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Pre-Drift Continental Nuclei

Two ancient nuclei appear to have had a peripheral growth and no pre-drift fragmentation and dispersal.

Patrick M. Hurley and John R. Rand

In a survey of the ages of continental areas we have compiled and plotted almost all of the available age data on continental basement rocks in North and South America, Africa, Europe, India, Australia, and Antarctica, representing two-thirds of the land area of the earth (see Figs. 1 to 7). Age dates for continental areas in the U.S.S.R. and China are not included because we could not obtain information on the actual location of samples. In making this survey we wished to add to some of the earlier compilations (*1*) and to bring together the available material (*2*) in unified form.

Much of the total area of the continents is overlain by a thin cover of sedimentary rocks and sediments, so there are large areas in which no information on the age of the basement rocks can be obtained. In some instances the ages of the basement rocks have been determined from samples obtained in core drilling for petroleum. Where the ages indicated are less than 440 million years, these are recorded only in the case of orogenic belts within which igneous and metamorphic rocks can be taken to represent the true crustal basement. However, the judgment that the area in question is an orogenic belt is always open to debate.

We have not attempted to indicate in Figs. 1 through 7 the age data for Phanerozoic folded and intruded mountain systems that have been adequately surveyed by ordinary geological methods. Information on the ages and locations of these Phanerozoic belts is available in geological maps for the various continents. The continental age provinces are therefore considerably better known than the points plotted for radiometrically measured ages would indicate.

Dr. Hurley is professor of geology at Massachusetts Institute of Technology, Cambridge; Dr. Rand is a geologist living in Freeport, Maine.

Pre-Drift Distribution of Age Provinces

For purposes of this discussion it does not matter if one uses the age of a metamorphic overprint in a region rather than the primary age; the matching is equally effective on this basis, and potassium-argon age data are more available.

We present the age data as three apparent-age units ("apparent age" refers to ages determined from radiometric age data) on the basis of a natural grouping of the age values in Figs. 1 through 7. This grouping is based on the following logic.

Much of the greatest area of the continental basement rocks is included in belts of orogenesis and rejuvenation that are post-Grenville. In Africa and South America the extensive regions included in the Pan-African and Caririan orogenies show almost continuous ranges in age values from about 700 million years to 400 million years, and thus they overlap in time the Phanerozoic events that culminate in the continental margins in western South America, eastern and western North America, North Africa, and southern Europe. Similar overlaps are found for Australia and Antarctica. Extensive late Precambrian activity is being found in the Appalachian and Hercynian provinces, in which age values in the range 550± million years typical of the Pan-African belt of central Africa are appearing in the heart of the previously presumed Paleozoic orogenies. On the other hand it still seems that there was a universal quiet interval between 700 and 900 million years ago. We have therefore set the time boundary for the younger basement-rock age provinces at 800 million years ago.

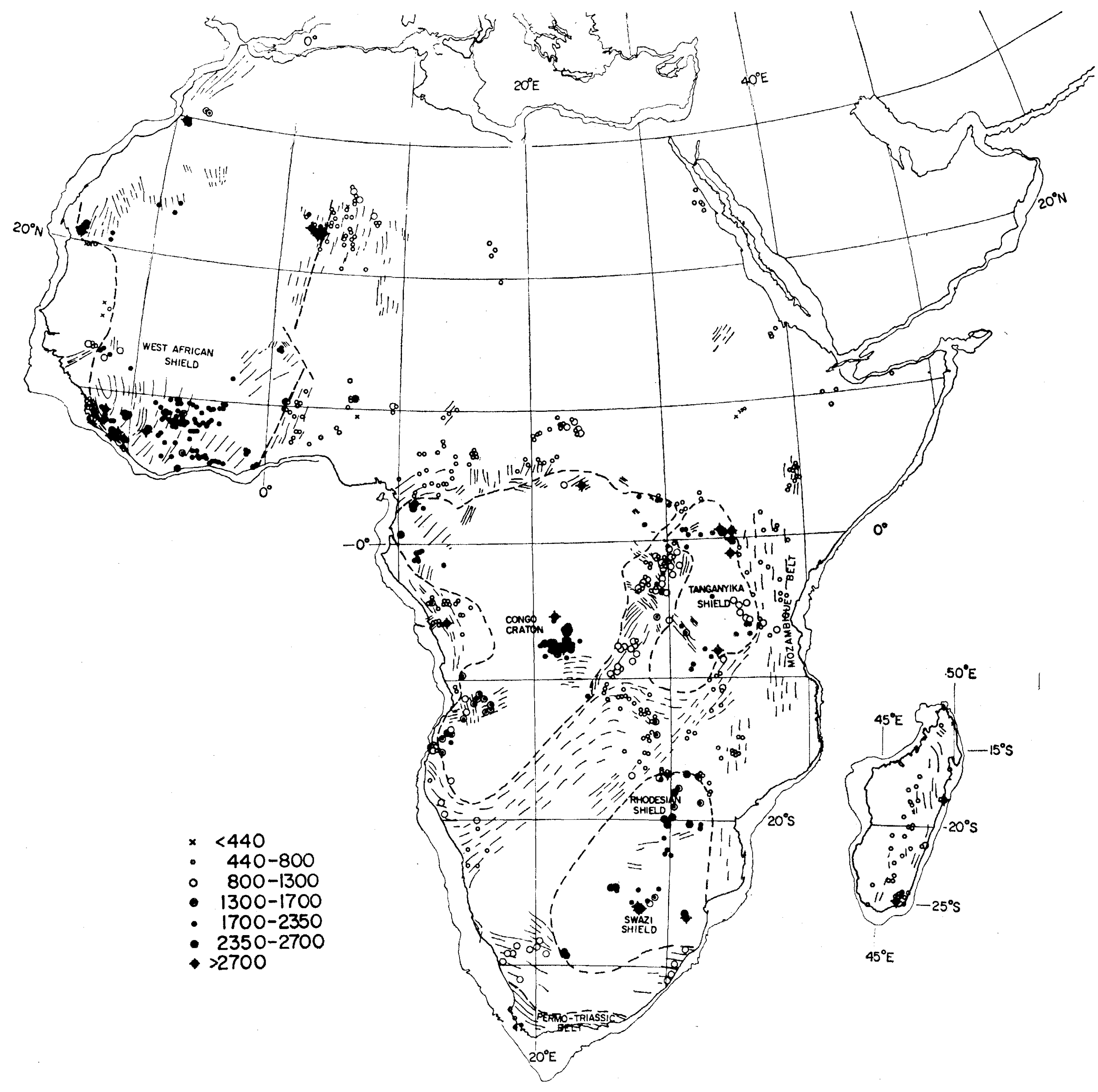
Selection of the time boundary between the middle and older provinces is much more difficult. If the age data for Africa and South America are considered together with those for North America and Europe, the previously observed groupings largely disappear. There seems to be a low point in geological activity in Africa at about 1300 million years ago, but this is compensated by an abundance of ages in this range for a great region in central North America. The abundance of age values varies rather uniformly in the range greater than 1300 million years until, at about 3000 million years ago, the number of apparent-age dates drops essentially to zero. There is a slight dip in the worldwide histogram of reported ages at 1700 million years, so we have arbitrarily chosen this value as the boundary between the two older age provinces. It should be remembered that this arbitrary boundary refers only to apparent ages (mainly obtained by the potassium-argon method) and is useful only for matching ancient blocks of crust. It has no other significance in this study.

If we now take the approximate delineations of the two older Precambrian age provinces that have been outlined for the various continental masses and bring them together in a geographical reconstruction for the period preceding the great drift episode that has occurred during the last 200 million years, we have the groupings that appear in Fig. 8. We have used the pre-drift reconstruction of Bullard, Everett, and Smith (*3*) for the continental land masses around the Atlantic Ocean. For India, Australia, and Antarctica we have used a composite reconstruction (Fig. 8, bottom right) that does not differ very much from the suggestions of most of the recent investigators of this problem. For the purpose of this article it does not greatly matter which of the proposed reconstructions of India, Australia, and Antarctica we choose.

