm 0.4$	−16
SNB-78-3	120	Quartz diorite	1.47	$+6.0 \pm 0.5$	−16
SNB-78-4	120	Granodiorite	2.51	-2.4 ± 0.6	+25
SNB-78-17	90	Granodiorite	2.04	-6.3 ± 0.5	+31
SNB-73-14	84	Granite	2.90	-6.3 ± 0.3	+30
SNB-73-25	79	Quartz monzonite	4.06	-7.6 ± 0.5	+54
SNB-FD33	~ 150	Volcanic composite	1.20	$+4.6 \pm 0.8$	−9
PRB-SM-1	120	Gabbro	0.23	$+4.7 \pm 0.6$	−15
PRB-WM-1	120	Granodiorite	2.19	$+3.6 \pm 0.5$	−13
PRB-RL-1	115	Granite	4.54	$+1.3 \pm 0.5$	−10
PRB-800	110	Tonalite	0.83	$+7.8 \pm 0.5$	−15
PRB-805	110	Granophyre	2.83	$+7.9 \pm 0.5$	+2
PC-30a	Precambrian	Schist	2.09	-15.4 ± 0.6‡	+440‡

*Sample locations, complete descriptions, and ages are given in (*10*) for samples labeled SNB-73 and PC and in (*11*) for samples labeled SNB-78. The Sr isotope data are from the same references. Descriptions and locations for samples labeled PRB are given in (*20*) (samples SM, WM, and RL) and in (*15*) (samples 800 and 805). Ages are from U-Pb zircon chronology (*15, 21*). †Uncertainties are ± 1 to 2 units except for sample PRB-RL-1, where the uncertainty is ± 5 units. ‡Measured values corrected for age to 120×10^6 years ago.

