

# Radiogenic Isotopes: The Case for Crustal Recycling on a Near-Steady-State No-Continental-Growth Earth [and Discussion]

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## Radiogenic isotopes: the case for crustal recycling on a near-steady-state no-continental-growth Earth

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Pb, Sr and Nd isotopes define rock ages and residence times in mantle and continental crust, but are not diagnostic of either crustal growth or recycling in a near-steady-state Earth.

Constancy of continental freeboard and uniformity of thickness of stable continental crust with age are the only two quantitative measures of crustal volume through time and these imply negligible crustal growth since 2.9 Ga B.P. Planetary analogies, Pb isotopes, atmospheric evolution, and palaeomagnetism also argue for early terrestrial differentiation. Rates of crustal growth and recycling are sufficient to reach a near-steady state over the first 1 Ga of Earth history, before widespread cratonization. Isotope compositions and ages of rocks are quantitatively compatible with near-steady-state recycling involving multiple complete reworkings of the crust by injection into the mantle along subduction zones.

The recycling process can be observed to occur on the Earth today. Continental crust is uplifted, reduced in area, and thickened in orogenic belts. It is then subject to erosion, an effective isotopic homogenization process. A fraction of the sediment flux reaches the ocean floor or accumulates along continental margins, while soluble elements and water become fixed in ocean crust and trapped in sediments. Subduction of altered ocean crust, sediment, microcontinents and fragments of basement ripped off the edges of continents completes the process whereby continental crust, enriched in radiogenic Pb and Sr and with relatively unradiogenic Nd, is returned to the mantle.

Pb, Sr and Nd isotopic compositions of igneous rocks from the mantle are explainable in terms of a near-steady-state model. The mantle buffer dominates observed isotope Sr and Nd evolutions. Mixing of crust and mantle causes all the isotope evolutions to approximate single-stage growth curves. Isotopic heterogeneity of the Earth increases as the rate of mixing declines.

The observed escape of primordial  $^3\text{He}$  from the mantle is not evidence for continuing continental differentiation or against early differentiation of the Earth. Even if nearly complete equilibrium chemical differentiation occurred at 4.6 Ga B.P., some  $^3\text{He}$  would remain dissolved in the interior and would escape as recycling continued.

A true steady state cannot be achieved because the driving energy declines with time and Earth surface processes have evolved with development of life and an oxygenated atmosphere. These unidirectional changes, plus variation in subduction rates and setting and style, and variation in rates of cratonization, provide a complex overprint on the near-steady-state background of continental evolution.

### INTRODUCTION

This paper will defend the proposition that continental crust is recycled into the mantle and that the Earth is in a near-steady state, with essentially constant volumes of ocean and crust through geological time. A contrasting view, that the continental crust has grown with time, has been repeatedly expressed by Moorbath (1975*a*, 1975*b*, 1976, 1977*a*, 1977*b*, 1978). His

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arguments against recycling are not persuasive, and the evidence that he presents is easily accommodated in a no-continental-growth model. His position boils down to a few specific points. First is the unsubductibility of continental crust, due to its buoyancy and 'proven' by the survival of Archaean cratons. Secondly, rock age and isotope data 'provide the strongest possible evidence that the continental crust has grown'. These isotope data include evidence for continental accretion, the low initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of granitic rocks (both modern and ancient), and apparent single stage evolution for initial Pb and Sr isotopes of Archaean magma sources.

Moorbath's conclusions are founded on the belief that sediment is not subducted into the mantle, because without this basic premise of previous growth models (Rubey 1951; Wilson 1959; Hurley *et al.* 1962; Engel 1963) the evidence presented is open to alternative interpretation.

I will review the evidence that significant volumes of sediment are being subducted. Proof of continental accretion is a neutral point, as it is an accepted view of both growth and no-growth recycling models. Low initial Sr isotope ratios are logical for rocks coming from the mantle, whether continents are growing or being recycled. The apparent single-stage evolution and homogeneity of Pb and Sr isotopes are themselves not proof of continental growth but rather evidence of isotopic homogenization processes being dominant during early Earth history. This apparently simple isotope evolution is a fact that can be accommodated in a model of 'irreversible chemical differentiation' only by rejecting evidence for early planetary differentiation.

I have broadened the discussion beyond the points raised by Moorbath to demonstrate the self-consistency of a no-growth, crustal-recycling hypothesis with all isotopic data.

#### EVIDENCE OF CONTINENT AND OCEAN VOLUME

There are few facts that directly reflect the volume of continents and oceans. The isotope data are not diagnostic; in fact quite different evolutionary models will converge on the present isotope complexion of the outer Earth, and the same isotope data have been used to argue both for and against growth. The *only* measure of Archaean continental volume is crustal thickness and position with respect to sea level. The closely linked observations are that average stable craton thickness has not changed with time (figure 1) (Cummings & Schiller 1971; Condie 1973; Davies 1979), and the near coincidence of sea level and erosion base level for ancient cratons with present sea level (figure 2). Wise (1974) and Armstrong (1968) discuss the implications of these observations. The logic as presented by Wise is simple and quantitative. If continental thickness is constant, the area of the Earth is unchanging, the linkage between freeboard, base level and volumes is as outlined by Wise's fig. 7 and there is no *loss* of continent or ocean, then the global system has remained within a small percentage of its present volumes for 2.9 Ga. Wise concluded that continent and ocean volumes have not changed significantly since the Archaean. On this cornerstone it is possible to build a no-growth continent-recycling model of global processes and history that is compatible with isotopic and chemical data.

Moorbath, who advocates continental growth (1975*a*, 1975*b*, 1976, 1977*a*, 1977*b*, 1978), has avoided explaining freeboard and continental thickness because they contradict conclusions reached from isotope data interpreted according to traditional geochemical viewpoints.

Growth models must dismiss or explain away the evidence of essentially constant continental

volume. Some authors have advocated underplating of continental crust on a global scale to thicken it as continent and oceans grow (Rubey 1951; Rogers & McKay 1972), but this idea has little independent support and is unnecessary.

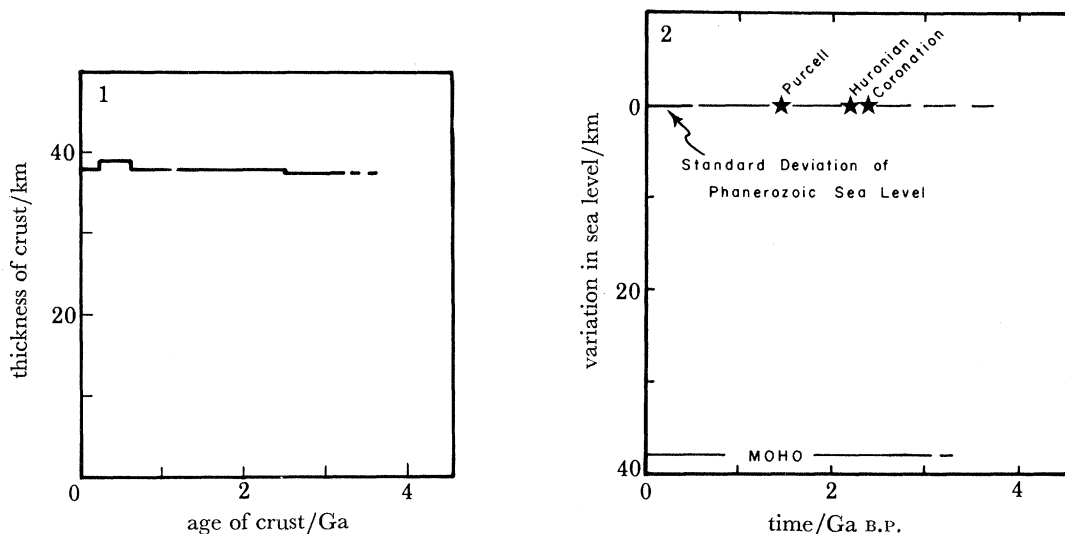


FIGURE 1. Average seismically measured thickness of stable crust of various geological ages. After Condie (1973).

FIGURE 2. Variation of sea level with respect to stable craton surfaces. Phanerozoic sea level variation from Wise (1974). The older points are a few well known examples where geosyncline onlap over stable platforms is preserved and is not far from present regional base level. The implication is that sea level and craton base level have been approximately coincident and show no secular rise or fall for at least 2.9 Ga.

#### EARLY PLANETARY DIFFERENTIATION

Growth models are difficult to rationalize on a cooling Earth. In their most extreme form (no differentiated continents of any great size before 3 Ga B.P.) they demand inhibition of crustal differentiation processes for the first, and presumably hottest, 1 Ga of Earth history. The formation and differentiation of the meteorite parent bodies and the moon nearly 4.6 Ga ago is an undisputed fact to cosmochemists (see, for example, Papike & Bence 1979). Rapid accretion of the Earth (Wetherill 1971, 1972) and presence of short-lived nuclear species like  $^{26}\text{Al}$  at the time of planet accretion (Lee *et al.* 1977) provide an initial endowment of energy for hot-Earth evolutionary models. Early core formation is suggested by palaeomagnetic intensity measurements (McElhinny & Evans 1968; McElhinny & Senanayake 1980) and Pb isotopic data (Murthy & Patterson 1962; Oversby & Ringwood 1971; Gancarz & Wasserburg 1977; Vollmer 1977) and is a logical deduction of hot-Earth evolutionary models (Wetherill 1972; Siever 1974). Core separation would further increase the initial heat endowment (Solomon 1980). As discussed later in this paper, many geochemists believe that the atmosphere was largely the product of catastrophic early degassing. These observations and ideas favour early differentiation of the Earth. There is good reason why this process should go to completion in a hot Earth; magma-crystal fractionation processes reach equilibrium even on a laboratory time scale. The popular notion of continent-ocean growth has been uniquely responsible for many cold-Earth evolutionary models because the rise in temperature would gradually bring about chemical differentiation of the planet's interior.

The Moon and meteorite parent bodies preserve evidence of their nearly instantaneous differentiation because they are 'tectonic failures'. The Earth, in contrast, is a dynamic body, but there is no need to doubt that it, too, differentiated into surface fluids, a primitive crust, mantle and core at a very early date. The Earth, like other bodies in the Solar System, was presumably subject to catastrophic meteorite impacts before 3.9 Ga ago (Frey 1980), but no evidence of this process is preserved. It would have been destroyed by early rapid crustal recycling.

#### CONTINENTAL ACCRETION AND DESTRUCTION

Moorbath puts considerable effort into arguing that continental accretion is *the* continent-forming process. Accretion is the rebuilding process whereby sediments and mantle-derived volcanic rocks are formed into mountain belts and ultimately added to cratons. The concept has many advocates (Wilson 1959; Engel 1963; Taylor 1967; Rogers 1977) who feel that proof of accretion is equivalent to disproof of the no-growth continental-recycling hypothesis, but I emphatically disagree. Proof of accretion is simply the proof of half the process of crustal recycling.

The counterbalance to continental accretion is destruction of cratons and orogenic belts by tectonic shortening, erosion, and loss of sediment and crust into the mantle. My interpretation of the evidence is that soon after the Earth formed it differentiated and quickly reached a near-steady state, with accretion and destruction approximately equal in rate, but constantly changing in detail and geometrical pattern.

Tectonic shortening in mountain belts, including areas of continental collision such as the Himalaya Mountains, results in crustal thickening and loss of area of ancient terrane (Dewey & Burke 1973; Powell & Conaghan 1973; Bird & Toksoz 1977). Then isostasy prevails; the thickened crust is eroded to base level and again stabilized as a 35–40 km thick craton. The eroded material becomes widely dispersed and isotopically homogenized. Erosion, transport and deposition are *the* most effective isotopic mixing process active on Earth and the singular reason for the smooth and simple-looking evolution of Pb isotopes. Irreversible growth models must invoke large-scale homogenization by poorly known processes in a demonstrably heterogeneous and highly viscous mantle.