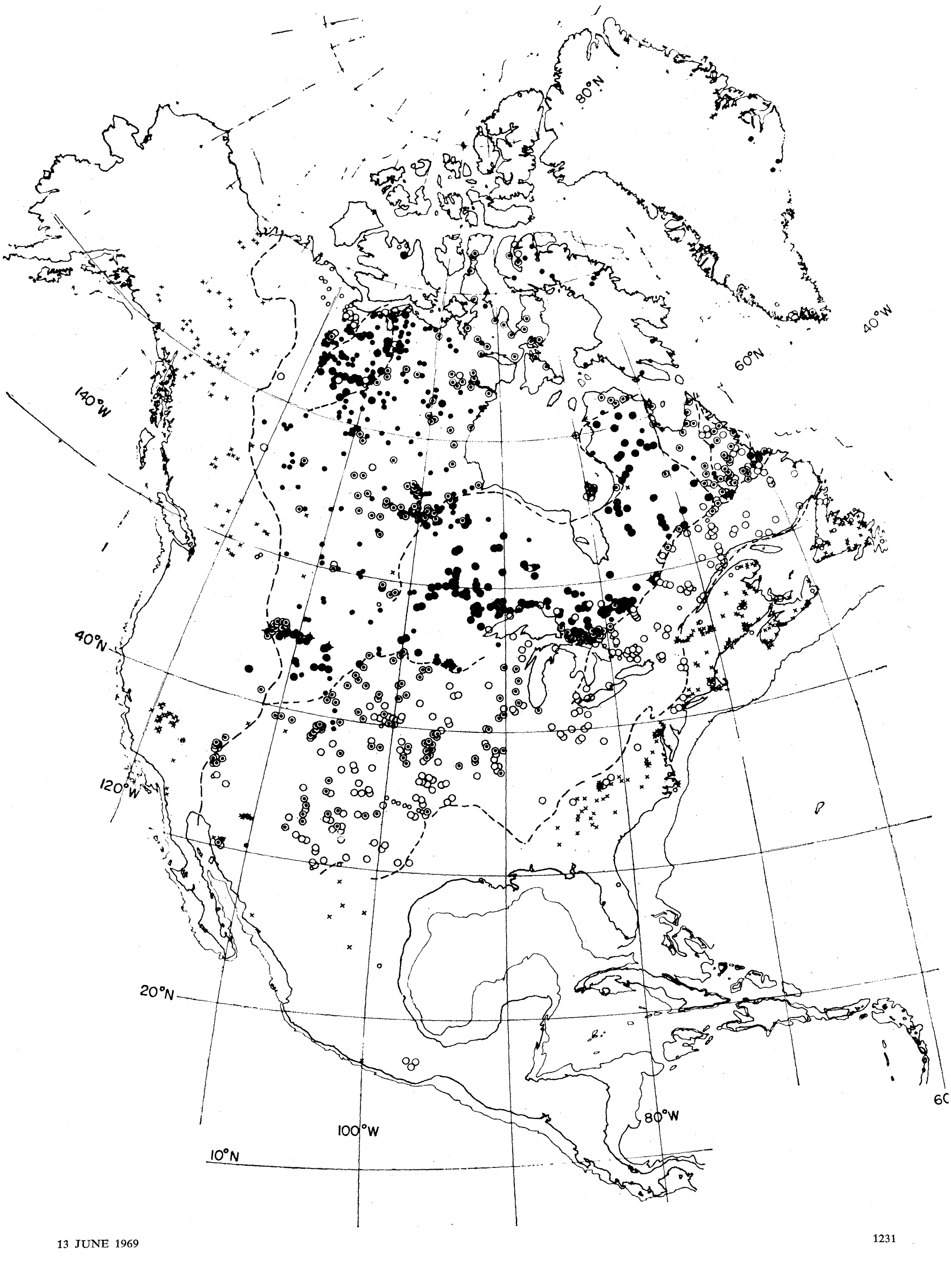
In Fig. 9 the Angara and Aldan shields of Siberia are added after those regions of the Arctic Ocean that are at depths greater than 1000 meters are closed up in a "best-fit" reconstruction (*4*). Only the provinces older than 1700 million years are shown in Fig. 9.

The presentations of Figs. 8 and 9 disclose an interesting fact. The continental basement complexes older than 800 million years now appear to fall into two rather closely unified groupings. The older province in the northern grouping includes the shield areas in Canada, Greenland, Scandinavia, the Ukraine, and the Aldan and Angara cratons of Siberia. These assemblages appear to have been chopped up by younger transcurrent, geologically active belts. It even appears that the older areas within each block of crust have strike directions that are nearly parallel (this is not shown in Figs. 8 and 9).

A similar effect is seen in the southern grouping, where the cratonic areas



Figs. 1–7 (pages 1230 to 1236). All available radiometric age data for basement rocks (mainly data obtained by the potassium-argon method) plotted on the continental areas indicated. The key given in Fig. 1 for identification of symbols applies to all seven figures. Data within geologic belts of known age in the Phanerozoic have been omitted.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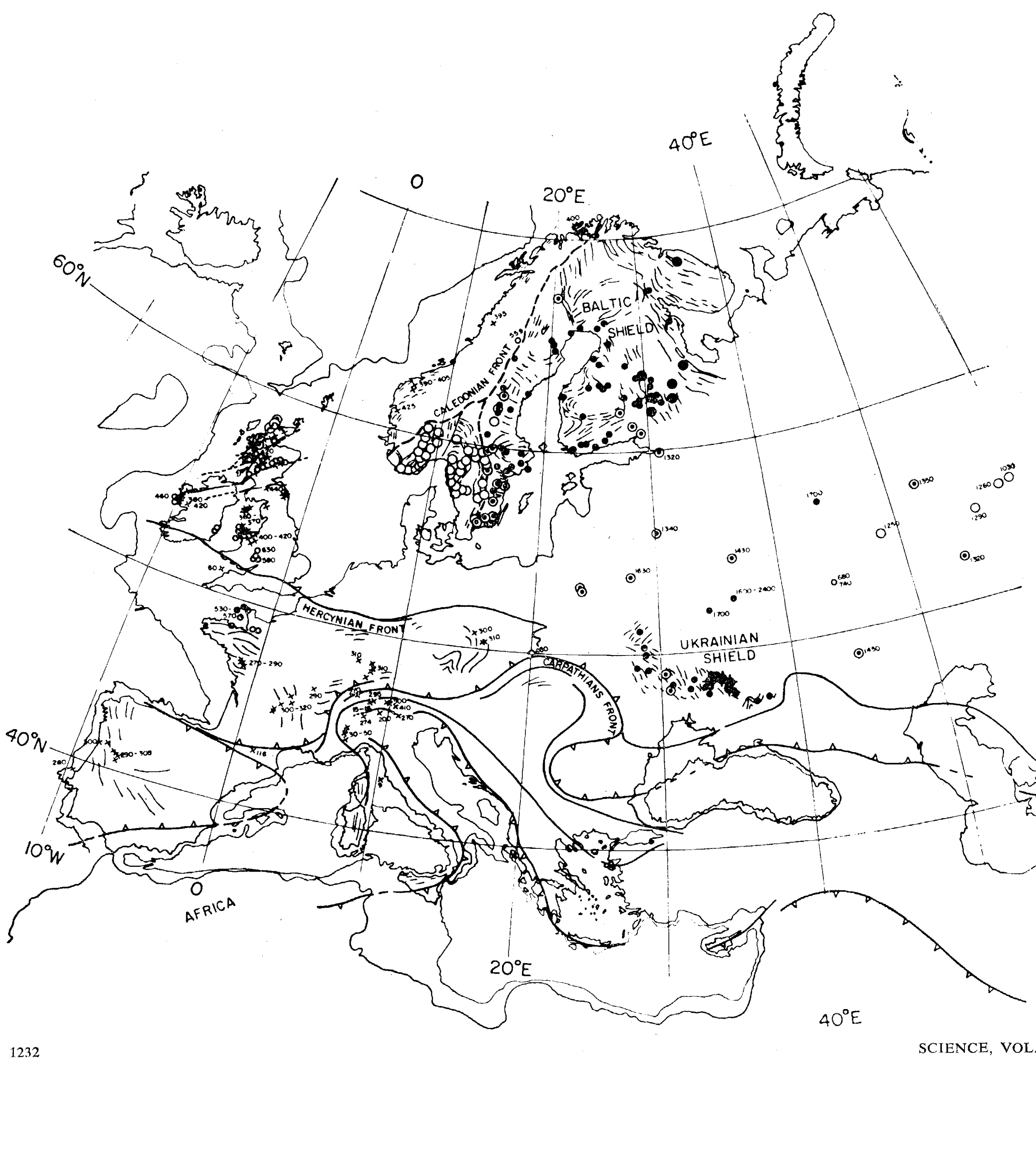
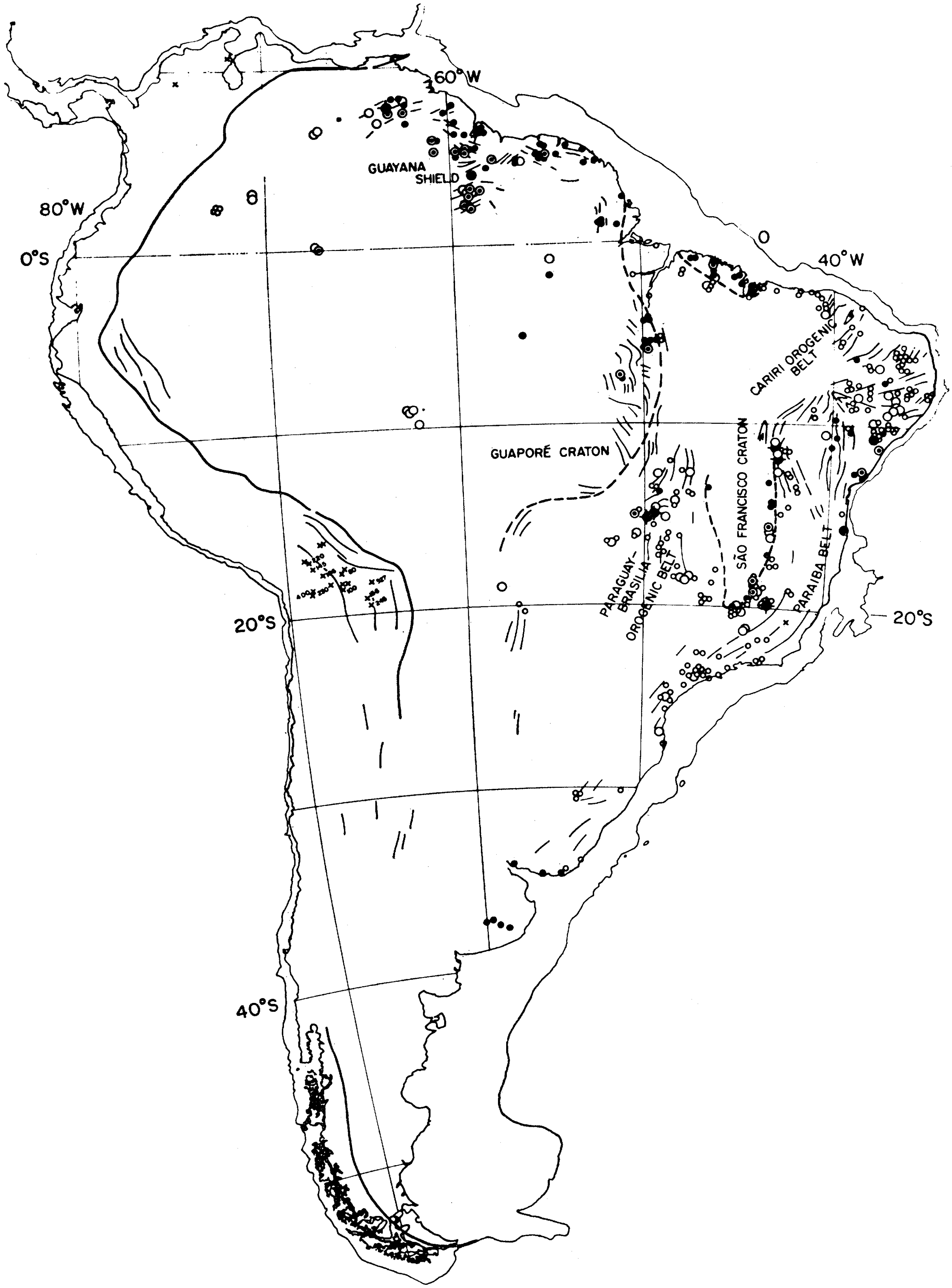
of South America, Africa, India, Australia, and Antarctica form a rather closely knit mosaic, again chopped up by younger and transcurrent active belts.