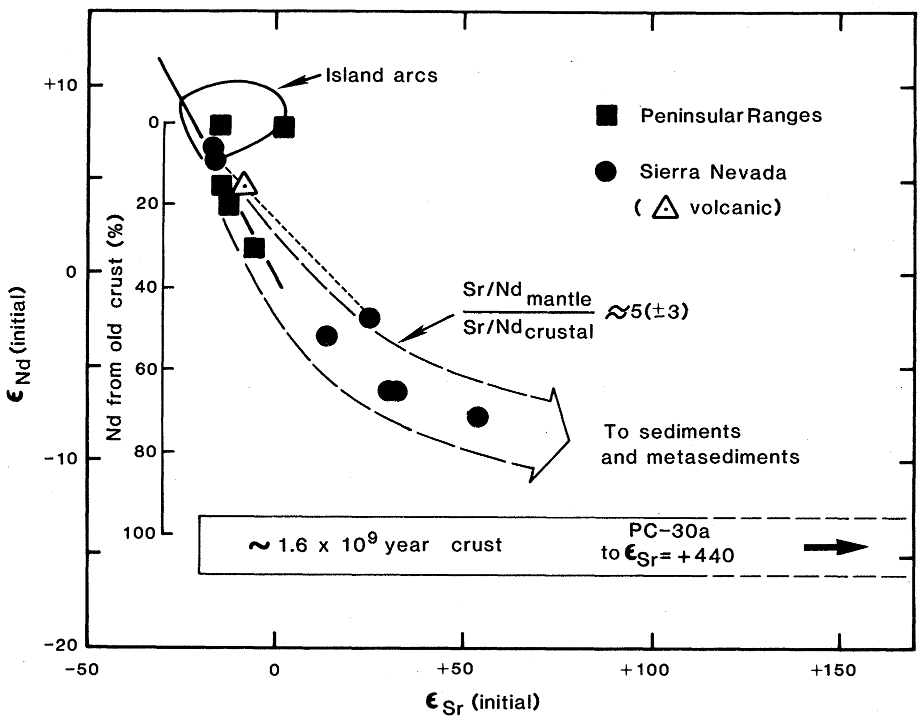

Fig. 2. The ϵ_{Nd} and ϵ_{Sr} data for the Sierra Nevada and Peninsular Ranges samples. Also shown are fields for island arcs (*24*) and 1.6×10^9 year crust. The solid diagonal line represents the oceanic basalt trend (*25*). The large dashed arrow shows the inferred mixing trend between a mantle-derived, island arc-type component at $\epsilon_{Nd} = +8$, $\epsilon_{Sr} = -17$ and a sedimentary (low Sr/Nd) crustal component with a provenance age of $\sim 1.6 \times 10^9$ years. The inset scale at the left refers to this two-component mixing model. The two Sierra Nevada plutonic samples (samples 3 and 4 in Fig. 1) connected by the dotted line are from localities only 7 km apart. Sample 805 which lies far to the right of the oceanic basalt trend, shows evidence of postemplacement exchange with a seawater-like fluid.

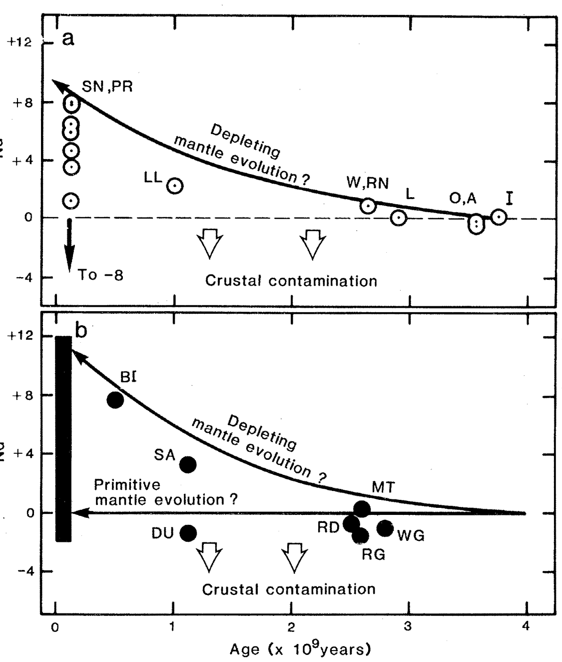

Fig. 3. Graphs of initial ϵ_{Nd} versus age for (a) silicic rocks and (b) mafic rocks. Curved arrows show possible ϵ_{Nd} evolution in a mantle reservoir that is being continuously depleted in Nd relative to Sm as a result of the growth of continental crust (*37*). The horizontal arrow in (b) indicates the evolution of primitive mantle. The solid vertical bar gives the range of ϵ_{Nd} in oceanic basalts. Data are from the present study and (*23, 33, 35, 36, 38*). Abbreviations: *SN*, Sierra Nevada; *PR*, Peninsular Ranges; *LL*, Llano; *W*, Louis Lake batholith; *RN*, Preissac Lacorne batholith; *L*, Lewisian gneisses, *A*, Amitsoq gneiss; *I*, Isua; *O*, Onvervacht; *BI*, Bay of Islands gabbro; *SA*, Sierra Ancha diabase; *DU*, Duluth gabbro; *RD*, Great Dyke; *MT*, Munro Township; *RG*, Rhodesian greenstones; and *WG*, Fiskenaesset anorthosite.

Earlier workers suggested that much of the Sierra Nevada magmas formed as a result of the melting of crystalline lower crust (*10, 11*). The Nd isotope data are more consistent with an "upper crustal" source for some fraction of the magmas. Typical crystalline lower crust with an age of 1.6×10^9 years would be expected to have ϵ_{Nd} and ϵ_{Sr} values lying near the left edge of the field shown in Fig. 2. The trend of the data array does not appear to be consistent with such a crustal component for a simple two-component model. However, the actual properties of any lower crust in the region at the time of formation of the batholiths are not known in detail. Lower crust could have been a major component if its properties were substantially different from those inferred. The inference that the crustal component was sedimentary in origin, based on the Sr/Nd considerations, is generally consistent with the O and Sr data reported by Taylor and Silver (*12*) on the PRB. They found a correlation between the O isotopic composition and $^{87}Sr/^{86}Sr$ and also concluded that the batholith contains a mantle component and possibly an old sedimentary component, although other alternatives were also discussed. The O, Sr, and Nd data appear to be qualitatively consistent, but further Nd data from the Peninsular Ranges will be necessary to confirm this. The conclusions given here also appear compatible with the petrologic inferences of Presnall and Bateman (*31*).