Much sediment is merely recycled between basin of accumulation and uplifted strata. Some becomes deeply buried and heated to enter the metamorphic realm. Some will even be melted in the crust or dissolved in magmas to become regenerated as igneous rock. Erosion of the sedimentary, igneous or metamorphic rock closes the traditional geological cycle. The controversial proposition of the no-growth hypothesis is that a fraction of the sediment flux into the oceans (1–3 km<sup>3</sup>/a out of a total 10–15 km<sup>3</sup>/a at present) is carried down into the mantle to mix with mantle rocks and lose its identity. In that way radiogenic daughter products are steadily transferred from crust to mantle while the chemical composition, heterogeneity, and mass of crust and mantle remain essentially constant. The next section of this paper will focus on the subduction process, and later sections on the isotopic consequences.



## SUBDUCTION OF SEDIMENTS

Evidence for the subduction of sediment is of two types. One is chemical and isotopic anomalies indicating sediment in the mantle source region of volcanic arc magmas; the other is volumetric measurements of accretion wedges showing that swept-in sediment has vanished along with the downgoing oceanic plate. The second type of evidence allows crude quantitative estimates of fluxes; the first is only qualitative. Proof of sediment subduction does not disprove continental growth, but it establishes the plausibility of no-growth models.

Moorbath (1977*a*) has stated that continental crust is not subductable into the mantle because it is too 'stable' and buoyant. Such argument is beside the point as we are not advocating bulk engulfment of cratons in subduction zones. The subduction of continents is achieved by tectonic mobilization, erosion and then subduction of sediments, chemically altered ocean crust, and small fragments of continents.

*Chemical and isotopic evidence*

The amount of sediment and continental crust that must be subducted today to satisfy a quantitative self-consistent recycling model is 1–3 km<sup>3</sup>/a, or about 10–20% of all the sediment eroded from the continents. Approximately 1–3 km<sup>3</sup>/a accumulates on the ocean floor (Li 1972; Broecker 1974; Davies *et al.* 1977). The subducted sediment flux is only a small percentage of the rock budget in volcanic-arc regions.

In 1968, when substantial sediment subduction was proposed (Armstrong 1968), seafloor spreading had just achieved widespread acceptance but sediment subduction was still an outrageous hypothesis. In the early 1970s it became clear just how easy it was to get some crustal material subducted when ocean-crust alteration processes were discovered. Early papers by Hart (1970, 1973), Miyashiro (1972), Spooner & Fyfe (1973) and Hart *et al.* (1974) led the way in describing the attachment of water, potassium, strontium and other crustal substances to basalts destined for subduction. This topic has received much attention since then. It is a mechanism that supplements sediment subduction in bringing about recycling of continental material, and balancing geochemical budgets (see, for example: Maynard 1976; Corliss *et al.* 1979).

A variety of alkali and alkaline-earth elements are enriched in volcanic arc rocks to a degree that is incompatible with a depleted mantle source like that which is beneath ocean ridges. This is especially notable for K, Rb, Cs and Ba and to some degree for Sr. Authors who have observed this and related it to sediment subduction include Armstrong (1971), Whitford (1975), Whitford *et al.* (1979), Whitford & Jezek (1979), Weaver *et al.* (1979), Ewart & Bryan (1973), James (1978), Kay *et al.* (1978), Cole (1978), Hawkesworth *et al.* (1979), Armstrong & Nixon (1981) and Kay (1980).

Further evidence of subducted Earth-surface material comes from studies of volatiles in volcanic rocks. Primitive arc magmas contain an order of magnitude more H<sub>2</sub>O and Cl than do ocean-floor basalts (Anderson 1974, 1975, 1978; Garcia *et al.* 1979). This is most easily explained as recycled sea water. Fyfe (1976, 1978) has estimated that all the H<sub>2</sub>O in the oceans is recycled by this process in just 1 Ga, and all the K in the continents in just 1.5 Ga; these are comparable to the crustal recycling rates needed for the no-growth, recycling model.

In some arcs there is isotopic evidence of subducted crustal material, although both this and trace element data are confused and obliterated by extensive reaction of magmas with crustal

rocks, especially where crust is thick and old. Radiogenic Sr from subducted crustal material in Indonesia was observed by Whitford (1975), Whitford *et al.* (1977), and Whitford & Jezek (1979). Sr and O isotopes point to sediment contamination in Indonesia and South America (Magaritz *et al.* 1978; James 1978). Nd and Sr isotopes indicate altered ocean-floor volcanics and sediment involvement in volcanic-arc rocks (Hawkesworth *et al.* 1977; DePaolo & Wasserburg 1977; Hawkesworth *et al.* 1979). Pb isotope evidence for sediment subduction has been discussed by Armstrong & Cooper (1971), Sun (1973), Kay *et al.* (1978) and Karig & Kay, this symposium).

Opponents of sediment subduction have focused on areas or elements where the evidence is weak or unresponsive of a crustal component. Particular emphasis has been given to the relatively young sediment-starved and ensimatic Kermadec–Tonga and Mariana arcs (Oversby & Ewart 1972; Ewart *et al.* 1973; Gill 1974; Meijer 1976; Ewart *et al.* 1977; Stern 1979; Dixon & Batiza 1979) and the Cascades (Church 1973). Those authors have concluded that major-element and isotope data keep bulk sediment mixing down to a small percentage of the magma-source inputs, but even they have conceded that radiogenic Sr, water and alkalis may come from altered ocean crust. This is not disproof of sediment subduction. These are examples where its importance in arc-magma genesis is minimal, but even in general the sediment input into magma source regions below volcanic arcs need only be a small percentage of the rock flux to satisfy no-growth continent-recycling Earth models. The mantle acts as a gigantic buffer in the magma genesis process, especially for major elements, so that to limit sediment involvement to a small percentage is not to defeat the recycling hypothesis.

Kay (1980) and Karig & Kay (this symposium) develop the discussion of crustal components in volcanic-arc magmas in quantitative detail. They conclude that, while the bulk of the magmas come from a mantle source, a sediment flux is required to explain K, Rb and Ba, concentrated rare-earth elements (r.e.e.), and Sr and Pb isotopes. For the Mariana arc, where sediment influx is probably minimal, they estimate the sediment contribution to magmas to be 6%, amounting to subduction of a 45 m thick sediment layer. The total amount of subducted sediment must be larger, because their calculation does not account for any sediment absorbed into the mantle.

It is clear that what goes on in arc-magma genesis is not simply bulk remelting of sediment after subduction, but a much more complex process. Many papers now favour subduction of altered crust (with or without sediment), distillation of volatiles and mobile elements as fluids or melts that alter overlying mantle, followed by melting of the modified mantle to give primitive arc magmas, with further contamination, magma mixing, and fractional crystallization before the magma reaches the surface (Nicholls 1974; Anderson *et al.* 1978; Kay 1978; Kay *et al.* 1978; James 1978; Cole 1978). It is no surprise that the imprint of sediment subduction is obscured and variable from arc to arc.

#### *Volumetric arguments for subduction of sediment*

The relatively small amount of sediment on the ocean floor and rarity of ocean floor sediment in mountain belts are observations of considerable significance that stand in contradiction to reasonable estimates of erosion and sedimentation rates (Gilluly 1955). Gilluly was forced to speculate on some sort of 'convection cells in the mantle' that 'rise beneath the ocean' and sweep sialic material back into and under continents. He also was forced to conclude that the entire sial endowment of the Earth must have been eroded six to eight times over geological

time. He could not reconcile these seeming contradictions with then current geochemical viewpoints on crustal evolution. Hurley *et al.* (1962) later showed that most sialic crust was not simply intracrustally recycled older crust, and Gilluly's simple observations and their implications were largely ignored.

The geophysical profiles of active trenches provide overwhelming evidence that sediment subduction occurs and is a major process in continental evolution. This conclusion has been approached historically with considerable hesitation, but is now strongly supported. For example, Karig & Sharman (1975) concluded that most sediment and some volcanic crust were probably scraped off the descending plate, but Moore (1975) pointed out the lack of pelagic sediment in circum-Pacific eugeosynclines and concluded that these sediments were being selectively subducted. This lack of pelagic sediment preserved in continental crust is itself a compelling argument against objections to sediment subduction. At a production rate of  $1 \text{ km}^3/\text{a}$ , 8% of the continents should be composed of Phanerozoic pelagic sediment, if all were accreted. This is simply not observed (Scholl & Marlow 1974). Most of it has vanished, most reasonably by subduction, and it is probably accompanied downwards by some trench and continental slope sediment. Davies *et al.* (1977) estimate an average Cainozoic ocean-floor accumulation rate of nearly  $3 \text{ km}^3/\text{a}$  and this, if true over Phanerozoic time, would make this argument even more persuasive.

The case for sediment subduction is strongly presented by Scholl *et al.* (1977) and Hussong *et al.* (1976). The deficiency of accreted ocean-floor sediment has been noted in South America, where  $20 \text{ km}^3$  of ocean-floor sediment is disappearing every  $10^6 \text{ a}$  along each kilometre of trench (Hussong *et al.* 1976). *In addition*, the sediment eroded from South America and trapped in the trench *plus* fragments abraded off the edge of Palaeozoic to Precambrian continental crust, which reaches the continental shelf in Peru and Chile (Cobbing *et al.* 1977; Munizaga *et al.* 1973), are being consumed. Some of this vanished material is balanced by accretion of new volcanic material. Baker & Francis (1978) estimate a minimum addition of  $8 \text{ km}^3$  per  $10^6 \text{ a}$  per kilometre of arc in the central Andes. Missing sediment has also been reported in the Mariana (Hawkins *et al.* 1979), Kamchatka (Scholl *et al.* 1978), Japan (Ludwig & Murachi 1979), and middle America (Moore *et al.* 1979) trenches.

The Deep Sea Drilling Project examinations of three trench inner walls during legs 56, 60 and 66 all reached very similar conclusions. To quote from the summaries in *Geo Times*:

'A great deal of sediment from the lower plate may not have been accreted but instead may have been subducted.' (April 1978; report on leg 57, Japan Trench);

'Though some rocks contained in the deepest holes in the trench may originally have been part of the Pacific Plate, it now appears that subduction is a smooth process, with little accretion of material from the Pacific Plate.' (October 1978; report on leg 60, Mariana Trench);

'Up to half the input sediment and perhaps all the oceanic component are being consumed by the subduction process.' (September 1979; report on leg 66, Middle American Trench).

The volumetric relations behind these conclusions are illustrated in figure 3.

One physical process by which sediment is trapped in ocean crust and consequently subducted has been clarified by marine seismic work on outer walls of trenches. Ludwig *et al.* (1966) observed horst and graben structure on the seaward walls of the Japan and Bonin trenches, due to tension in the bending plate. Schweller & Prince (1978), Schweller & Kulm (1978) and



Hilde & Sharman (1978) describe how these types of fault structures in other trenches trap sediment and carry it down out of sight. The cross sections can be graphically described by the term 'chain saw', as the effects are analogous.

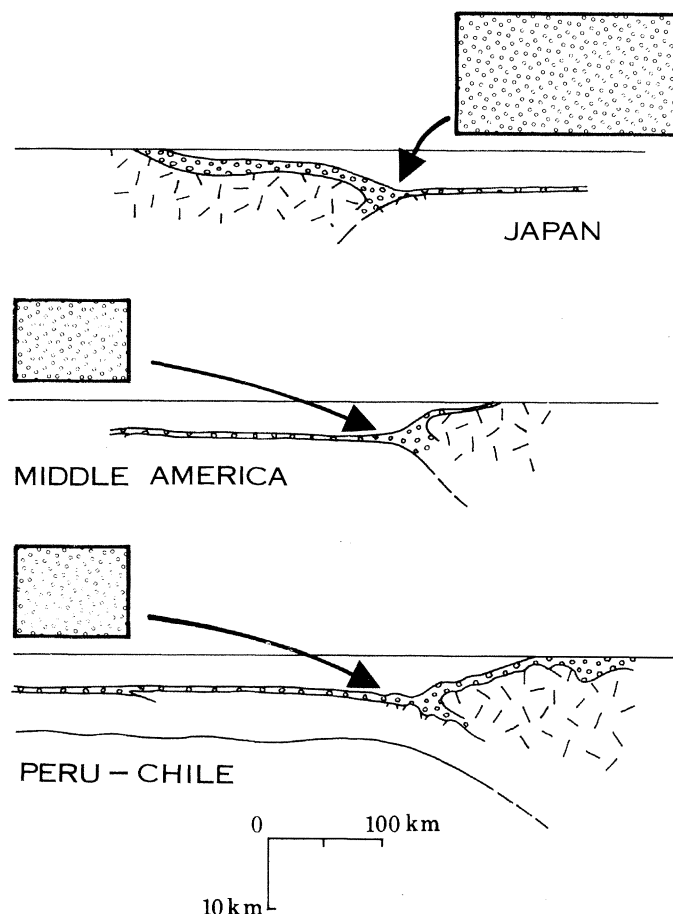


FIGURE 3. The pelagic sediment deficiency of accretion wedges at circum-Pacific trenches. The three examples have been reduced to a common scale. The boxes show the cross section of Cainozoic pelagic sediments brought to the trench by seafloor motion. Cainozoic sediment and accretion wedge are stippled [stippled pattern]. Pre-Cainozoic rocks shown with hatchures [hatched pattern]. Japan Trench after leg 57 report (*GeoTimes*, April 1978), Middle America after leg 66 report (*GeoTimes*, September 1979), and Peru-Chile after Hussong *et al.* (1976).