The two regions of crust older than 1700 million years can be enclosed within rather smooth ovoidal boundaries, and essentially all of the older age measurements that have been reported have been obtained within these boundaries. This is true not only of potassium-argon age measurements but also of measurements made by the most trustworthy methods. In other words, with possible exceptions that have escaped our attention, there are apparently no ancient continental basement rocks outside these relatively small regions on the earth's surface.

Moreover, we are now finding that, within many of the younger transcurrent zones of geological activity within these two regions, there are isolated relict masses with whole-rock age values comparable to those for the adjacent cratonic regions. For example, several ancient ages have been found in Nigeria almost in the center of the Pan-African belt between the West African craton and the Congo craton. Lenses of ancient rocks (3000 million years old) have been found in the belt between the West African shield and the Guayana shield of Venezuela, which extends through the coastal regions of Sierra Leone and Liberia. Scattered ancient age values have been obtained within the Cariri orogenic event between the northern cratons of Brazil, and within the Paraguay belt between the craton of Guaporé and the craton of São Francisco. Ancient age values have been obtained by A. R. Crawford in Ceylon, in the eastern Ghats region of India, and in other supposedly young parts of the Indian subcontinent. Similarly, such ages are being found in the western part of Australia within areas where potassium-argon dating has given ages that are quite young.

The ancient cratons are not scattered uniformly throughout the pre-drift continental crust, as one might expect them to be if they had been initially isolated or separated on the earth's surface and had been brought together by a gathering process prior to the recent drift. Instead, they are all centrally located within the so-called supercontinents of




60°W
GUAYANA SHIELD
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0°S
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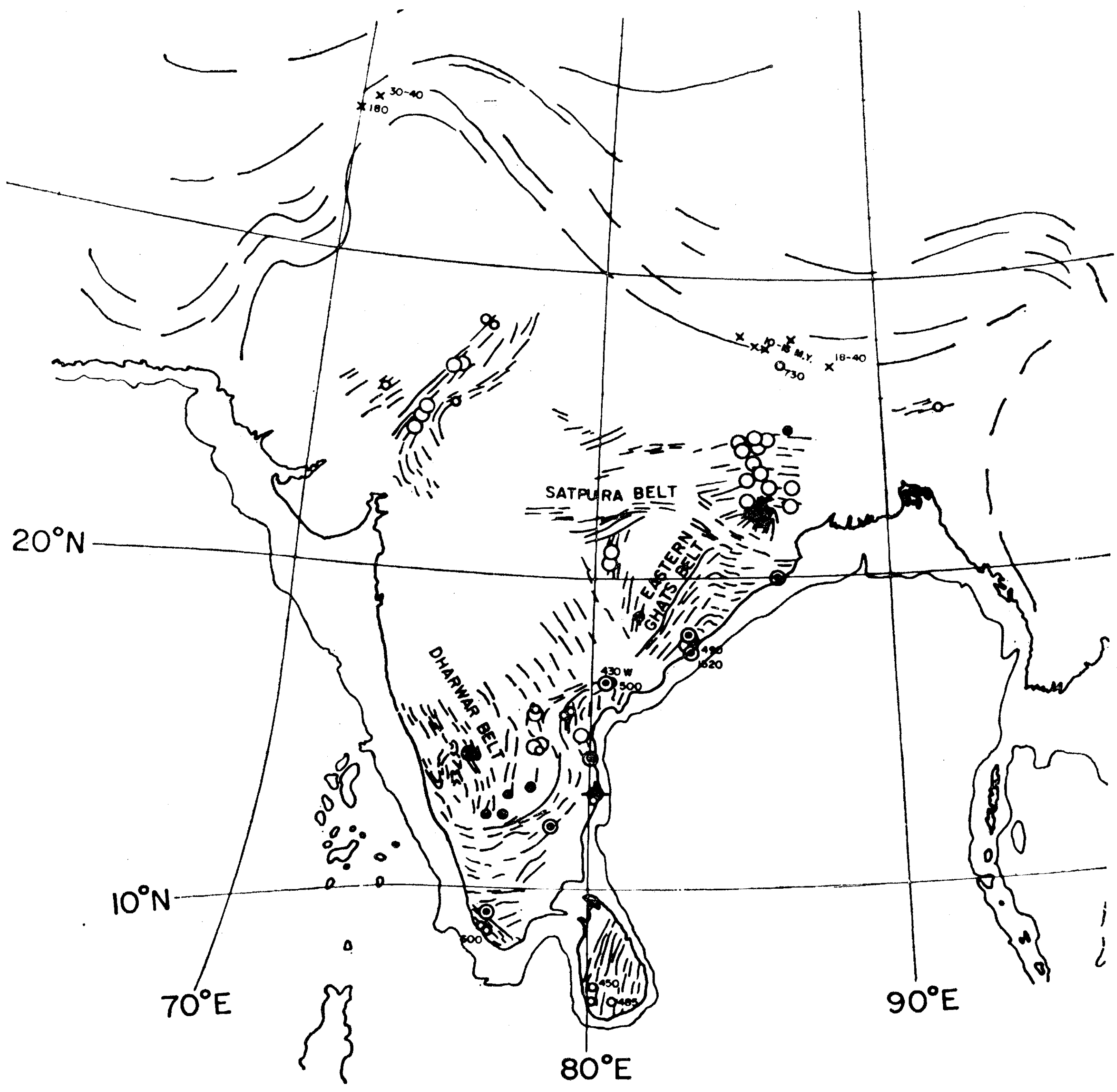
CARIRI OROGENIC BELT
GUAPORÉ CRATON
SÃO FRANCISCO CRATON
PARAGUAY-BRASILIA OROGENIC BELT
PARAIBA BELT
20°S
20°S
40°S

"Laurasia" and "Gondwanaland" (5), and encircled almost entirely by belts of younger continent. This concentric arrangement and the limited degree of scattering of the ancient continental cratons make it difficult to conceive of a series of drift motions prior to the breakup that occurred within the last 200 million years.

In Fig. 10 we present an unrelated observation that should be investigated further. In Fig. 10 some of the better-known occurrences of deep-seated crustal rocks, such as granulites and charnockites, have been roughly plotted on the reconstruction of Fig. 9. We have made no attempt to be accurate or exhaustive in our search for these occurrences, and have used only those that come readily to mind. Again, a coherent pattern seems to emerge. Also, the general strike of the basement rocks in most of the localities roughly parallels a line drawn from the upper right to the lower left in Fig. 10. In most cases the granulite bodies occur within a tectonic belt of intermediate age, although many of them show ages greater than the age of the thermotectonic activity.