The ostensibly simple mixing model proposed here would nevertheless be consistent with a wide variety of complex petrologic models for the generation of the granitic magmas. For instance, the "mantle" component could be (i) magmas derived directly from the mantle during the main Mesozoic magmatic events, (ii) deeply buried mantle-derived volcanic rocks generated during earlier Mesozoic or Paleozoic orogenic episodes, or (iii) the local upper mantle itself. Mixing of the sedimentary material with the mantle component could be a result of wall-rock assimilation by mantle-derived magmas or interlayering of sediments and older mantle-derived volcanics which were then buried and melted. Independent of the model, the fraction of Nd atoms present in the batholiths which was derived from the old crust can be estimated from the isotope data as shown in Fig. 2. This calculation assumes a mantle component with $\epsilon_{Nd} = +8$ and a crustal component with $\epsilon_{Nd} = -14$. For some rocks of the SNB, especially those from the east side, 50 to 70 percent of the Nd may have been derived from older crust. Some of the samples from the west side contain essentially no Nd from the crust and can be considered to represent wholly material newly extracted from the mantle and added to the crust.

According to current theories of magma genesis at convergent plate margins, the parental magmas for the batholiths could have been derived in part from subducted oceanic crust (*8*). However, if the ubiquitous hydrothermal exchange between seawater and oceanic crust at oceanic ridges (*32*) causes the ϵ_{Sr} of the oceanic crust to be substantially shifted to more positive values, this would be reflected in the isotopic composition of magmas melted from the subducted crust (*24, 33, 34*) which would lie to the right of the ϵ_{Nd}-ϵ_{Sr} correlation trend (Fig. 2). Only one sample (sample 805) shows evidence for seawater interaction, but this sample also exhibits abundant evidence for postcrystallization interaction with a seawater-like fluid, based on O isotopes in altered feldspars (*17*). Thus, the effect shown by this sample is likely to be unrelated to the magma source. From the limited sampling investigated, it must be concluded that there is little evidence that hydrothermally altered subducted oceanic crust has been used in the generation of these magmas. Such a model clearly cannot explain the high ϵ_{Sr} values found in many of the batholith rocks (*10–12*), since these rocks also have negative ϵ_{Nd}.

The mantle component which can be deduced from Fig. 2 appears to have $\epsilon_{Nd} = +8$ and $\epsilon_{Sr} = -17$. The positive ϵ_{Nd} indicates that the mantle from which the new crustal material is derived is "depleted mantle," that is, it has been tapped of a crustlike component in the past (*35*). This is in apparent contrast to Archean crustal rocks, which have $\epsilon_{Nd} \approx 0$ and therefore must have come from essentially unfractionated mantle reservoirs with chondritic relative abundances of rare-earth elements (*33, 36*). The initial ϵ_{Nd} values measured on silica-rich crustal rocks of different ages (Fig. 3a) demonstrate the difference between the SNB and PRB samples and the rocks of older age (*23, 33, 35–38*). The Nd isotope data presented here would be consistent with a model such that a limited volume of the earth's mantle (approximately 20 to 30 percent) has been repeatedly tapped throughout earth history to produce new continental crust, and the extraction of the crustal material has caused this part of the mantle to become substantially depleted in those elements (including Nd, Sm, Rb, Sr, and K) that show marked enrichment in the crust. This suggests that the average chemical composition of new crustal additions today may differ from the composition of average Archean crust, which would have been derived from mantle which at the time was much less depleted than the present-day upper mantle.

Comparison of Fig. 3, a and b, shows that the model of a depleting mantle source appears to fit for both the silicic rocks of the continental crust and the oceanic and continental basalts. This implies that the isotopic history of the upper mantle may be recorded in the granitic crustal rocks as well as in the basalts. This finding may greatly aid in the study of mantle evolution, since oceanic basalts, which are the best indicators of mantle composition, can be identified only with great difficulty at times earlier than Mesozoic, the age of the oldest ocean floor.