#### QUANTITATIVE SIMULATION OF THE NO-GROWTH HYPOTHESIS

The assertion that observed isotopic data for ancient and modern rocks disprove no-growth models can be laid to rest by showing that no-growth models predict the same observations. In fact the isotope data cannot resolve the debate. All that can be done is to show them to be compatible with a no-growth model and to point out the logical inconsistencies created by the continental-growth hypothesis.

The no-growth simulation that was carried out is similar to that of Armstrong & Hein (1973). The computation was reprogrammed for greater flexibility, enlarged to include all parent-daughter systems, and modified by subdividing crust into upper and lower halves (as was done by Doe & Zartman (1979)) and mantle into a more rapidly interacting upper part and less mobile, but much more massive, lower part.

The addition of lower mantle to the interacting geochemical systems is a contentious point. Earth evolution models have considered it variously as enriched, depleted, greatly involved, weakly involved, and isolated. The popularity of whole-mantle convection has increased in recent years (O'Connell 1977; Elsasser *et al.* 1979; Schubert 1979). In the models computed, the degree of upper mantle – lower mantle interaction has varied. The assigned chemical composition of lower mantle has been kept the same as that of the upper mantle, but the lower mantle can be effectively depleted or enriched by changing its mass in the calculation.

TABLE 1. CHEMICAL CHARACTERISTICS OF MASS AND MAJOR DOMAINS  
IN A SELF-CONSISTENT EARTH MODEL

(Two-thirds of the values generated by the randomization procedure in the simulation calculation fall within the limits given below the mean values.)

model	upper crust	lower crust	upper mantle	lower mantle	bulk Earth	bulk Earth of O'Nions <i>et al.</i> (1979 <i>b</i> )
mass/(10 <sup>26</sup> g)	0.101	0.101	40.57	32.78	59.76	—
K/(μg/g)	17000	7800	7.79	210	185	200
<sup>36</sup> Ar/(10 <sup>-8</sup> cm <sup>3</sup> /g)	10370–28050	4758–12870	185–238	200–221	0.07 (diss.) 2.25 (atmos.)	4.6
Rb/(μg/g)	80	33	0.3	0.29–0.32	0.40	0.67
Sr/(μg/g)	49–132	20–54	0.26–0.34	30	22.0	21.0
K/Rb	213	236	700		463	300
<sup>87</sup> Rb/ <sup>86</sup> Sr	0.77	0.21	0.029		0.053	0.087
U/(μg/g)	3.0	0.4	0.02	0.019–0.021	0.019	0.020
Th/(μg/g)	2.2–4.1	0.30–0.54	0.019–0.022	0.05	0.062	0.080
Pb/(μg/g)	15	1.4	0.046–0.054	0.16	0.13	0.13
<sup>0-4</sup> K/U	6.7–15	2.0–4.5	0.145–0.18	0.154–0.17	0.97	1.0
<sup>3</sup> He/(10 <sup>-8</sup> cm <sup>3</sup> /g)	0.567	1.95	1.05	0.022	0.015 (diss.) 0.059 (atmos.)	—
<sup>238</sup> U/ <sup>204</sup> Pb	0.022	0.022	0.022	8.3	9.8	10.2
<sup>232</sup> Th/ <sup>238</sup> U	19.9	8.8	2.5	0.5	3.2	4.0
Sm/(μg/g)	5	3	0.5	0.49–0.52	0.35	0.32
Nd/(μg/g)	3.7–6.8	2.2–4	0.46–0.54	1.5	1.08	0.97
<sup>147</sup> Sm/ <sup>144</sup> Nd	25	12	1.4–1.6	1.46–1.55	0.197	0.199
	18.5–34	9–16				
	0.12	0.15	0.20			

For example, a half-mass lower mantle is equivalent to a lower mantle depleted in all elements of interest by a factor of two or to a lower mantle of which half is completely isolated from interaction with outer Earth systems. The surface effects of these two options are similar, the bulk-Earth statistics will be somewhat different. The relative contributions of the four major domains can be further adjusted by changing subsystem sampling probabilities. The results illustrated in figures 5, 8, 9 and 13 are based on relative sampling of 6% upper crust, 4% lower crust, 8% upper mantle and 2% of a half-mass lower mantle in each mixing event. These mixing events are carried out in a prescribed sequence. At each specified time between 4.57 and 0 Ga B.P., the program randomly selects ten subsystems from both crust and mantle domains, updates them for radioactive decay since the last time they were filled, and returns

them (with newly homogenized isotopic compositions but the same average chemical compositions and variability) to the WORLD array. Rare gases are removed to the 'atmosphere' each time a subsystem is processed. At the end of a run, at 0 Ga (today) or any specified time in the past, all systems are updated and the results plotted on various isotope-ratio and time diagrams that describe the status of the WORLD array, and summary ratios, regressions and sums are printed out. By changing element concentrations and ratios (table 1), sampling probabilities and mixing times, a variety of no-growth models can be tested for internal consistency.

The elements are distributed in the WORLD array with log normal distribution, but mean concentration in each major domain as given in table 1. The variability of any element in the crust is specifiable, based on its observed scatter in analytical data. Variability of upper mantle and lower mantle subsystems are reduced because much larger volumes are included in each subsystem.

The model maintains a constant level of chemical heterogeneity and remains differentiated for all of Earth history. Isotope heterogeneity increases with time as the rate of mixing decreases.

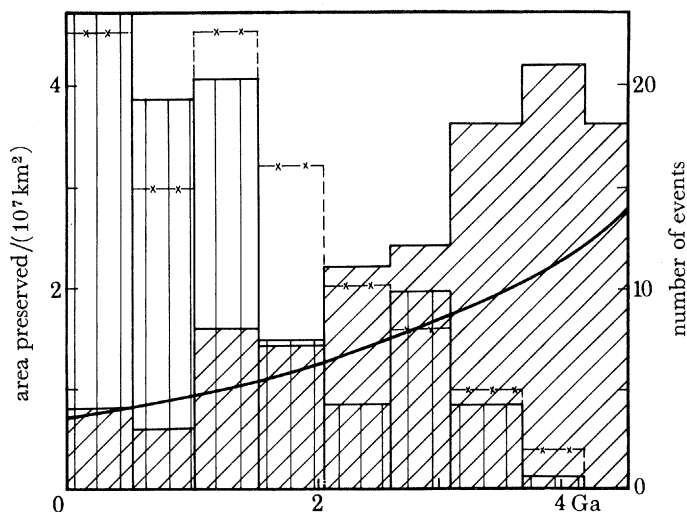


FIGURE 4. Histograms of basement rock ages and mixing times:  $\square$ , basement age distribution of Hurley & Rand (1969);  $\square$ , the mixing frequency for one run of the isotope-evolution computer simulation. The histogram traced by the line marked with  $\times$  symbols is the rock-age distribution created by that same run. The Hurley & Rand distribution can be created by resetting of crust ages at an exponentially declining rate. The rock-age histogram is not a perfect fit to the Hurley & Rand curve because of the randomness of the resetting process. The distributions of rock age are sensitive to changes in the mixing times and different from run to run. A more elaborate model would be required to produce a closer fit. The isotope evolution patterns remain similar regardless of the particular run and minor details of its rock-age output. The scarcity of crust more than 3 Ga old is the result of extremely high resetting probabilities during early Earth history. The decline of heat generation by long-lived radioactive elements is shown by the heavy line.

#### *The choice of mixing times*

The time of last creation of each subsystem in the model calculation is analogous to whole-rock Rb–Sr, U–Pb, or Sm–Nd dates. The distribution of these dates is largely an inverse function of the mixing times distribution that is specified when the simulation is run. The first requirement of any model is that it produce an upper-crust rock-date distribution like the one observed by Hurley & Rand (1969). They reviewed world literature to produce an age-of-basement curve. K–Ar and Rb–Sr dates were adjusted by them for crustal history before final

cooling to give the curve plotted in figure 4. Their conclusion was that, without recycling, the consolidation of stable cratons has accelerated through time.

The present rate of crustal growth implied by the Hurley & Rand curve is higher than the rates suggested by any recent pro-growth isotope or geochemical models. Moorbath (1976), O'Nions *et al.* (1979*b*), McCulloch & Wasserburg (1978) and Jacobsen & Wasserburg (1979) specify declining growth rates through post-Archaean time. Karig & Kay (this symposium) argue that the recent rate of continental growth is much less than the long-term average rate. There is a contradiction here that may be reconciled by a reappraisal of rock-age data or may indicate an inconsistency in the growth models. In either case the model calculation shown in this paper is at an extreme of the crustal recycling spectrum. The amount of sediment subduction implied in the computer model, 3 km<sup>3</sup>/a, is the maximum possible value. In reality the amount could be, and probably is, less and thus even easier to accommodate within present-day physical, chemical and isotopic evidence for sediment subduction.

The mathematics of basement-age resetting has been exhaustively discussed by Veizer & Jansen (1979). They show how resetting leads to exponentially rising basement-age histograms as observed by Hurley & Rand. Veizer & Jansen (1979) rejected a strictly recycling model in favour of gradual growth, because they accepted conventional Sr isotopic dogma, not because of any basic flaw in the recycling concept.

Shown on figure 4 is a mixing-time sequence used for model calculations and its consequent rock-age distribution using the same class intervals as Hurley & Rand. The only mixing-time distributions that give reasonable rock-age histograms are those that decline overall exponentially and somewhat irregularly with time. The decline is even steeper than the drop in heat production by U, Th, and K, but is quite reasonable for a terrestrial thermal history with an initial heat endowment (accretion, core separation, short-lived radioactive species) followed by heat production from long-lived species (Schubert 1979).

The implication of this exponentially declining mixing-time distribution in real-world terms is that subduction in the past was much more intense than at present. Some sort of convective overturn is required to provide a rational thermal model for the early Earth (Bickle 1978). There is widespread acceptance that some sort of plate tectonics prevailed in Archaean time, with thinner lithosphere, smaller plates, more rapid overturn, steeper thermal gradients and more extensive melting in magma generation (Burke *et al.* 1976; Watson 1978; O'Nions *et al.* 1978; Davies 1979). Bickle (1978) estimates that Archaean ocean-floor creation occurred at six times the present rate. If sediment subduction proceeded apace, the rarity of crust more than 3 Ga old is easily explained.

#### *Chemical composition of the Earth*

Many geochemists have discussed the abundance of radioactive elements and their parent to daughter ratios in the Earth. Mutually consistent values are defined by heat flow, element abundances, and isotopic measurements on rocks from the crust and mantle. The values chosen for one reasonably self-consistent evolution model are given in table 1. In general they are close to the abundances selected by O'Nions *et al.* (1979*b*) for crustal-growth model calculations. Important exceptions will be discussed in greater detail.