The reconstructed continental nuclei with the boundaries shown in Fig. 9 are surrounded by great sweeping belts of younger crust. These belts are not shown on the maps because of the difficulty of projection. Laurasia, the northern nucleus, would be bounded by the Appalachian, Hercynian, and Alpine belts along the southeastern perimeter, with the Himalayan, East Asian, and western North American belts forming the remaining perimeter. Gondwanaland, the southern nucleus, would have peripheral belts that included the Atlas; the Pan-African of northeast Africa and of Arabia; the sequence of geosynclines in eastern Australia, including the Adelaide, Tasman, and adjacent younger ones; the similar sequence in western Antarctica; and the inner and outer belts in the Cordillera of South America and in the coastal republics of northwest Africa from Sierra Leone to Morocco.



Most of these show a sequence of ages from older to younger, proceeding outward from the core of the continental nucleus. Thus, the pre-drift reconstruction makes the suggestion of continental accretion (*6*) more plausible; however, in this case the accretion is relative to the two nuclei, not to the continents as they now exist.

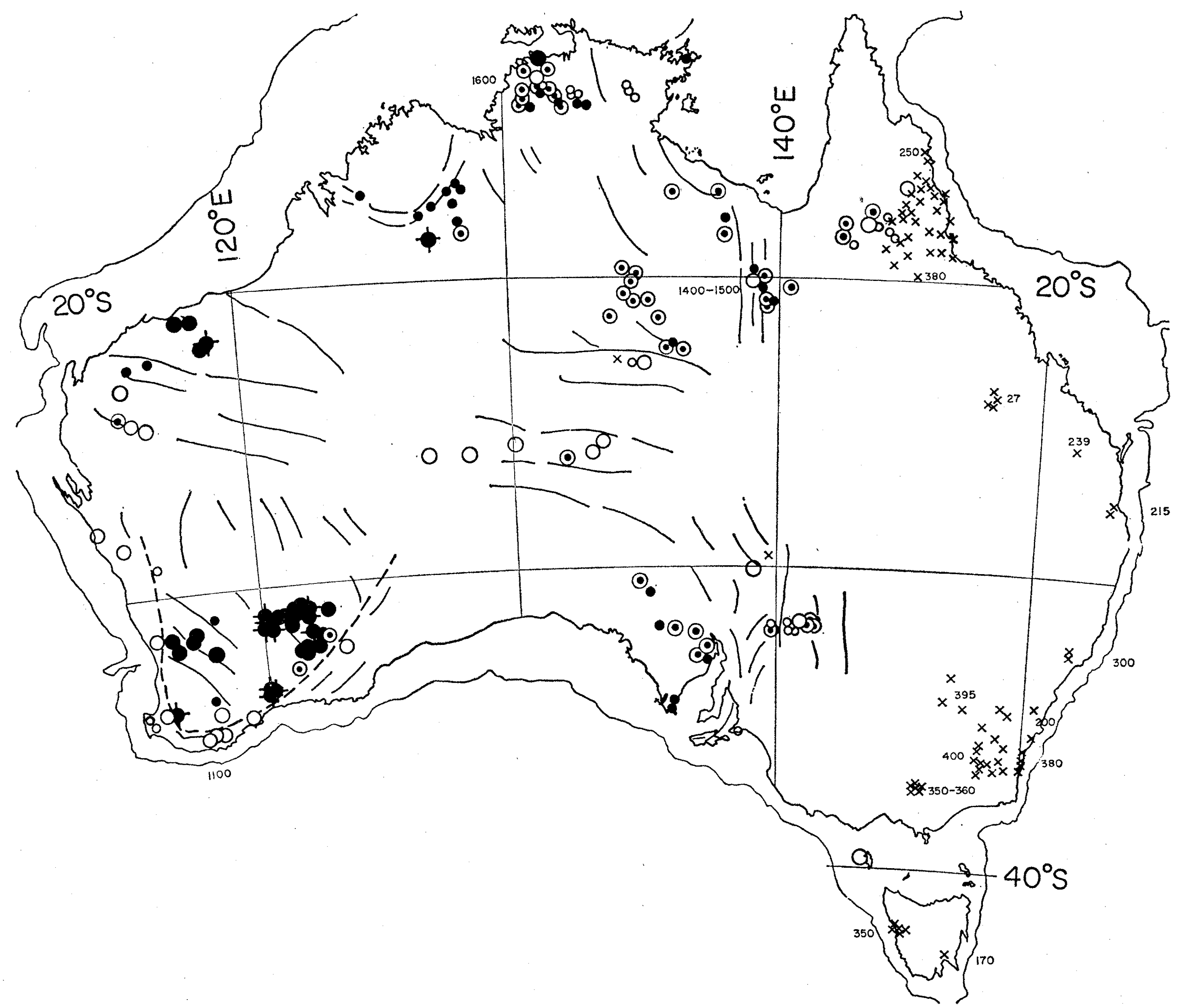
The peripheral development of active belts could have been due in part to sea-floor motions (*7*) directed inward toward the continental regions. If this was the case, it would suggest a centripetal motion of the asthenosphere into the continental hemisphere acting over a long period of time. Recently Orowan (*8*) has suggested that there may have been a reversed, or outward-moving, flow of the asthenosphere from the predrift continental hemisphere, causing the rifting and drifting of the continents. The great concentration of radioactive elements in the continental nuclei may have caused a thermal imbalance in the earth that brought on the reversal.

We have no ready explanation for the transcurrent belts of thermotectonic activity that cut across the ancient cratonic regions, showing relict masses of ancient rocks in zones of younger igneous and sedimentary rocks, sometimes uplifted after deep burial, and sometimes exposing rocks characteristic of the lower crust, such as the granulites mentioned above. These belts suggest rifting that opened up gaps of, at most, a few hundred kilometers, with sediments and subsequent igneous activity filling the rifted zones.

The question of the possible existence of a separate Laurasia and Gondwanaland farther apart than they would appear to have been from the Bullard construction (*3*) is not easily settled without more paleomagnetic information. It is therefore too soon to speculate on the possible locations of these two continental nuclei, or on the question of whether they were a single nucleus at the outset. We are concerned at this time only with the suggestion that the early land masses had remained grouped into one or two assemblages prior to the last drifting activity and had not been previously split and scattered over the surface of the earth, as Wilson believed they had been (*9*).

True Crustal Ages and Apparent Ages

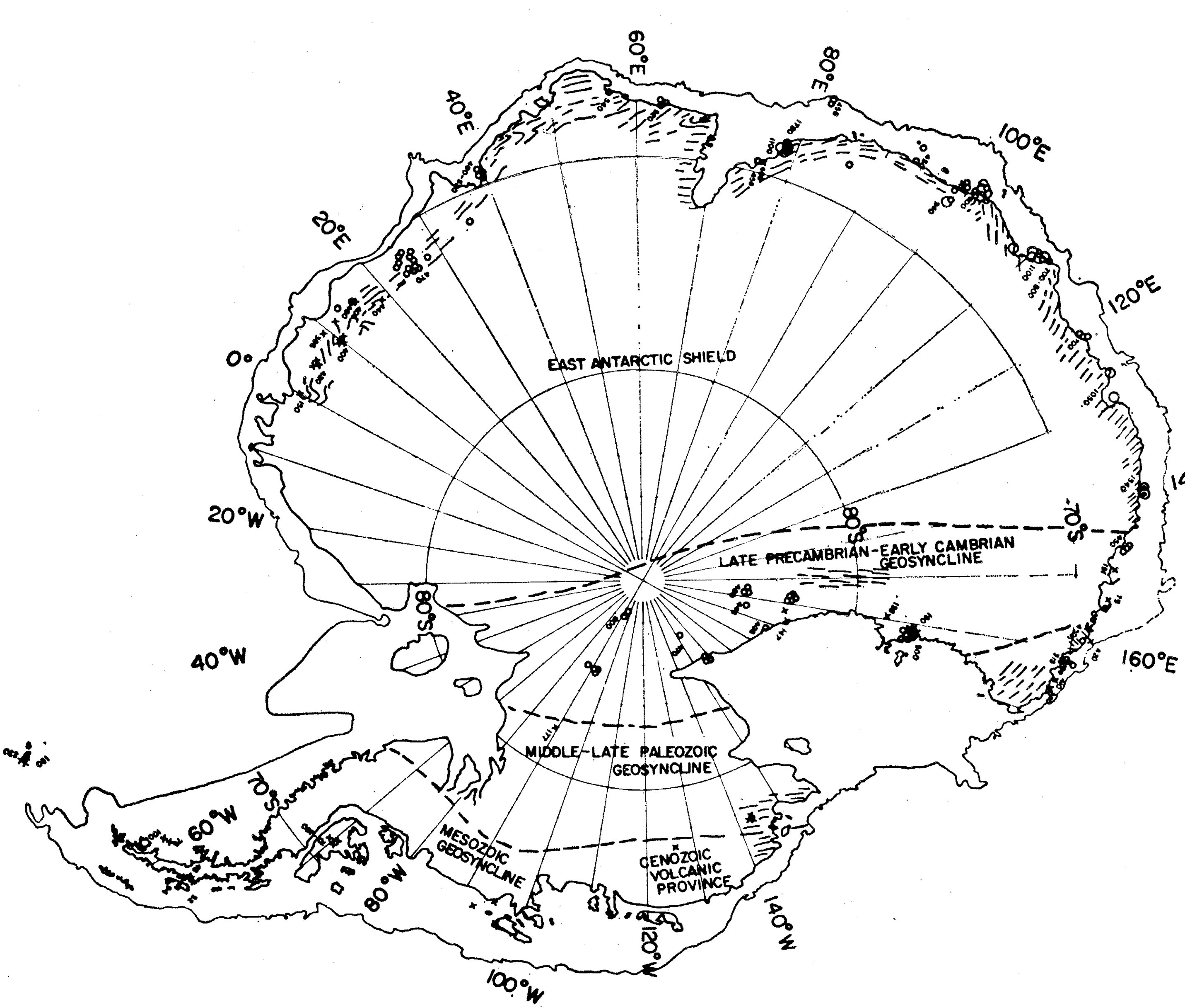
We now evaluate the usefulness of apparent radiometric ages in trying to reconstruct the actual development of the crust. Such an evaluation requires that we define some form of absolute age for crustal material and relate this in some way to the apparent ages de-