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$$\epsilon_{Nd}(0) = \left[\frac{^{143}Nd/^{144}Nd_{meas}}{^{143}Nd/^{144}Nd_{\oplus}(0)} - 1\right] \times 10^4$$

and

$$\epsilon_{Sr}(0) = \left[\frac{^{87}Sr/^{86}Sr_{meas}}{^{87}Sr/^{86}Sr_{\oplus}(0)} - 1\right] \times 10^4$$

where the subscript $\oplus$ signifies the value for the earth. In a similar manner, the initial ratios for a rock of age T may be expressed as follows:

$$\epsilon_{Nd}(T) = \left[\frac{^{143}Nd/^{144}Nd_{I}(T)}{^{143}Nd/^{144}Nd_{\oplus}(T)} - 1\right] \times 10^4$$

$$\epsilon_{Sr}(T) = \left[\frac{^{87}Sr/^{86}Sr_{I}(T)}{^{87}Sr/^{86}Sr_{\oplus}(T)} - 1\right] \times 10^4$$

where the subscript I refers to the initial value, $^{143}Nd/^{144}Nd_{\oplus}(T) = {}^{143}Nd/^{144}Nd_{\oplus}(0) - 0.1936\,[e^{\lambda_{Sm}T} - 1]$; $^{87}Sr/^{86}Sr_{\oplus}(T) = {}^{87}Sr/^{86}Sr_{\oplus}(0) - 0.0839\,(e^{\lambda_{Rb}T} - 1)$; $\lambda_{Sm} = 0.00654$ per 10^9 years; and $\lambda_{Rb} = 0.0139$ per 10^9 years.
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$$T_{CHUR} = \frac{1}{\lambda_{Sm}} \ln\left[1 + \frac{^{143}Nd/^{144}Nd_{meas} - {}^{143}Nd/^{144}Nd_{\oplus}(0)}{^{147}Sm/^{144}Nd_{meas} - {}^{147}Sm/^{144}Nd_{\oplus}(0)}\right]$$

T_{UR} is the analogous model age defined for Rb-Sr.
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Foraminifera: Distribution of Provinces in the Western North Atlantic

Abstract. *All published distributional data on recent benthic foraminifera of the North American Atlantic continental margin were archived into computerized catalogs. Cluster analysis of these data delimited seven large, marginally overlapping provinces exhibiting a congruous relationship with western North Atlantic water masses. The single major latitudinal faunal change occurs at Cape Hatteras.*

Benthic foraminifera occur abundantly in all marine environments. The number of living foraminifera usually exceeds 10^6 per square meter, and wet-weight biomass estimates range from 0.02 to over 10 g/m^2 (*1*). Because of the biologic and geologic importance of the foraminifera, a vast literature exists on their distribution. During the last 130 years, we know of 142 papers that were published on the distribution of recent benthic foraminifera from the eastern continental margin of North America. Analysis of such a large data set by traditional methods of preparing maps or tables for all taxa is impossible. To obtain a synthesis of the foraminiferal distribution along the eastern margin of North America, one of the most completely studied areas in the world, we compiled a computerized catalog of the published occurrences (presence or absence data) from Newfoundland to the Bahamas (*2*). The catalog archives the distribution of 1303 species names from 542 localities. Through synonymization, achieved by reference to published illustrations and specimens lodged in the U.S. National Museum collections, and by consultation with several researchers on benthic foraminifera, the number of species names was reduced to 876. We report here the outcome of a cluster analysis of these data and relate the resulting distributions to major water masses. As far as we know, this is the first study to use all available data to synthesize distributional patterns over an entire continental margin.

For the cluster analysis, computer limitations forced us to reduce the number of localities to 350 by randomly deleting localities. These 350 localities contained 791 species. We analyzed this data matrix in the Q-mode by clustering Jaccard

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