The values for Ar, K, U, Th and Pb are interrelated by the geochemical coherence of K and U, Pb isotope ratios, heat flow, and the Ar content of the atmosphere. Hurley (1968) estimated a bulk-Earth K abundance of 140 µg/g. O'Nions *et al.* (1979*b*) use 200 µg/g. Given the observed

$^{36}\text{Ar}$  and  $^{40}\text{Ar}$  in the atmosphere and the age distribution of crustal rocks, any value greater than the  $185\ \mu\text{g/g}$  in table 1 gives unreasonable model computation outputs. Even that value requires trapping of considerable  $^{40}\text{Ar}$  in rarely sampled mantle subsystems. Higher values lead to much more than the observed  $^{40}\text{Ar}$  in the atmosphere; values below about  $150\ \mu\text{g/g}$  require an efficient degassing of the deep mantle. The upper crust is given a value (1.7%) close to that observed in deeply eroded Precambrian shields (Lambert 1971). The whole-crust value, 1.24%, is lower than most estimates (1.7% for the whole crust by Turekian (1972); 1.6% for the whole crust, presuming a depleted lower crust, by Ronov & Yaroshevskiy (1976)), but close to Hurley's (1968) estimate of 1.35%. Even so, the mantle value is quite low ( $210\ \mu\text{g/g}$ ), only about one-fifth to one-sixth of the value observed in ocean-floor basalts ( $1160\ \mu\text{g/g}$  according to Hart (1971)). This means that for reasonable model calculation results the mantle, on average, is less enriched in K than is implied by the most-depleted pyrolite model of Ringwood (1962) and that the entire mantle is probably as depleted in K as the source of 'depleted' ocean-floor basalts.

The K/U ratio for the bulk Earth seems well agreed upon as  $1 \times 10^4$  (Wasserburg *et al.* 1964). The exact value in table 1 is  $0.97 \times 10^4$ . The uranium in crustal rocks is concentrated in the upper crust (Lambert 1971). The average crustal value ( $1.44\ \mu\text{g/g}$ ) is between estimates of Lambert (1971) and Ronov & Yaroshevskiy (1976). Total Earth U, like K, is only slightly below the value of O'Nions *et al.* (1979*b*). For the mantle a U value of  $20\ \text{ng/g}$  is about one-fourth of the best figure of  $78\ \text{ng/g}$  for ocean-floor basalts (Fisher 1979) and in the range of a very depleted pyrolite.

K in the core is limited to an amount about equal to the bulk-Earth K given in table 1 by heat-flow considerations and is considered unimportant by Oversby & Ringwood (1972) and Ganguly & Kennedy (1977). If any K is present in the core, it cannot have contributed much  $^{40}\text{Ar}$  to the atmosphere; core-derived  $^{40}\text{Ar}$  would only force a self-consistent model Earth crust and mantle to be more K-depleted than the Earth described in table 1.

Th and Pb values are those that give reasonable self-consistent results in model calculations. Th is significantly lower than the value used by O'Nions *et al.* (1979*b*) because the mantle Th/U ratio is taken to be that of ocean-floor basalts (Condie 1976; Kay & Hubbard 1978). In the model the lower mantle is believed to be a reservoir of low Th/U ratio that is only rarely tapped in crust-forming processes, so that crustal and outer Earth Pb does not reflect the average Th/U ratio of the Earth. The Pb value in table 1 is identical to the value given by O'Nions *et al.* (1979*b*) and is not particularly controversial. The  $^{238}\text{U}/^{204}\text{Pb}$  ratio of the outer Earth cannot be greater than 9.7, the value inferred from Earth surface Pb ores (Doe & Zartman 1979; Stacey & Kramers 1975). The bulk-Earth value is likely to be somewhat less, especially if the mantle is a relatively low U/Pb environment, as is indicated by the lower  $^{207}\text{Pb}/^{204}\text{Pb}$  of oceanic volcanic rocks. A large amount of Pb may be stored in the core of the Earth, but it is ignored in the figures of table 1.

The figures for Rb and Sr in the crust are close to those of Hurley (1968), and the mantle values are about one-fourth of the concentrations for ocean-floor basalts (Hart 1971; Kay & Hubbard 1978). This gives a much lower Rb/Sr and Rb content than suggested by O'Nions *et al.* (1979*b*), but similar Sr. As for Th, the lower mantle is believed to be a reservoir depleted in Rb (and in radiogenic Sr as well). It is not valid to use Nd–Sr isotope correlations of the upper mantle to estimate global Sr isotopic ratio and Rb/Sr ratio (DePaolo 1979), because the crust–mantle enrichment factors are distinctly different. Recent volcanic rocks are not likely



to be representative samples of the whole Earth nor of any perpetually undifferentiated part of it.

The round figures chosen for Sm and Nd abundances give total crust and Earth concentrations and ratios virtually identical to the values of Taylor (1977) and O'Nions *et al.* (1979*b*).

The values for initial  $^{36}\text{Ar}$  and  $^3\text{He}$  are based on the atmospheric abundance of  $^{36}\text{Ar}$ , and the ratios of planetary and solar rare gases (Mazor *et al.* 1970). Virtually all of the Earth's  $^{36}\text{Ar}$  is now in the atmosphere. Initial partitioning between dissolved and atmospheric gas is based on solubility of Ar in enstatite melts (Kirsten 1968). The  $^3\text{He}$  to  $^{36}\text{Ar}$  ratio in meteorites does not vary much beyond 0.10 to 0.015. A ratio of 0.03 is probably within a factor of two correct for the initial Earth. The partitioning between dissolved and atmospheric He is, as for Ar, based on its solubility in enstatite melts. The relative solubility of He is significantly greater than that of Ar, and this has important consequences that will be discussed later.

TABLE 2. INITIAL VALUES (O'Nions *et al.* 1979*b*; Mazor *et al.* 1970)

$^{40}\text{Ar}/^{36}\text{Ar}$	0.0001
$^{87}\text{Sr}/^{86}\text{Sr}$	0.69898
$^{206}\text{Pb}/^{204}\text{Pb}$	9.307
$^{207}\text{Pb}/^{204}\text{Pb}$	10.294
$^{208}\text{Pb}/^{204}\text{Pb}$	29.476
$^4\text{He}/^3\text{He}$	3333.3
$^{143}\text{Nd}/^{144}\text{Nd}$	0.50682
starting time	4.57 Ga B.P.

In summary, the composition chosen for model calculations is in the range of accepted values for crustal abundances, even a bit low for K, and gives a mantle quite similar to a 'depleted' pyrolite source for ocean-floor basalts. There cannot be any large volume of undepleted mantle underlying depleted asthenosphere (e.g. as suggested by Hofmann *et al.* (1978) or Wasserburg & DePaolo (1979)), because the amounts of heat and  $^{40}\text{Ar}$  generated would be excessive. The Earth of table 1 generates about half the currently observed heat flux (Williams & Von Herzen 1974). As discussed by Schubert (1979) and O'Nions *et al.* (1978), this is consistent with present ideas on the Earth's thermal history, with a time lag of the order of 1 to 2 Ga and possible carry-over of primordial heat, and heat from a crystallizing core or K in the core.

The values for initial isotopic compositions (table 2), decay constants, age of the Earth and masses of crust, mantle and core are well established (Stacey & Kramers 1975; Doe & Zartman 1979; O'Nions *et al.* 1979*b*; Steiger & Jaeger, 1977).

#### Pb ISOTOPE EVOLUTION

Figure 5 shows the initial ratios and present isotope compositions for upper mantle and lower and upper crust produced by the computer simulation. Actual isotopic compositions of volcanic rocks and ocean-floor sediments are shown for comparison in figures 6 and 7. The plumbotectonics model of Doe & Zartman (1979) is very similar to the model illustrated in this paper. Their discussion goes into much greater detail than the brief comments that follow here. In a no-growth model the mixing of crust and mantle Pb dominates the evolution and makes terrestrial Pb approximate a single-stage growth curve. The crust remains perpetually enriched in U and Pb and higher in U/Pb than the mantle. This explains the generally higher  $^{207}\text{Pb}$

and  $^{206}\text{Pb}$  of crustal rocks. Well mixed crustal Pb, in the form of sediments, is subducted. This results in loss of radiogenic Pb from the crust and gain by the mantle. Pb in volcanic rocks from contaminated mantle approximates average crust plus upper mantle Pb and is relatively homogeneous. Volcanic rocks from depleted mantle show chronic  $^{207}\text{Pb}$  depletion but considerable heterogeneity. The  $^{206}\text{Pb}$  enrichment in hot-spot volcanics is attributed to small-volumetric-scale unusual enrichments of heat-generating elements on a last 1 to 2 Ga time scale. Lower mantle or core reservoirs containing ancient non-radiogenic Pb are complementary to crust and upper-mantle average Pb with excess  $^{206}\text{Pb}$  and  $^{207}\text{Pb}$  (negative single-stage model ages). As discussed by Doe & Zartman (1979), the lower crust shows  $^{206}\text{Pb}$  depletion. This is due to isolation of old low U/Pb subsystems. The  $^{206}\text{Pb}$  depletion in lower crust does not require that the average U/Pb of the lower crust be lower than the mantle ratio, as it is in the Doe & Zartman model.

The tectonic stability of regions of lower crust that are U-depleted is probably enhanced so that such regions are more prevalent in the real world than is implied in the computer model with random recycling probabilities.

As shown by Stacey & Kramers (1975), Pb evolution can be approximated in two stages, the first with lower U/Pb lasting until 3.7 Ga B.P., and the later, higher U/Pb stage continuing

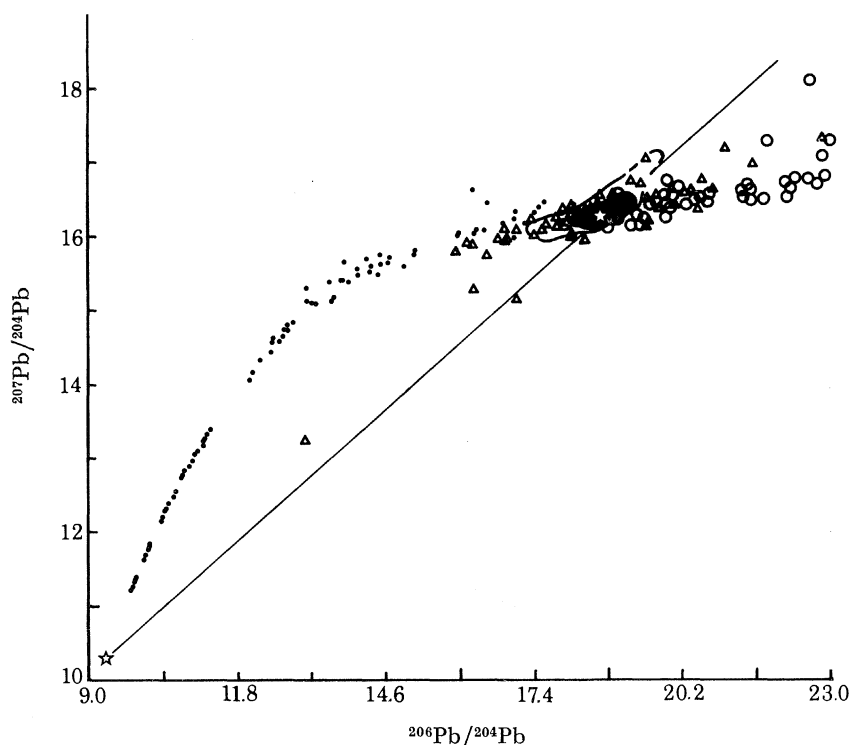


FIGURE 5. Computer simulation of Pb isotope evolution plotted in  $^{207}\text{Pb}/^{204}\text{Pb}$  against  $^{206}\text{Pb}/^{204}\text{Pb}$  coordinates: ☆, initial and final values for total Earth; —, the 4.57 Ga B.P. isochron (zero single-stage model age); ●, successive initial ratios created during the run. Note the close approach to a single-stage growth curve (with  $^{238}\text{U}/^{204}\text{Pb} = 9.2$  in the particular run illustrated) before 3 Ga B.P. The last initial ratios lie somewhat to the right of the zero model-age isochron but are covered by other symbols. Lower crust shown by Δ; upper crust by ○. Note the survival of non-radiogenic Pb in old, lower-U/Pb, lower-crust systems and the general  $^{206}\text{Pb}$  and  $^{207}\text{Pb}$  enrichment of the upper crust. Upper- and lower-mantle systems lie almost entirely inside of curved outline and mostly are in the dark area surrounding the present-day Earth symbol (☆).

until today. The present computer model does not incorporate the changes needed to explain this observed pattern. The likely explanation is Pb loss to the core during more pervasive internal convection immediately after formation of the Earth or entrapment of non-radiogenic Pb in the lower mantle. By 3.7 Ga B.P. the present outer Earth mixing system was established and deep mantle convection had declined in importance.