termined from radiometric age data. Before doing so we should define a few terms. R_0 = the average value for the earth's Sr^{87}/Sr^{86} ratio at the time of the earth's origin; R_m = the Sr^{87}/Sr^{86} ratio for the source region at the time of separation of crustal material, as defined below; R_i = the Sr^{87}/Sr^{86} ratio for stabilized crustal rock at the time the rock became closed to migrations of rubidium and strontium; R_s = the Sr^{87}/Sr^{86} ratio for the rock sample analyzed; r_c = the average Rb^{87}/Sr^{86} ratio for the continental crust; r_s = the Rb^{87}/Sr^{86} ratio for the rock sample; r_e = the average Rb^{87}/Sr^{86} ratio for the earth; T_0 = the age of the earth (in millions of years); T_m = the time of separation (millions of years ago) of crustal material, or "total crustal age"; T_i = the time the rock system became closed to migrations of rubidium and strontium ["whole-rock rubidium-strontium isochron age" (in millions of

Table 1. Measured areas of continental basement rocks included in apparent-age provinces each covering 450 million years.

Continent	Area (in square kilometers)						
	0–450 million years	450–900 million years	900–1350 million years	1350–1800 million years	1800–2250 million years	2250–2700 million years	2700–3150 million years
Africa	2,371,300	17,349,800	1,953,100	315,000	6,559,500	1,826,700	289,800
South America	5,139,800	10,995,600	699,300		4,769,100		42,100
North America	12,831,700	3,825,400	3,988,300	3,912,500	5,091,300	3,162,100	
Australia	2,806,600	1,607,400	3,359,400	1,192,100	490,400	322,200	694,500
India	1,761,100	1,679,100	1,194,300	506,200	606,000	356,500	39,200
Antarctica	5,751,600	5,378,600	768,300	511,300			
Europe	7,562,500	312,200	2,677,200	2,287,300	1,914,400	516,400	
Total	38,224,600	41,148,100	14,639,900	8,724,400	19,430,700	6,183,900	1,065,600



years)]; λ = the decay constant of Rb^{87} per million years.

We use the term *continental crust* to mean the present-day material above the continental Mohorovičić discontinuity. Also, we may use the extent to which the rubidium-strontium ratio for the crust exceeds that for the whole earth as an additional criterion in defining average continental crust as it pertains to the question under consideration. The forming of crustal material may involve a series of steps of rubidium enrichment, but for the sake of simplicity (and because of lack of knowledge) we consider this to be a single step. Thus, the "crustal prehistory" is given by $(T_m - T_i)$ and is defined as follows. If it takes one or more geologic cycles for material to become stabilized as final average crust, with a gradual rubidium enrichment such that Rb^{87}/Sr^{86} finally becomes r_c, and with an increase in the ratio of radiogenic Sr^{87} to common Sr^{86}, during this period, equal to $(R_i - R_m)$, we can arbitrarily define a time $(T_m - T_i)$ in which a single-step enrichment would develop the same increase in the ratio of radiogenic Sr^{87} to common Sr^{86}. Thus, by definition,

$$\text{"Crustal prehistory"} = (T_m - T_i) = \frac{R_i - R_m}{\lambda r_c} \quad (1)$$

and, by definition,

$$\text{"Total crustal age"} = \frac{R_s - R_i}{\lambda r_s} + \frac{R_i - R_m}{\lambda r_c} \quad (2)$$

or the total crustal age is the sum of the whole-rock rubidium-strontium isochron age and the crustal prehistory of the material, it being assumed that Rb^{87}/Sr^{86} equaled r_c prior to the time rubidium and strontium become stabilized in the rock unit sampled. Obviously this value for Rb^{87}/Sr^{86} during the prehistory stage is not valid for the individual case, since r_c is an average. Thus it is necessary to restrict the estimate of the total crustal age to large units of crust, in which the value for r_c will be reasonably meaningful.

Thus, since

$$R_m = R_o + r_c \{\exp [\lambda(T_o - T_m)] - 1\} \quad (3)$$

and, for a large block of continental crust having approximately the same total crustal age throughout,

$$\text{Av. } T_m \cong \frac{1}{n} \sum_{j=1}^{n} \left(\frac{R_s - R_i}{\lambda r_s} + \frac{R_i - R_m}{\lambda r_c} \right)_j \quad (4)$$

a solution for T_m can be obtained if R_s, R_i, r_s, and the appropriate value of R_m (discussed below) are determined for individual rock samples numbered 1 to n taken at uniform intervals over the block of crust. The solution also depends on a knowledge of T_o, λ, R_o, r_e, and r_c.

Evaluation of Parameters

As noted, the total crustal age is based on the total increase in the Sr^{87}/Sr^{86} ratio, starting from some precrustal value (R_m) that pertained to the mantle or other source material from which the crust was derived. Any at-

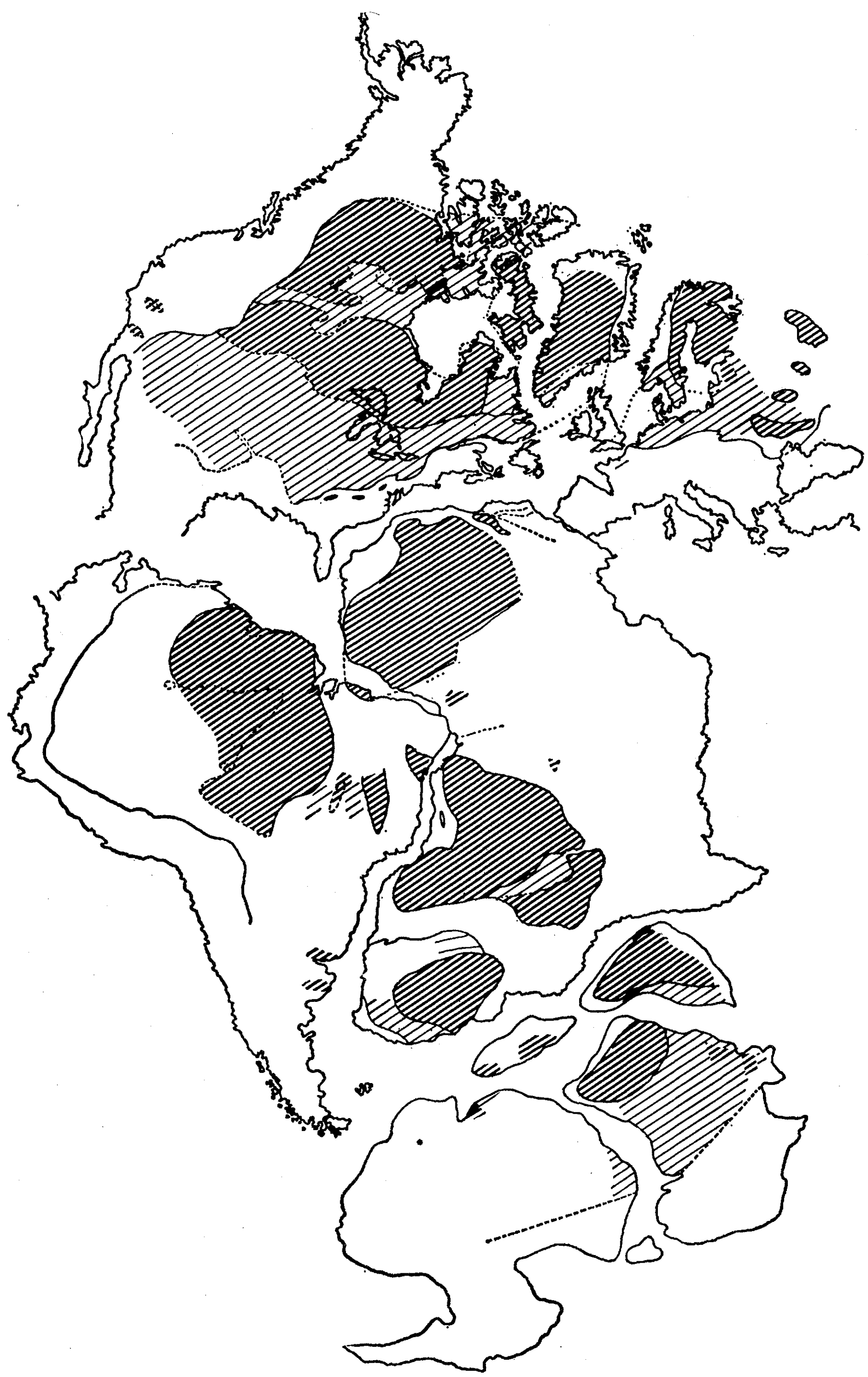


Fig. 8. Continents reassembled in a pre-drift reconstruction. (Lighter hatching) Regions underlain by rocks having apparent ages in the range 800 to 1700 million years; (heavier hatching) regions having apparent ages > 1700 million years. It appears that there are two (or one) central regions of older rocks, transected and totally surrounded by belts of younger rocks. This suggests that there was no significant fragmentation or scattering of the continental nuclei prior to the last great drift episode.