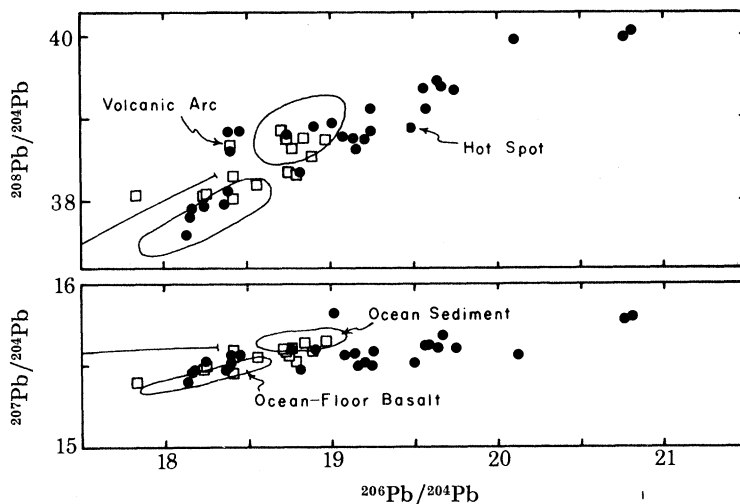


FIGURE 6. Pb isotope data for modern volcanic rocks and ocean-floor sediments (erosion-averaged upper crust). Pb data sources are summarized in Armstrong & Cooper (1971), Sun (1973), Sun & Hanson (1975), with additions from Oversby & Ewart (1972), Church & Tilton (1973), Lancelot & Allegre (1974), Meijer (1976) and Dosso *et al.* (1979). Large ovals outline the fields of ocean-floor basalt and sediment:  $\square$ , average compositions for different volcanic-arc suites;  $\bullet$ , average compositions for ocean-island or hot-spot (plume) volcanic suites. The growth curve of Cooper *et al.* (1969) is shown (—), terminated at the point of zero model age (intersection with the 4.57 Ga B.P. isochron). This termination is equivalent to  $\star$  of figure 5.

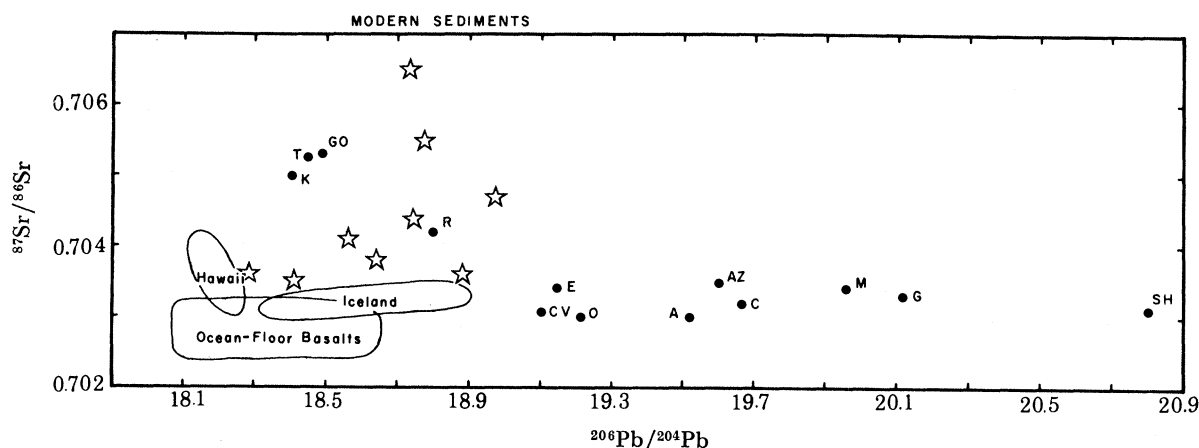


FIGURE 7. Sr and Pb isotopes in modern volcanic rocks:  $\star$  volcanic-arc averages (notable is the fairly narrow range of  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios and generally higher  $^{87}\text{Sr}/^{86}\text{Sr}$ );  $\bullet$  with letter acronyms, averages of sample suites from islands. Kerguelen (K), Tristan da Cunha (T) and Gough (GO) are unusual, with K-rich chemistry, radiogenic Sr, and normal mantle Pb. Reunion (R) is intermediate in isotopic characteristics. Hawaii has slightly radiogenic Sr, unradiogenic Pb. Iceland is variable from normal to radiogenic Pb, with slightly radiogenic Sr and a positive Pb and Sr isotope ratio correlation. Other islands show slightly radiogenic Sr (generally higher than ocean-floor basalts) and very radiogenic Pb. CV, Cape Verde; E, Easter; O, Oregon Coast Range; A, Ascension; AZ, Azores; C, Canary; M, McMurdo; G, Guadalupe; SH, Saint Helena. Data sources as for figure 5.

## Sr AND Nd ISOTOPE EVOLUTION

The initial ratios for  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  produced by the computer simulation are shown in figures 8 and 9. Present-day Sr and Nd isotope compositions are shown together in figure 8. For comparison, observed Sr and Nd initial ratios are shown in figures 10 and 11, respectively, and the coupled Sr–Nd evolution and present-day ratios of selected volcanic rocks and sediments in figure 12.

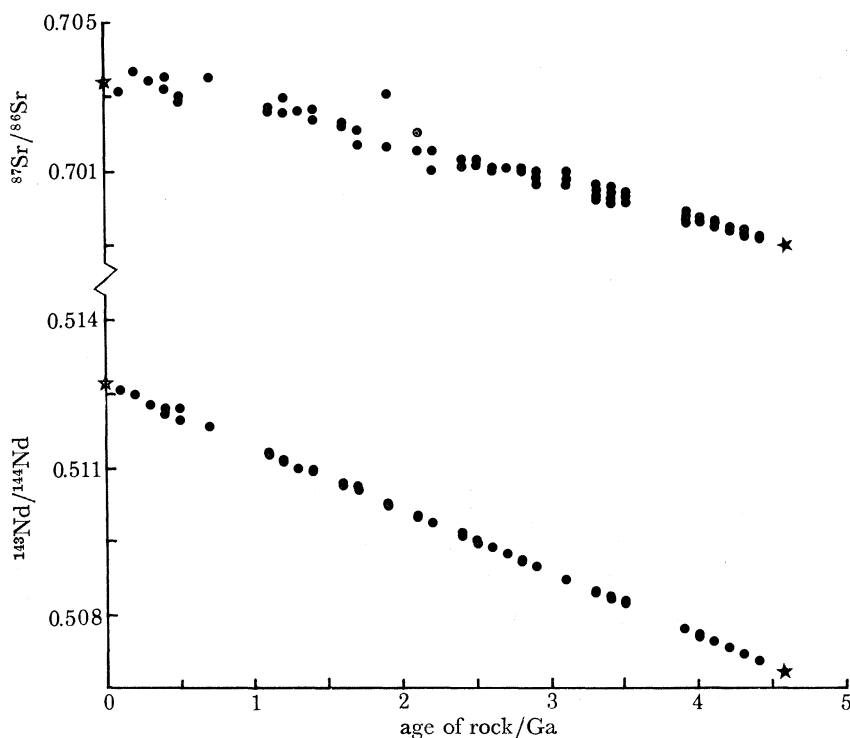


FIGURE 8. Computer-generated Sr and Nd initial ratios. The Sr scatter is greater and evident much earlier in spite of identical mathematical treatment. The difference is due to contrasting crust–mantle enrichment factors and geochemical covariance. The outer-Earth mixing processes hold the points close to single-stage evolution lines, in spite of real source heterogeneity and complex history.

In both cases the initial ratio growth curves mimic single-stage growth because of crust–mantle mixing processes. Nd evolution shows less scatter because of the close geochemical coherence of Sm and Nd, so that Sm/Nd ratios are much less variable than Rb/Sr ratios, and the lesser crustal enrichment of the rare-earth elements, so that the essentially chondritic and relatively uniform mantle dominates the observed growth curve. The scatter in Sr initial ratios (figure 10) is partly analytical error, but also due to crustal contamination and variously reset isotopic systems. Data quality and resistance to resetting processes are superior for Nd, so that the single-stage growth curve is well preserved (O’Nions *et al.* 1979*a*). Carefully selected Sr data approximate a linear growth curve (Hart & Brooks 1977; Peterman 1979).

The rather good Nd–Sr correlation in mantle-derived volcanic rocks has previously been explained as a mixing line between old and young mantle systems (Richter & Ribe 1979) or between depleted mantle and more enriched mantle or lower crust (DePaolo & Wasserburg 1979). I will suggest later that it is a mixing line between depleted mantle and ancient crust.

*Low initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios*

Low initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of rocks in newly accreted crust are one cornerstone of Moorbath's opposition to crustal recycling, following the lead of Hurley *et al.* (1962). In the no-growth continent-recycling model the low ratios are *not* a problem or contradiction. The ratios are low because the mantle contains abundant non-radiogenic Sr and acts as a buffer during genesis of volcanic rocks. Magmas coming from the mantle will have ratios close to mantle values in either

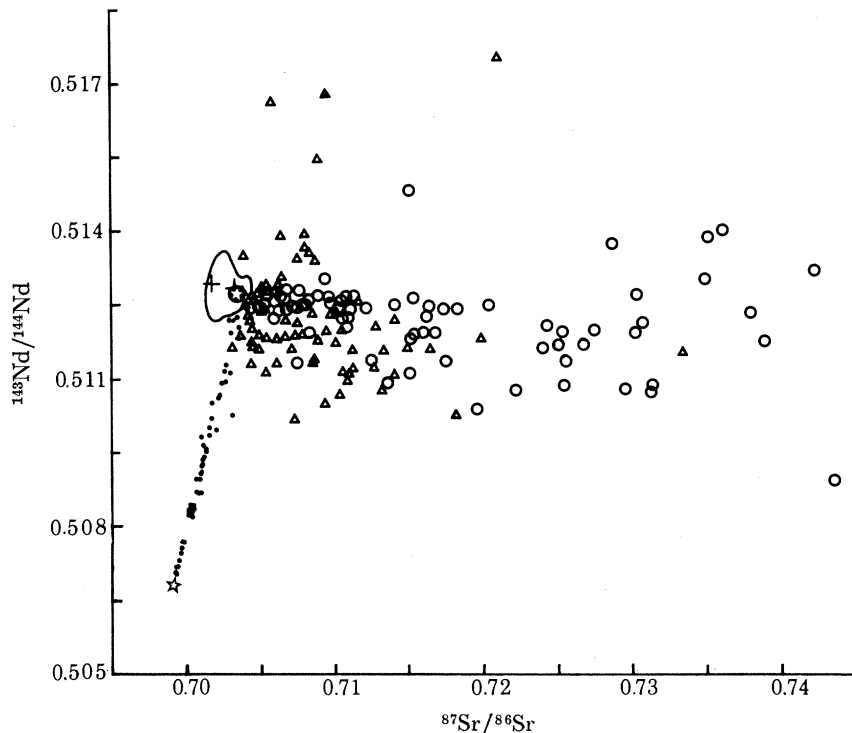


FIGURE 9. Nd against Sr isotope plot with symbols similar to figure 5: ☆, ⊛, respectively beginning and ending total-Earth averages; ●, successive initial ratios obtained during the run; ○, △, upper and lower crust, respectively; the solid line (—) bounds area within which most upper-mantle systems lie; +, lower- and upper-mantle average values. The distributions on this plot compare favourably with real data summarized by DePaolo & Wasserburg (1979) and O'Nions *et al.* (1979*a*). The 'mantle array' can be explained as a mixing line between depleted mantle and old crust-contaminated mantle. Volcanic-arc samples lie on mixing lines between normal mantle and present upper crust and average crust. None of these mixing lines necessarily contains the average-Earth point, although some may accidentally pass through it. The very radiogenic lower crust points are old systems with high Sm/Nd produced in the computer simulation, which creates chemical systems with Sm and Nd concentrations randomly scattered about mean values. The program does not include a covariance term associating geochemically related elements, and thus probably exaggerates the variability of lower-crust Sm/Nd. This, combined with the survival of old lower-crust systems (due to their relatively low probability of being sampled and reset) causes the wide scatter of lower crust Nd isotopic compositions.

growth or no-growth models. The small, but real, deviations of arc volcanics towards radiogenic Sr, as seen on figure 12, are quantitatively reasonable for a no-growth model. They are positive evidence of enrichment of mantle Sr with a small percentage of crustal Sr, all that is needed to accommodate complete crustal recycling in less than 2 Ga. This small enhancement of  $^{87}\text{Sr}/^{86}\text{Sr}$



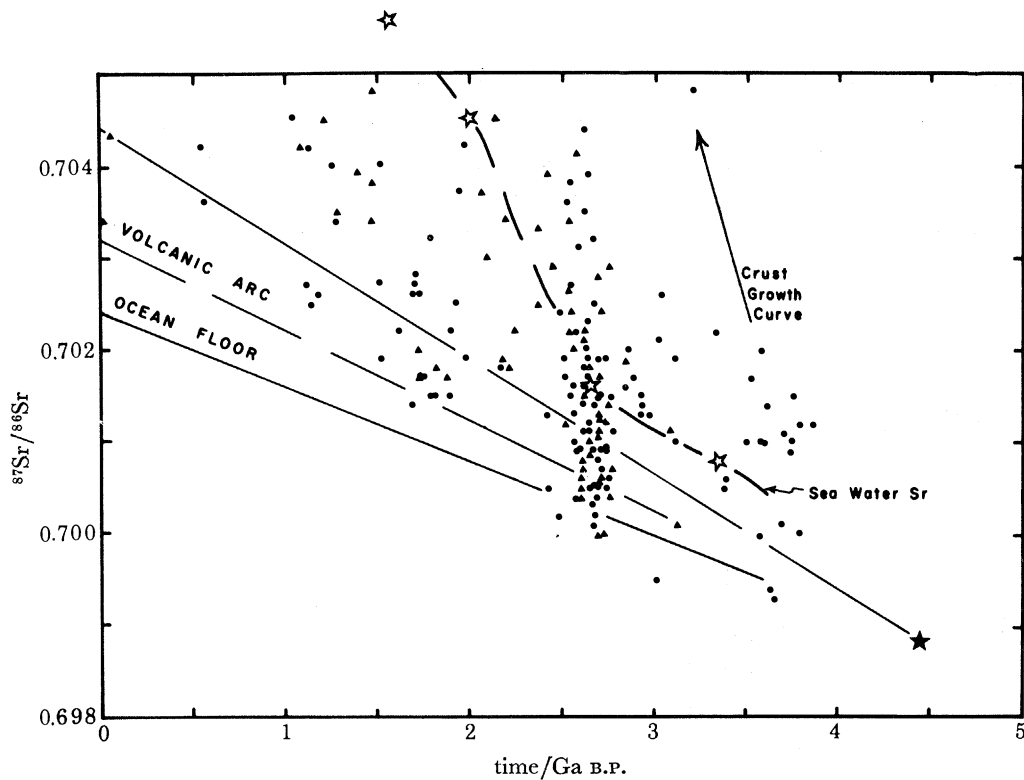


FIGURE 10.  $^{87}\text{Sr}/^{86}\text{Sr}$  initial ratios with time; vertical scale expanded so that spread in values is accentuated. Only samples with  $1\sigma$  errors less than 0.0015 are included. Data from North America, Africa, Australia and Europe collected from more than 60 published papers. Most of those are shown by Glikson (1979*b*) and cited by Moorbath (1977*a*) or Hart & Brooks (1977). Symbols:  $\blacktriangle$ , mafic rock;  $\bullet$ , siliceous-rock initial ratios; — — —, seawater Sr curve marked by  $\star$  based on references cited in text. Growth lines projected from initial Earth value ( $\star$ ) bound ranges of present-day values for ocean-floor basalt and for volcanic-arc magmas that are not greatly contaminated by the continental crust on which they lie.

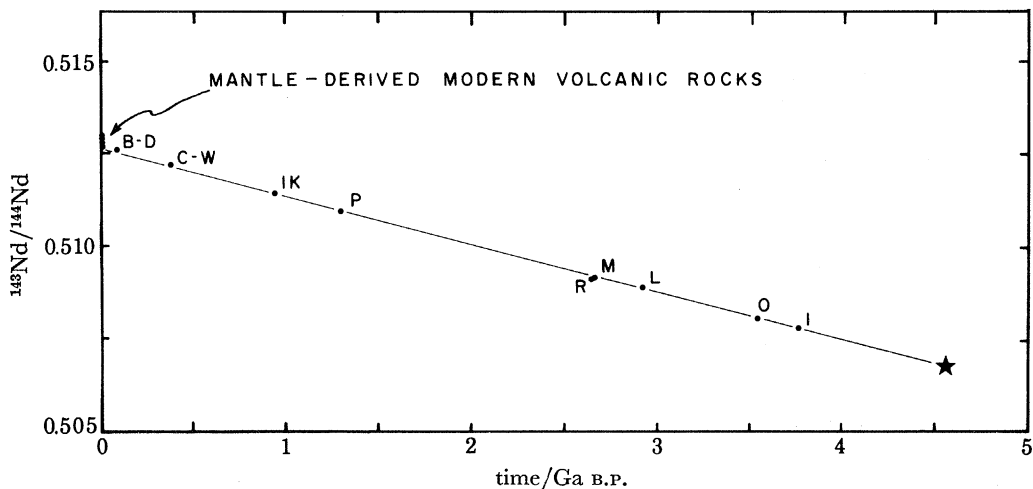


FIGURE 11.  $^{143}\text{Nd}/^{144}\text{Nd}$  initial ratios. Data summarized by O'Nions *et al.* (1979*a*), Basu & Tatsumoto (1979) and Zindler & Hart (1979). B-D, Bulfontein and DeBeers kimberlites; C-W, Colorado and Wyoming kimberlite; IK, Indian kimberlites; P, Premier kimberlite; R, Rhodesia; M, Munro township; L, Lewisian; O, Onverwacht; I, Isua;  $\star$ , initial Earth value. In this and figure 12 the Nd isotope ratios are those calculated according to the conventions used by the Lamont group (O'Nions *et al.* 1979*a*).

is in accord with the loss of radiogenic Sr from a constant-volume crust and the gradual increase in radiogenic Sr in a severely and perpetually Rb-depleted mantle. The present isotope composition of crust and mantle can only give average ages or residence times for Sr and Nd in crust and depleted mantle (Jacobsen & Wasserburg 1979). The values they obtain, 1.5 to 1.8 Ga, are in good agreement with the computer simulation. The upper crust for the computation illustrated has an average Sr isotope age of  $1.6 \pm 0.6$  Ga. This sort of distribution is inherent in any multi-stage mixing model and may explain the mantle isochron for oceanic basalts observed by Brooks *et al.* (1976).

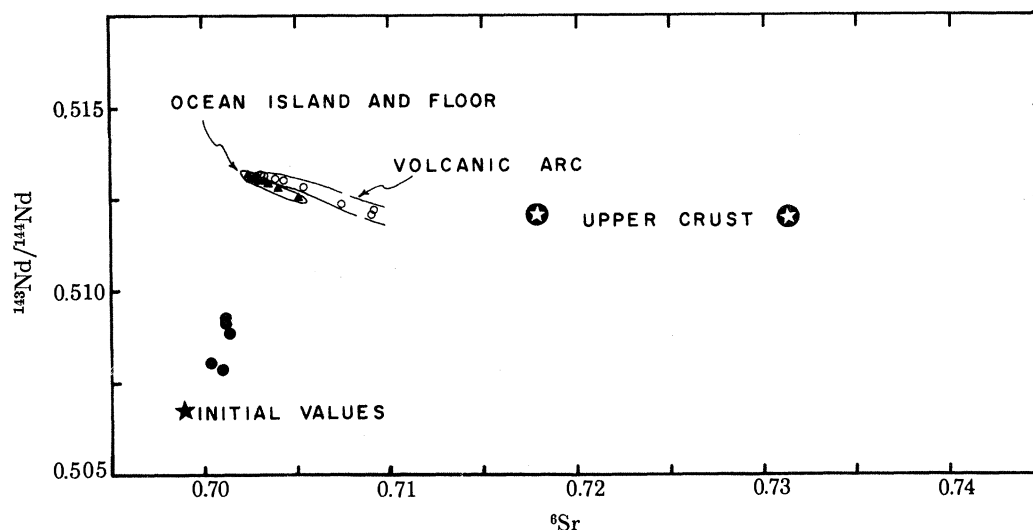


FIGURE 12. Nd and Sr isotopes in selected rock suites: ★, Earth initial value; ⊙, loess and shale, representing erosion-average upper crust (McCulloch & Wasserburg 1978); ●, initial values for Precambrian rocks, from several sources (Zindler & Hart (1979) and O'Nions *et al.* (1979a) for Nd; Jahn & Shih (1974) and Moorbath (1977a) for Sr); ▲, selected ocean-floor and island-basalt values from O'Nions *et al.* (1979a) and DePaolo & Wasserburg (1979); ○, volcanic-arc samples from De Paolo & Wasserburg (1977), Hawkesworth *et al.* (1977, 1979) and Hawkesworth & Vollmer (1979). The volcanic trends are mixing lines between mantle and old crustal or modern crustal rocks, respectively.

#### APPARENT SINGLE-STAGE EVOLUTION OF Pb AND Sr ISOTOPES IN ANCIENT ROCKS

Moorbath claims that the observed magma source homogeneity of initial Pb and Sr isotopes in ancient rocks is evidence for crustal growth. I disagree. Isotopic homogeneity as a result of intense mixing (rapid crustal recycling) in a chemically heterogeneous Earth is a prediction of the no-growth hypothesis. Isotopic homogeneity can only be maintained in a heterogeneous Earth by a short residence time in closed systems. In an Earth without an effective mixing process the homogeneity can exist only if no differentiation has occurred. Moorbath's view implicitly requires inhibition of chemical differentiation in the Earth for hundreds of millions of years after its accretion, a concept in contradiction with lunar and meteorite parent-body histories (Wetherill 1972; Lowman 1976). Any selective migration of U or Rb to the Earth's surface would soon be followed by measurable accumulation of radiogenic Pb and Sr in surface rocks and sea water. This accumulation is not observed. In fact, early Archaean mixing of crust and mantle was so effective that seawater Sr remained close to the single-stage growth curve until the first time of widespread cratonization 2.6 to 2.8 Ga ago (Perry & Murthy 1970;

Perry *et al.* 1971, 1975; Veizer & Compston 1976; Veizer 1976). The seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  curve is shown in figure 10. If recycling is denied, one must accept that terrestrial continent differentiation did not progress rapidly until the late Archaean. Alternatively, the Earth's surface was dominated by very effective mixing and crustal recycling processes before then. Accepting the second alternative removes all objections to the no-growth model. The second alternative is consistent with crustal thickness, freeboard observations and other arguments for early terrestrial differentiation.

The apparent single-stage growth of Pb-, Sr- and Nd-isotope initial ratios in ancient rocks is simply a consequence of rapid recycling. It does not require or imply chemical homogeneity. Evidence for chemical and isotopic heterogeneity of crust and mantle in ancient rocks (Oversby 1978; Manhés *et al.* 1979; Jahn 1976; Sun & Hanson 1975; Sun & Nesbitt 1977, 1978) and for ancient depleted mantle is in accord with the no-growth hypothesis. There is nothing remarkable about the similarity of Archaean and modern volcanic rocks (Glikson 1979*a*) in a perpetually differentiated, near-steady-state Earth.