tempt to evaluate R_m as a function of time is bound to be open to controversy. Fortunately the limits set by most reasonable models do not vary so much as to cause a serious error in the analysis that follows. We therefore select the model of our choice and state that the Rb^{87}/Sr^{86} ratio for the mantle was originally 0.10. This value is based on an estimate (*10*) that the abundances of strontium and rubidium in the earth are about 69×10^{15} and 2.4×10^{15} tons, respectively. The value of Sr^{87}/Sr^{86} for the mantle therefore would increase at a rate of approximately 0.0014 per billion years. The decay of the parent Rb^{87} is included in the calculations. Starting with a value of 0.699 (from meteorite isochrons), we find that the average value of Sr^{87}/Sr^{86} for the mantle would have been 0.700 at about 3500 million years ago, at the time the earliest crustal materials were being formed. The sudden appearance of early crust in numerous places at this time (or shortly thereafter) suggests a major event in the history of differentiation of the mantle (possibly core infall and first separation of hyperfusibles from the lower mantle).

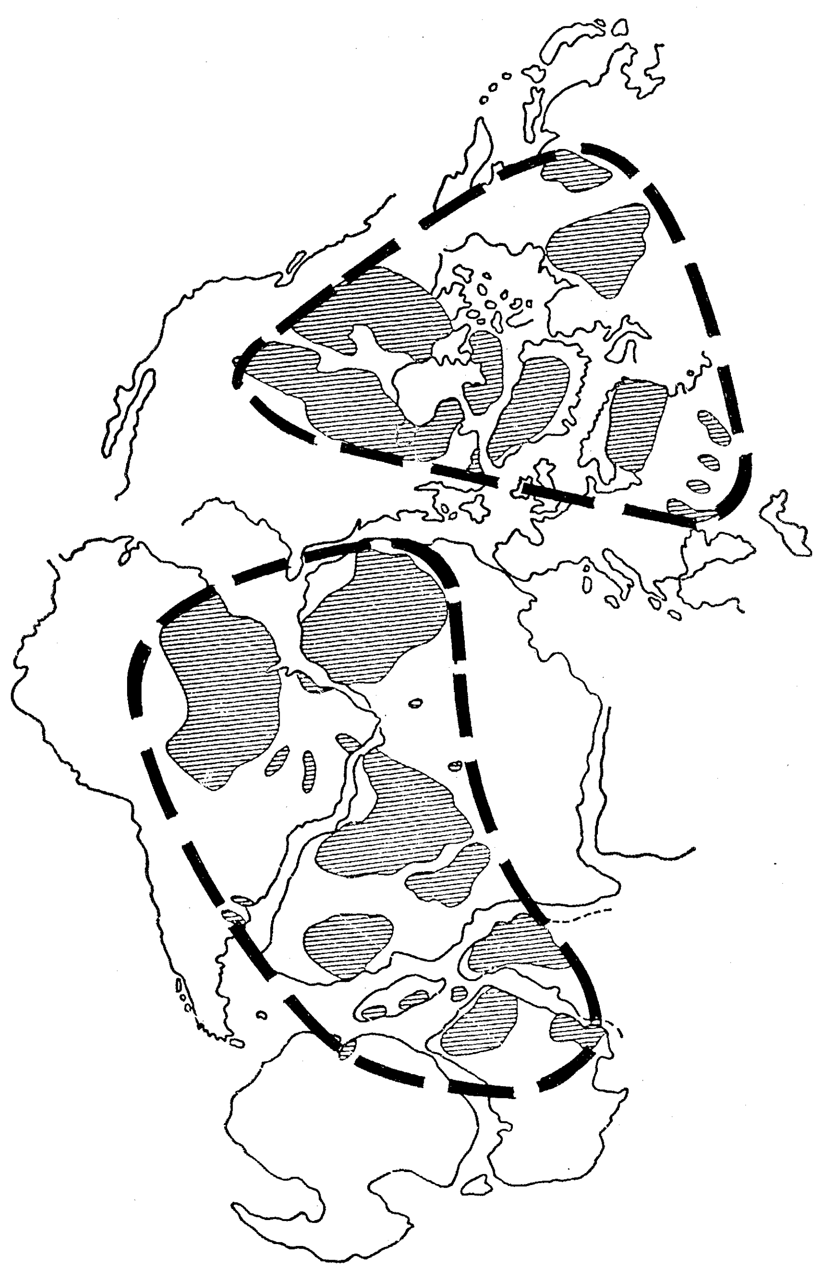


Fig. 9. A pre-drift reconstruction in which the continental blocks having apparent ages > 1700 million years (hatched areas) appear to be in a coherent grouping within two restricted regions. These blocks are transected and circumscribed by belts of younger rocks. It seems unlikely that during the time between 1700 and 200 million years ago the continents were scattered and drifting, only to be reassembled with this degree of ordering at 200 milion years ago. Instead, there appear to have been nonmoving ancient nuclei and continental accretion up to the time of the great drift.

In order to fit the present Sr^{87}/Sr^{86} values for oceanic alkalic and abyssal basalts (0.704 and 0.702, respectively) (*11*), we assume that mantle regions that were partially depleted in trace components and had relatively low rubidium-strontium ratios at this early time eventually became the source of abyssal tholeiites (*12*), and that mantle regions enriched in trace elements and having rubidium-strontium ratios approximately the same as the average ratio for the entire earth became the sources of the crust. This model could equally well be applied to the concept of surface cycling of a protocrustal material. Our principal point is that the source materials of the crust are believed not to have had a low Sr^{87}/Sr^{86} ratio, like the present abyssal tholeiites, but, rather, to have had an even higher Sr^{87}/Sr^{86} ratio than the present oceanic basalts. This view is supported by observations on initial ratios in those young continental volcanics that appear to have been directly derived from the mantle, in which Sr^{87}/Sr^{86} values in the range 0.704 to 0.706 are common (*13*).

Favoring the above arguments slightly, we arrive at average values for the Sr^{87}/Sr^{86} ratio in the source materials that formed the crust, as a function of time, as indicated in Fig. 11. These would be average values for the earth with a primordial rubidium-strontium ratio of 0.035, or a Rb^{87}/Sr^{86} ratio of 0.10. Thus, when we use the values $T_o = 4550$, $R_o = 0.699$, and $\lambda = 1.39 \times 10^{-5}$ per million years, the value for R_m in Fig. 11 is given by Eq. 3 as follows:

$$R_m = 0.699 + 0.10 \{\exp [1.39 \times 10^{-5} (4550 - T_m)] - 1\} \quad (5)$$

The value of r_c, the average Rb^{87}/Sr^{86} ratio for the crust, is determined by a combination of data on the nature of the crust. Geophysical surveys involving seismic refraction profiles and heat-flow determinations, in combination with geological information on rock types and densities and geochemical information on trace-element abundances, have yielded estimates, by various workers, that are reasonably close. Pakiser and Robinson (*14*) give a density-depth distribution for typical segments of the continental crust; Birch, Roy, and Decker (*15*) and Hyndman, Lambert, Heier, Jaeger, and Ringwood (*16*) demonstrate the decrease in uranium, thorium, and potassium with depth; and when we consider these estimates in combination with known variations in the potassium-rubidium ratio (*17*) and with the results of experimental work on the crustal stability of granulite facies rocks under high pressure (*18*), we arrive at an estimate of the total rubidium and strontium in the crust (*10*). From these studies, the value of r_c is taken to be 0.43.

Rate of Development of the Continental Crust

In order to investigate the history of the development of the continental crust it is necessary to obtain widespread information on total crustal ages as defined above. By defining the crust as that material which is present today above the Mohorovičić discontinuity, we can ignore material which may have been crust previously but which has returned to the mantle. Also, if material has cycled through the mantle and returned to the crust but has lost its radiogenic Sr^{87} on the way, we refer to this as new crust, thus removing the condition imposed by Armstrong (*19*), who postulated such a cycling process.

The most widespread geochronological information on the continental crust is in the form of potassium-argon measurements on rock minerals. Whole-rock rubidium-strontium isochron information is relatively scanty, but when the available isochron information is applied to the age provinces that have been outlined by potassium-argon measurements, its usefulness can be greatly extended. For example, the eastern part of the Appalachian belt shows potassium-argon ages generally in the range 250 to 400 million years. A few studies on whole-rock rubidium and strontium, together with geological selection of important rock units, have indicated that the whole-rock isochron ages in this region do not exceed the potassium-argon values by more than about 200 million years at most, and that the initial Sr^{87}/Sr^{86} ratios for the rock samples all fall within a well-limited range. We have therefore made a survey of whole-rock isochron age measurements for regions in which potassium-argon data have outlined reasonably isochronous areas, using the available data, published and unpublished, from all continents. More than 150 cases have been found in which both the isochron age value and the initial Sr^{87}/Sr^{86} ratio can be compared with the apparent age of the area as indicated by potassium-argon dating.