A distinction must be made between crustal volume growth, which does not appear to have been important, and cratonization, which most geochemists have seen and discussed as crustal growth. The state of being a craton is simply long-term avoidance of tectonism and erosion. The amount of craton is a function of crustal recycling processes (Wasserburg 1961). If the probability of reworking is low, there will be lots of ancient cratons. If the reworking is rapid, as it is believed to have been in early Archaean time, there would be no ancient cratons, but just a crust composed of young mountain belts and recently accreted material. Much of the evidence mustered against the no-growth model is evidence of cratonization and not of crustal growth.

#### UNIQUENESS

The non-uniqueness of isotope data themselves in resolving different crustal evolution models is demonstrated by a run of the simulation program starting with a homogeneous Earth but retaining the same subsystem sampling, mixing and restoration rules. After 4.57 Ga B.P. the isotope arrays look identical to those generated with an initially differentiated Earth. By 2 Ga B.P. the initially homogeneous Earth had evolved a crust containing 92% of its present-day incompatible element concentrations, and by 4.57 Ga B.P. the crust was within 1% of its present-day values. By imposing assumptions of element abundance and geochemical processes, numerous Earth evolution models have been published that match some subset of the isotopic data. It is doubtful that any is a unique solution.

#### INERT GASES: $^3\text{He}$ AND $^{36}\text{Ar}$

The amounts of  $^3\text{He}$  and  $^{36}\text{Ar}$  escaping from the Earth do not contradict an early differentiated Earth with extensive crustal recycling and negligible later crustal growth. Recent general reviews of atmospheric evolution support a model of early catastrophic degassing (Fanale 1971; Li 1972; Walker 1977; Shimizu 1979; Thomsen 1980), and this is a conclusion in favour of early differentiation. It is logical to have escape of volatiles accompany chemical separation of the low-melting-temperature crustal fraction during initial differentiation rather than to divorce the processes.

The flux of primordial  $^3\text{He}$  from the mantle at a rate of about 3 atom/( $\text{cm}^2$  s) was first

detected by Clarke *et al.* (1969) and Mamyryn *et al.* (1969). Craig *et al.* (1978) and Tolstikhin (1978) review the data now available for  $^3\text{He}$  in different rocks and volatile fluxes. The amount of  $^3\text{He}$  in ocean-floor basalts is about  $1 \times 10^{-10} \text{ cm}^3/\text{g}$ , and the  $^3\text{He}/^4\text{He}$  ratio is  $1.4 \times 10^{-5}$  (ten times atmospheric). Generation of a lithosphere from pyrolite at  $2.6 \text{ km}^2/\text{a}$  would give a maximum flux of  $2 \times 10^7 \text{ cm}^3/\text{a}$ . This is similar to the Craig *et al.* (1975) estimate of  $4 \text{ atom}/(\text{cm}^2 \text{ s})$  ( $1.4 \times 10^7 \text{ cm}^3/\text{a}$ ) based on  $^3\text{He}$  anomalies in ocean water. Tolstikhin's (1975) estimate of  $> 100 \text{ atom}/(\text{cm}^2 \text{ s})$  seems too high. He argued for a continuous degassing model and did not accept early catastrophic degassing.

TABLE 3. RARE GAS ABUNDANCES, SOLUBILITIES AND FLUXES

meteorite abundance $10^{-8} \text{ cm}^3/\text{g}$	initial Earth endowment:		solubility $\text{cm}^3/(\text{g atm}\dagger)$	amount dissolved after initial degassing:		present flux from mantle $10^7 \text{ cm}^3/\text{a}$	ratio of flux to amount dissolved
	specific $10^{-8} \text{ cm}^3/\text{g}$	total $10^{20} \text{ cm}^3$		specific $10^{-8} \text{ cm}^3/\text{g}$	total $10^{20} \text{ cm}^3$		
$^3\text{He}$ 0.06	0.074	0.044	$1.2 \times 10^{-4}$	0.015	0.008	1.4 to 2	$2.25 \times 10^{-11}$
$^{36}\text{Ar}$ 1-10	$> 2.32$	$> 1.37$	$0.2 \times 10^{-4}$	$> 0.07$	$> 0.044$	6	$< 1.36 \times 10^{-11}$

Present mantle turnover rate  $2 \times 10^{-10} \text{ a}^{-1}$ .

$\dagger 1 \text{ atm} \approx 101\,325 \text{ Pa}$ .

Degassing models depend on initial endowment of  $^3\text{He}$  as well as present flux. The  $1.37 \times 10^{20} \text{ cm}^3$  of  $^{36}\text{Ar}$  in the atmosphere would be accompanied by  $1.47 \times 10^{22} \text{ cm}^3$  of He in typical meteorites (planetary gas composition of Mazor *et al.* (1970)), and, if this gas had a solar  $^3\text{He}/^4\text{He}$  ratio (Cameron 1968), this would mean a minimum of  $4.4 \times 10^{18} \text{ cm}^3$  ( $7.4 \times 10^{-10} \text{ cm}^3/\text{g}$ ) of  $^3\text{He}$  accreted with the Earth. The amounts of  $^{36}\text{Ar}$  in chondritic meteorites usually vary from  $10^{-8}$  to  $10^{-7} \text{ cm}^3/\text{g}$  (Zahringer 1968; Heyman 1971). Carbonaceous chondrites are much richer. A value of  $2.3 \times 10^{-8} \text{ cm}^3/\text{g}$  would supply the  $^{36}\text{Ar}$  in the atmosphere; this is very close to the estimate of Hamano & Ozima (1978). Thus an Earth assembled from typical meteoritic material would have at least the amount of  $^3\text{He}$  estimated above.

The present  $^3\text{He}$  flux is about  $10^{11}$  times less than the minimum initial endowment, and this is not inconsistent with early degassing and subsequent gradual loss as outlined below.

The  $^{36}\text{Ar}$  flux from the mantle is a controversial topic, but a majority of authors have estimated it to be small (or in other words the  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio in gas from the mantle is large) and indicative of early catastrophic degassing (Schwartzman 1973, 1978; Hart & Hogan 1978; Ozima 1973; Hamano & Ozima 1978). An estimate of  $3 \times 10^{-10} \text{ cm}^3/\text{g}$  for  $^{36}\text{Ar}$  in ocean-floor basalts by Hart & Hogan seems quite reasonable. This implies early catastrophic degassing of the Earth. The present-day flux of  $6 \times 10^7 \text{ cm}^3/\text{a}$  involved in lithosphere generation differs from the initial endowment of  $> 1.37 \times 10^{20} \text{ cm}^3$  by a factor of  $2 \times 10^{12}$ .

The  $^3\text{He}$  flux is much more evident and accurately measurable than the  $^{36}\text{Ar}$  flux because of the loss of He from the atmosphere: the small  $^3\text{He}$  flux is more easily detected against much smaller background contamination. The difference between the relative depletions of  $^3\text{He}$  and  $^{36}\text{Ar}$  can be explained by the difference in their solubilities in molten silicates. The unique data for solubility of He and Ar in enstatite melts (Kirsten 1968) and for solubility of Ar in basalt melts (Hayatsu 1978) permit an instructive calculation (table 3).

We first assume that the Earth accreted with the rare-gas endowments discussed above, and completely differentiated into core, mantle, crust, and surface fluids. The amounts of He and Ar remaining dissolved in the Earth, if one assumes equilibrium as measured by Kirsten (1968) and no loss of initial atmosphere, will be approximately 20% and 3%, respectively. Note that the solubility of He is much greater than that of Ar, and so more He than Ar remains trapped in the Earth. The remaining gas slowly escapes as the depleted mantle convects to the surface and loses and gains volatiles. Some  $^{36}\text{Ar}$  may be recycled, but the  $^3\text{He}$  continues to escape to surface fluids and eventually to space.

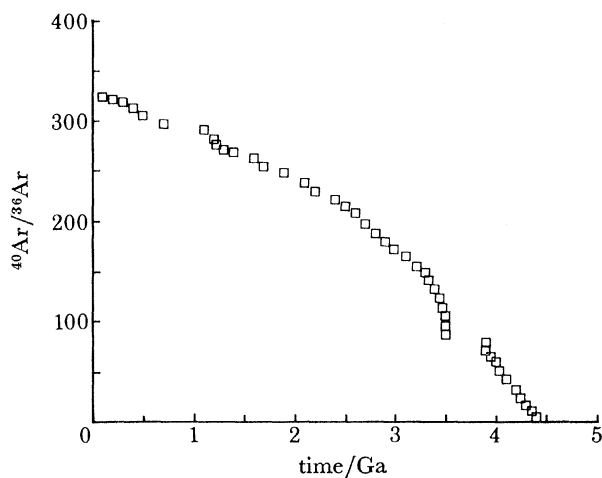


FIGURE 13. Growth curve for Ar isotopes in computer simulation. Horizontal offsets are the result of major time gaps between mixing events. The calculated end value is slightly high, compared to the real world, due either to overestimate of the K content of rocks, or to an excessively efficient degassing function (100% at each time the subsystem is reset) and/or excessive stirring of the deep mantle in the computer model.

The *calculated* ratio of initially dissolved  $^3\text{He}$  to  $^{36}\text{Ar}$ , 0.2, is remarkably like the observed ratio in ocean-floor basalts, 0.3 (Dymond & Hogan 1978; Hart & Hogan 1978). The present  $^3\text{He}$  flux ( $1.4$  to  $2.0 \times 10^7 \text{ cm}^3/\text{a}$ ) is about  $4 \times 10^{10}$  times less than the initial amount dissolved ( $\geq 8 \times 10^{17} \text{ cm}^3$ ). This factor is similar in magnitude to the present annual recycling rate for lower mantle in the computer model (1 in  $5 \times 10^9$ ) or the annual recycling rate for total mantle in lithosphere production today (1 in  $5 \times 10^9$ ). Thus it is easy to reconcile the present rare-gas flux with early catastrophic atmosphere creation, and to believe that differentiation into crust and mantle occurred at the same early time. The important point is that complete differentiation does not mean complete degassing. Volatiles, including inert gases, are soluble in silicates, so that some remain behind. The measured solubilities suggest that a significant fraction remains dissolved and any inefficiency in the catastrophic degassing event will only *increase* that fraction. The greater initial relative solubility of He, and its loss from the atmosphere, are the reasons for  $^3\text{He}$  degassing appearing at first to be different from  $^{36}\text{Ar}$  degassing, and for the contrast in conclusions reached in studies of the two rare gases.

#### *Atmospheric evolution in the computer model*

The model evolution of  $^{40}\text{Ar}/^{36}\text{Ar}$  in the atmosphere is shown in figure 13. The steady increase from an initial low value is a consequence of escape of radiogenic Ar when new mantle



or crust systems are formed. The rate of increase declines as heat production (and rock production) decreases and as  $^{40}\text{K}$  is consumed. The one possible measure of ancient argon (Cadogan 1977) is consistent with such a growth curve. He reported a Devonian value of 291, 98.5% of the present  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio.

#### STABLE ISOTOPES IN SEDIMENTS AND OCEAN WATER

Stable isotopes of C, S and O in sediments show remarkably little of the secular changes that might be expected with reservoir growth and crustal evolution. Carbon is constant from at least 3.3 Ga B.P. to today (Schidlowski *et al.* 1979; Eichman & Schidlowski 1975), sulphur likewise (Vinogradov 1972; Monster *et al.* 1979). Beaty & Taylor (1979) report Archaean sea water to be indistinguishable from modern in  $^{18}\text{O}$ , and this implies a steady state already reached between reservoir size and distribution and is most easily understood on no-growth recycling models (Muehlenbachs & Clayton 1976). Secular changes in O of chemical-organic sediments are attributed to changes in ocean temperature (Oskvarek & Perry 1976; Knauth & Lowe 1978). Chase & Perry (1972) pointed out that models for O isotopes with steady-state recycling are most stable. None of the growth models were successful. An extreme possibility is that the oceans are actually shrinking somewhat as the crust and mantle cool and hydrate (Fyfe 1976).

#### STEADY-STATE CHEMICAL SEDIMENTOLOGY

The notion that sediment chemistry can be explained by recycling on a steady-state Earth was germinated by Sillen (1967) and developed to a widely accepted viewpoint by Siever (1968) and Garrels & Mackenzie (1969, 1971). Condie (1967) and McKay & Rogers (1972) have commented on the essentially constant chemistry of geosynclinal sediments from Archaean to present time.

#### SECULAR CHANGES

So far this paper has emphasized that continental crust has not grown in volume or greatly changed in composition through geological time. This does not mean that secular changes are not important. Of major importance and effect are the decline in heat flux and consequent decreasing rate of recycling and the complementary process of increasing cratonization. This will produce changes in magma genesis, plate tectonic style, and upper crust – lower crust isotope and chemical contrasts.

At the Earth's surface, oceans and sediments have undergone changes as reviewed by Veizer (1973) and Holland (1972, 1976). These changes are in response to changing tectonic patterns and styles, decreasing rates of volcanism and sea floor generation, evolution of life, and increase in atmospheric oxygen. None of these changes are necessarily monotonous; they go on in bursts and pauses leading to a complex geological record. The shift of  $\text{CaCO}_3$  deposition from shelf to deep sea only about 200 Ma ago (Sibley & Vogel 1976) is a drastic change that should permanently offset the geochemical cycle of Ca. Whether this will show up in volcanic arc magmas depends on the effectiveness of the mantle buffer. Pelagic carbonate subduction may partially explain the late Phanerozoic decrease in  $^{87}\text{Sr}/^{86}\text{Sr}$  of sea water (Veizer 1976).

## CONCLUSION

The subduction of sediment in trenches has been shown to occur by geophysical measurements and deep-sea drilling. Sediment flux calculations, comparing conveyor belt transport on moving ocean floor with observed accumulations of pelagic sediment, do not balance unless sediment is lost into the mantle. The rates of loss are consistent with the continental recycling that is required to reconcile isotope and geological evidence for continental accretion with constancy of freeboard and crustal thickness.

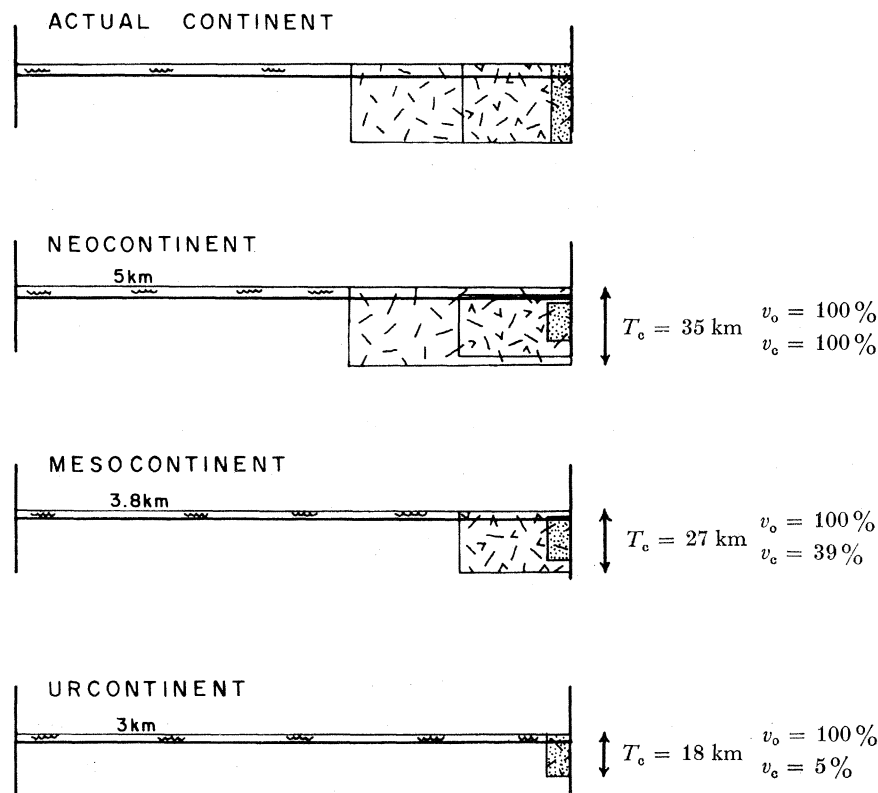


FIGURE 14. Contrasting growth patterns for continents on two types of world: one with continental recycling and the other with continental volume growth. Both assume early degassing of volatiles to give a near-present-volume ocean. In the growth models, ancient continental nuclei should become underplated, buried and lost from sight. The real world pattern is one of resetting, recycling and progressive cratonization, not continental volume growth. Symbols:  $T_c$ , thickness of stable cratons;  $v_c, v_o$  volumes of continental crust and ocean water respectively, relative to present-day values.

Petrological models for andesite genesis in volcanic arcs now converge on multi-stage-multi-component hypotheses that bring water and fusible components from the ocean floor into the zone of magma generation. Radiogenic isotopes themselves can be used as tracers of this process.

Comparative planetology leads to models of early planet differentiation and degassing (Lowman 1976; Walker 1977). Terrestrial isotopic data for K–Ar, U–Th–Pb–He, Rb–Sr and Sm–Nd are all quantitatively consistent with early differentiation, if continental crust is being recycled. An effective crust–mantle mixing process can reasonably explain the apparent single-stage evolution of radiogenic isotopes in Archaean time.

A constant-volume – crustal-recycling model reconciles contradictions that growth models must ignore. Figure 14 contrasts the two concepts in very basic geological and volumetric terms. The zonation of continental crust into laterally juxtaposed belts of different age, but constant thickness, is a continent recycling evolutionary pattern. Given isostasy and erosion to base level, the growth of continents must be accompanied by increasing crustal thickness, whether sea water has increased in volume or not. As shown in the figure, all ancient cratons in a crustal growth situation would become engulfed in younger crust, underplated, injected or covered by younger rocks. This is not the pattern observed, so that the growth models, based on isotope evidence and the belief that continent recycling cannot occur, are confronted by a serious contradiction. The obvious interpretation, continental recycling, cannot be easily dismissed.

A corollary to early global differentiation and crustal recycling is the conclusion that ‘primordial’ or ‘undepleted’ mantle, implying that some part of the mantle has its initial homogeneous-Earth composition, does not exist. The mantle source region of ocean-floor basalts is depleted, and the mantle is heterogeneous. That is all we know. That heterogeneity is acquired when magmas are formed, leaving depleted residue, when enriched magma or fluids come to rest, leaving modified enriched mantle, and when a fraction of the mantle is involved in a mixing episode with crustal materials in a subduction zone. The heterogeneity is perpetual. The fact that the mantle sources of Pb, Sr and Nd isotopes follow single-stage near-average-Earth growth lines is entirely a consequence of mixing processes, not chance preservation of primordial undifferentiated material. The complementary isotopic homogenization and exchange processes of erosion, melting of complex subducted mixtures and magma fluxing continually bring upper mantle and crust towards their overall average isotopic compositions whenever crust and mantle are regenerated. Each time a mantle fraction is moved from its depleted evolution line back to the outer-terrestrial isotope growth curves, it undergoes chemical processing that creates a new mantle, with heterogeneous parent–daughter ratios, that is isotopically homogenized. On average, the new mantle is chemically depleted, but locally it may acquire a strong crustal imprint.

Where enrichment in incompatible elements is strong, that mantle fraction becomes a potential ‘plume’ source, enriched in radioactive and radiogenic isotopes and enhanced in heat production. Consequently today’s ‘undepleted’ or plume-source mantle can be viewed as depleted mantle, contaminated long ago with continental crust. There is a necessary time lag for the generation of heat and the distinctive isotopic characteristics of plumes. These mixtures will of necessity be nearly coincident with bulk outer-Earth chemical and isotopic properties.

The plume source shows an additional signature of its subduction-zone genesis. The relatively high Ta and Nb concentrations that are distinctive of plumes are relatively depleted elements in volcanic-arc magmas (Wood *et al.* 1979). This can be attributed to accumulation in the mantle of a stable residual phase or phases during arc magma production and the breakdown of the same phase(s) under the different conditions in a plume magma source.

The isotope heritage of volcanoes within plates thus comes from the same subduction zone source as fresh additions to the crust. The outer-Earth isotope growth curves are approximations of a well mixed evolutionary system. This system is driven by internal heat, and as that heat declines the world becomes increasingly heterogeneous isotopically. Secular changes in tectonics and Earth-surface chemistry occur against the background of constant continent and ocean volume and crustal recycling by plate tectonic processes. The near-steady state was

reached in the first few hundred million years of Earth history, before the geological record begins. Details of the transition from accretion to near-steady state on the Earth are entirely in the realm of speculation.

This paper was written while enjoying the freedom and financial security of sabbatical leave from The University of British Columbia and a Killam Senior Fellowship. The arguments have been germinating for years and have been practised on many friends and colleagues. Roberta Crosby expedited manuscript preparation to meet a meeting deadline. I thank S. Moorbath for provocation and the opportunity to prepare this paper. The manuscript has benefited from reviews by Tom Ewing, Barry Ryan, John Tarney and Paul Taylor.

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### Discussion

R. S. HARMON (*Isotope Geology Unit, Scottish Universities Research and Reactor Centre, East Kilbride, Glasgow G75 0QU, U.K.*). As indicated by Dr Armstrong in his discussion, Magaritz *et al.* (1978) have correctly recognized that the  $^{18}\text{O}$ -enrichment of the andesitic lavas of south Peru ( $\delta^{18}\text{O} = 7.0\text{--}8.6\text{‰}$  s.m.o.w.†) requires a sialic component in their genesis. However, they argue that the best candidate for such a contaminant to a mantle-derived magma was geosynclinal sediments that had been subducted and become involved in partial melting processes at depth. This view, as shown by Thorpe *et al.* (this symposium), is incorrect as it was largely based on the absence of an O–Sr isotopic correlation, which has now been shown to exist both on an individual sample basis in specific areas like the Cerro Galan volcanic centre in northwest Argentina and overall across the Andes as a whole. The observed O–Sr isotopic correlation ( $\delta^{18}\text{O} = 6.5\text{--}10.7\text{‰}$ ,  $(^{87}\text{Sr}/^{86}\text{Sr})_{i\ddagger} = 0.70378\text{--}0.71125$ ) is similar to that observed by

† Standard mean ocean water. ‡ Subscript i stands for initial.

Taylor & Silver (1978) for the Peninsular ranges of southern California and Baja California and by Harmon & Halliday (1980) for the Late Caledonian granites of Britain. The lower slope of the O–Sr correlation for the Andean lavas strongly suggests that the crustal contaminant is old (Precambrian or early Palaeozoic) granitic or gneissic upper crust which has the required isotopic characteristics to explain the O, Sr and Nd isotopic variations observed in the Andean lavas, whereas young geosynclinal, continental or pelagic sediments do not.

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R. L. ARMSTRONG. There is certainly abundant isotopic and chemical evidence of crustal contamination of magmas erupted through continental crust. While I agree that much of this contamination takes places within the crust it is possible for the same observations to be a result of sediment or crustal-fragment subduction. In the Andes I would expect both processes to be operative. A unique conclusion could only be reached if we had access to samples representing magma at the point that it entered into the crust.

The proper approach to a valid magma genesis scheme for an Andean arc is one where fluxes, mass balances and reservoirs are taken into account in quantitative plausibility arguments, as was done by James (1978). Only in that way can the question of subducted crust cf. intracrustal contamination of mantle-derived magma be tested.

An oceanic ensimatic volcanic arc, on the other hand, has no continental crust that can be cannibalized to explain isotope anomalies: a young oceanic arc must show the isotope character of the magma coming from the mantle. Even in those cases there is evidence for subducted water, alkali, alkaline earths, and heavy metals.

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