The composite results are plotted in Fig. 12. In each case the isochronous geologic area is a significant part of the crust. The isochronous areas vary in size, but they were selected and weighted so as to give a reasonably fair representation of the differences between the potassium-argon and the whole-rock rubidium-strontium isochron age measurements. It may be seen in Fig. 12 that there is a progressive average change with time in the difference in the ages obtained by the two methods. The curved line of Fig. 12 is fitted to the plotted points and yields the information needed to obtain estimates of whole-rock age values from potassium-argon data.

We next measured the total area of continental crust for each of a series of 450-million-year age intervals indicated by the potassium-argon age data plotted in Figs. 1 through 7. The data for the two-thirds of the total continental region of the earth for which considerable information on the age of basement rocks is available are given in a forthcoming publication (*20*). We assume the same distribution in the remaining third, and consider the sampling representative of the total continental crust. The area (in square kilometers) of basement rocks for each of these age intervals is given in Table 1.

By adding the difference between whole-rock isochron measurements and

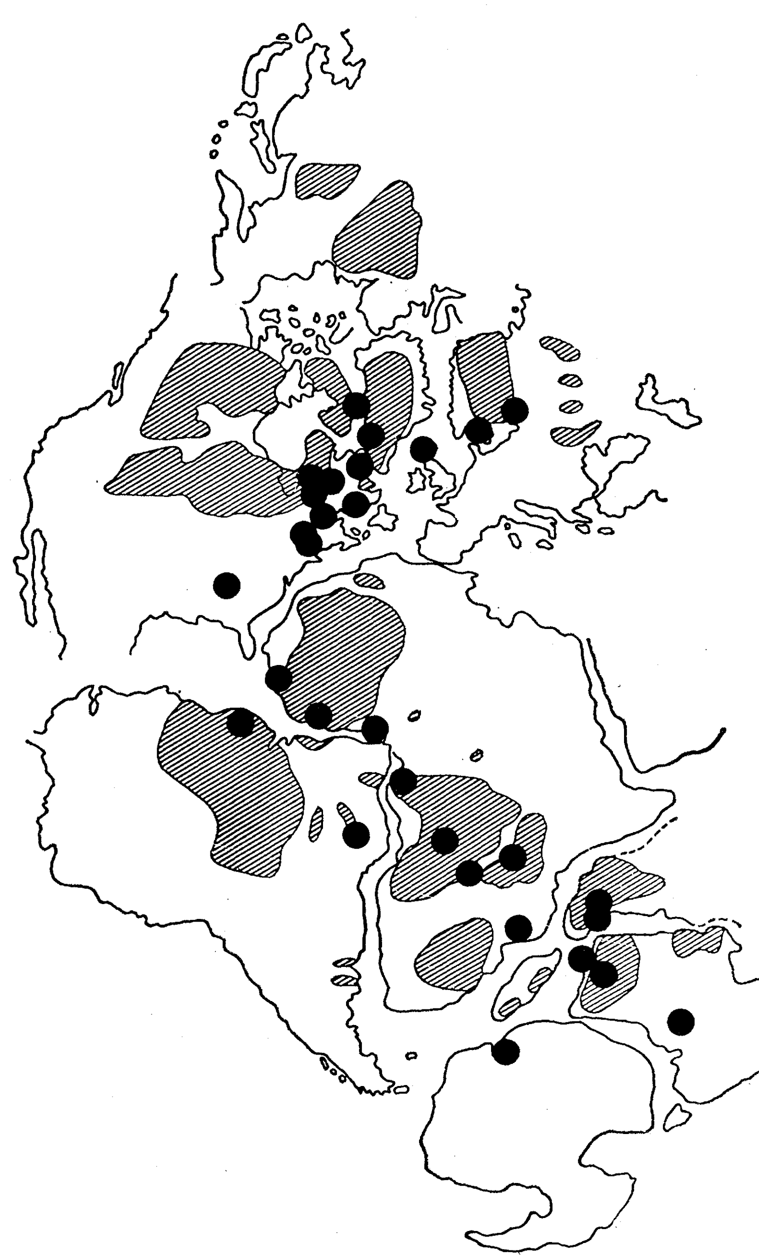


Fig. 10. Some of the major occurrences of deep-seated granulite facies rocks plotted on the groupings of older Precambrian rocks of Fig. 9. The coherence of this distribution is unexplained, but again suggests no drift prior to the drift of 200 million years ago.

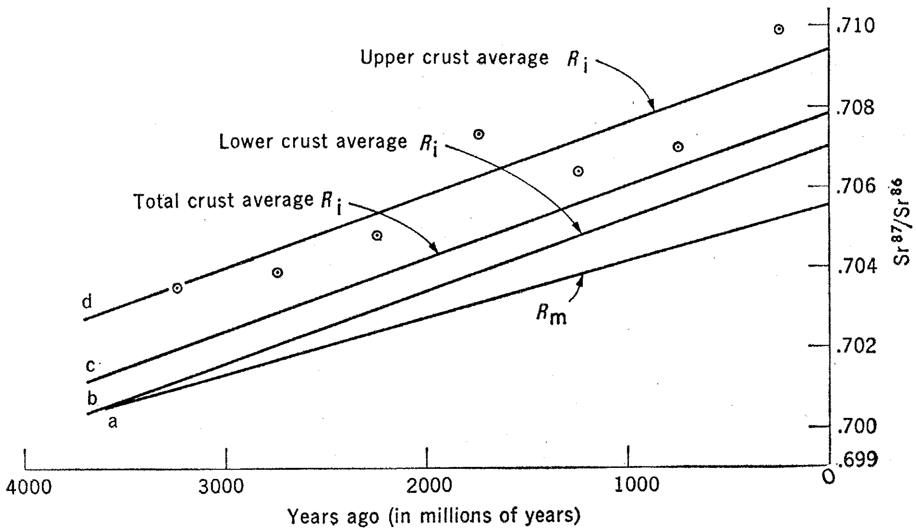


Fig. 11. (Curve a) Estimated increase, with time, in the Sr^{87}/Sr^{86} ratio for mantle source regions from which continental material was separated. (Curve b) Estimated plot of R_i for lower crust. (Curve c) R_i values for total crust as a function of time. (Curve d) Data points and plot of R_i showing weighted averages of the initial Sr^{87}/Sr^{86} ratio for upper crustal rocks for each 500-million-year interval.

potassium-argon age values from Fig. 12 to the age intervals in Table 1, we obtain an evaluation of the areal distribution of T_i values throughout time. In this procedure we have used the copious potassium-argon data to obtain the areal distribution and the less abundant but more accurate whole-rock isochron data to correct the age scale. The advantage of first using the more abundant potassium-argon data to obtain the areal distribution more than offsets the disadvantage of using the imprecise average difference between the ages obtained by the two methods in converting the age scale back to whole-rock isochron values. It should be remembered that any error in the whole-rock isochron age value is more than compensated by a complementary and opposite error in the value for the crustal-prehistory period, because the same isochron data are used in each case. For example, if a mixture of rock units is used in an isochron plot that gives too low an age, this will mean that the initial value of Sr^{87}/Sr^{86} is too high. Because the same initial value is now used in calculating the crustal prehistory, the calculated value for this period will be too great. Also, because the average value for the ratio of crustal rubidium to crustal strontium is lower than the rubidium-strontium ratio for most rock samples used in obtaining isochron age measurements, the negative error in T_i will be more than compensated by the positive error in $T_m - T_i$, and thus the value for T_m, the total crustal age, will be too high. Since most isochron age values are probably too low if they are incorrect at all (see, for example, *21*), the resultant error will usually be too great a total crustal age.

The next step is to determine the average value for R_i, the Sr^{87}/Sr^{86} ratio, for the crustal materials represented by the different age intervals. For this purpose we use the same 150 whole-rock isochron analyses that we used before. Table 2 gives the average values for three categories of upper-crustal basement rocks, within age intervals of 500 million years, as determined from the isochrons. The values used for an average composition of the upper 10 kilometers of continental crust are weighted on the basis of the assumption that the schists and gneisses are equal in weight to the granites but weigh twice as much as the mafic rocks. The final results are insensitive to this particular assumption. A plot of these values of R_i for upper-crustal rocks is given in Fig. 11.

Table 2. Initial Sr^{87}/Sr^{86} ratios for upper crustal basement rocks, as determined from whole-rock rubidium-strontium isochrons.

Age interval (in millions of years) from isochron values	Sr^{87}/Sr^{86} ratios				Number of cases*
	Schists and gneisses	Granites	Mafic rocks	Weighted average	
0–500	0.7100	0.7115	0.7066	0.7099	41
500–1000	.7075	.7072	.7057	.7070	13
1000–1500	.7060	.7063	.7074	.7064	32
1500–2000	.7060	.7100	.7043	.7073	21
2000–2500	.7045	.7053	.7045	.7048	16
2500–3000	.7034	.7060	.7005	.7039	15
3000–3500	.7015	.7055		.7035	4

* Number of cases in which whole-rock isochrons were compared with potassium-argon data.

It is believed that the lower two-thirds of the continental crust has almost the same strontium composition as the upper crust but much less rubidium. Measured R_s values for samples of deep-crustal rocks are generally in the range 0.707 ± 0.002. This result is in agreement with the findings of the authors mentioned in the discussion of the value of r_c (see *16* and *17*). We have therefore used the lower-crustal values of R_i, starting originally at R_m and reaching a present value of 0.707, to give the final total crustal values of R_i shown in Fig. 11.

These average values of R_i for each age interval of crustal material may now be applied to the solution for Av. T_m, the total crustal age for the average material in each block, from Eq. 4:

$$\text{Av. } T_m = \text{Av. } T_i + \frac{\text{Av. } R_i - \text{Av. } R_m}{\lambda r_c}$$

and

$$\text{Av. } R_m = R_o + \lambda r_e(T_o - \text{Av. } T_m)$$

Using the estimated values given above for r_c, r_e, R_o, T_o, and λ, we find values for crustal prehistory, $T_m - T_i$, and for total crustal age.

It is now possible to construct the histogram of Fig. 13, which shows the rate of areal development of the continental crust in terms of the total crustal age of the blocks. As discussed above, this represents a *maximum* estimate of total crustal age because the isochron data used are minimum values. Through restrictive definition of the terms used, we have avoided the question of recycling of crust through the mantle, or the question of a partially enriched protocrust (*19, 21*). Under these restrictions we find that the continental crust has developed at an accelerating rate, equal to about 20 km^2 per million years for each advance of 1 million years in time. Between 500 and 1500 million years ago the new age provinces were developing at a rate of about 80,000 km^2 per million years as compared to 20,000 km^2 per million years at 3000 million years ago. The process appears to have started about 3800 million years ago and does not show the discrete pulses at times of so-called universal orogeny that have been reported in the literature. The mean total crustal age of the continental crust is found to be 1450 million years.

The histogram of Fig. 13 does not extend to the present because it will require several hundred million years, on the average, for new crustal material from the mantle to become stabilized and incorporated into the permanent crust, and an additional period before this stable crust rises to the surface where it can be sampled and dated. Although new crustal material (including recycled material, defined above) is being added to the crust continuously, and some of it is incorporated immediately into the permanent stable crust, the crustal block representing the youngest age interval includes much older material, so that the average total crustal age of the block is several hundred million years, as shown in Fig. 13.

Summary and Conclusions

We have plotted almost all available radiometric age data, representing about two-thirds of the continental area of the earth, on maps of the continents to indicate the distribution of geologic age provinces. These are mostly data obtained by the potassium-argon method, so the patterns of the various age intervals represent a mixture of primary ages and thermal overprints. When we use a reconstruction representing the probable assemblage of land areas just prior to the last drift episode (at about 200 million years ago), the distribution of age provinces in the ranges 800 to 1700 million years and $>$ 1700 million years shows a geographical coherence—a grouping within two restricted regions. For the $>$ 1700-million-year age provinces, these two regions, combined, represent about one-third of the present continental area of the earth. When the two regions are theoretically extended to include all the basement areas showing apparent ages $>$ 800 million years, the total area is only slightly larger.

These groupings, and the coherence of the patterns, suggest that these two regions were not scattered and brought together by earlier drift motions but were always essentially intact prior to the last great drift episode.

We suggest that the growth pattern of the continents has been largely peripheral and concentric about the ancient nuclei in their predrift positions. At least some of the accretion process appears similar to the kind of orogenesis observed today when sea floor moves under the edge of a continent, so sea-floor motions could have existed prior to the drifting of the continental blocks.

We have attempted to determine the rate of generation of the continental crust, using the partition of rubidium into the crust, relative to strontium, as a criterion. By the use of restrictive definitions, the average total crustal age of blocks of crust is obtained from whole-rock rubidium-strontium isochron age values and from initial Sr^{87}/Sr^{86} ratios for stabilized crustal rocks. Because of the relative scarcity of whole-rock rubidium-strontium isochron measurements, we have used potassium-argon measurements for determining distributions of area relative to age, and have converted the results to equi-

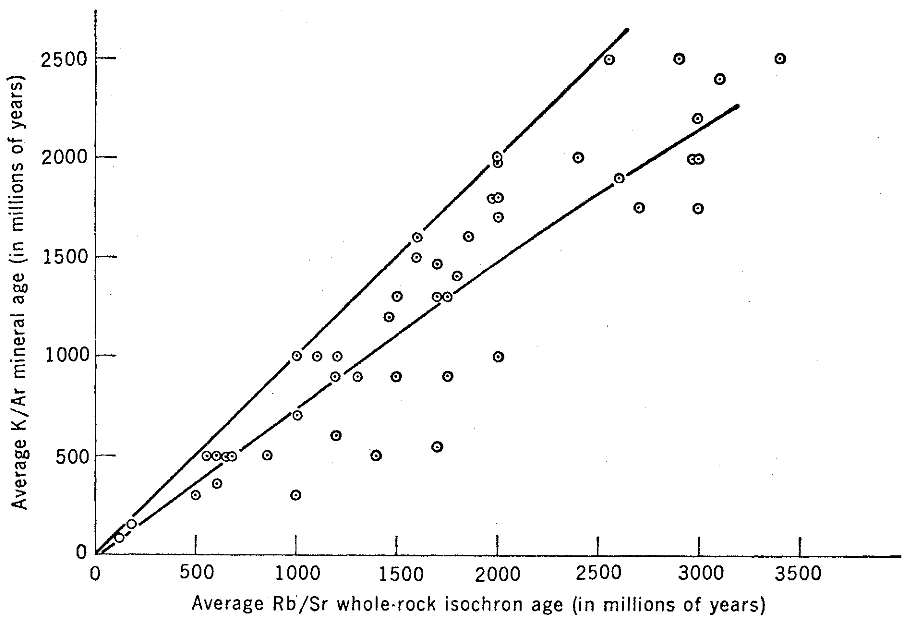


Fig. 12. Comparison of potassium-argon age values and whole-rock rubidium-strontium isochron age values for selected blocks of continental crust for which the data are reasonably good. The lower curve is derived from the average difference in the ages obtained by the two methods within successive age intervals.

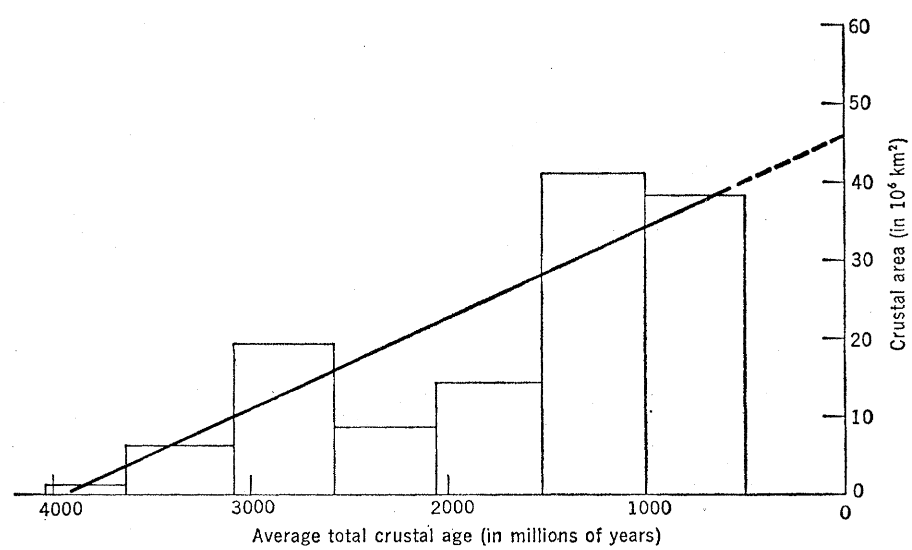


Fig. 13. Histogram showing the area of continent underlain by rocks within successive intervals of total crustal age. The total-crustal-age values are the sum of the whole-rock rubidium-strontium isochron age and a crustal prehistory. The differences in the Sr^{87}/Sr^{86} ratios and in the rubidium-strontium ratios for average crust and average earth are used to determine the duration of the crustal prehistory in the block of crust represented in each age interval.

valent whole-rock isochron values. The crustal prehistory, or the average time crustal material is cycled prior to final stabilization in a permanent crust, is determined from the average values for the initial Sr^{87}/Sr^{86} ratio in various types of basement rock as a function of time.

A histogram (Fig. 13) showing the areal extent of stabilized crust for various intervals of total crustal age indicates an accelerating generation of crustal material amounting to 20 km^2 per million years, per million years, or about 600 km^3 per million years, per million years, if it is assumed that the upper crust and lower crust are complementary parts of the differentiating crustal system. Under the terms of the definitions and assumptions given, the process would have started about 3800 million years ago. The nature of the analysis is such that the age values given are probably maximum values.

References and Notes

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2. The literature covered includes all the standard journals, privately published bulletins or laboratory reports, and some unpublished age data. The maps therefore include some information that will not be published for a year or more. On the other hand there may be serious omissions of available data through oversight. We hope that, in the future, such omissions will be avoided through establishment of an international data center to which all age measurements will be reported. The bibliography is too extensive to be given here. A selected list will appear in a forthcoming article [P. M. Hurley and J. R. Rand, *The Sea*, in press]. The complete list is available from us on request.
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