THE ORIGIN AND GROWTH OF CONTINENTS

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"The inherent difficulties of the science, Lyell thought, had rendered it peculiarly susceptible to the interpretations of ancient miracle mongers and their modern successors."

(Gillispie, 1951, p.127)

SUMMARY

Geophysical evidence for continental origin and growth may be summarized as follows: (1) The overall mass of the crust and mantle to a depth of about 500 km is the same on a broad scale beneath oceans and continents. (2) The heat flow in shield areas is less than in orogenic areas and the mantle under shield areas is cooler than under the oceans. (3) The average continental crust is about 40 km thick. Shield areas are 40–45 km thick and orogenic areas have thinner crust, typically about 35 km thick, but much thinner (20 km) in areas such as the Pacific coastal region of California.

Geological evidence indicates that: (1) mountainous areas are destroyed by erosion in a few million years; (2) shield areas remain stable for long periods; (3) the continents have grown throughout geological time and are now more extensive than previously; (4) calc-alkaline volcanic rocks, in particular andesites, are characteristic of orogenic areas.

Geochemical evidence shows that: (1) the continental crust has an overall composition (for major elements) equivalent to an intermediate rock with a silica content about 60%; (2) the sedimentary rare-earth pattern is typical for the crust exposed to weathering, and may be typical of the whole crust; (3) the Sr isotope data indicate that the amount of Rb available is sufficient only for about 20 km of granodiorite, so that the lower crust must contain much lower concentrations of Rb; (4) there has been a strong vertical concentration of the heat producing elements in the earth.

A simplified model for continental origin and growth is proposed, with the following stages:

(1) An initial geochemical fractionation leads to the concentration of the lithophile elements in the upper 1,000 km.

(2) Lateral variations in the distribution of the heat producing elements in the uppermost mantle localise the sites of continental nuclei.

(3) Continental areas grow mainly by the addition of andesites and

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associated calc-alkaline rocks in orogenic areas. Granodiorites and granites are mainly formed by partial melting, leaving a lower anorthositic crust. The overall composition of the continental crust is close to that of calc-alkaline or orogenic andesites.

(4) Depletion of the subcontinental mantle in heat-producing elements terminates the process.

(5) Erosion of shield areas removes K, U and Th and reduces the heat flow to levels below those of present orogenic areas.

INTRODUCTION

The origin of continents is a basic problem in geology and there have been two opposing schools of thought since the subject received scientific attention. The first holds that continental material was formed very early in the history of the earth. There are two main variations of this idea, one group favouring an early separation of the earth into core, mantle and crust and other workers suggesting that the silica rich material came from space, early in the history of the earth, but subsequent to its formation. According to the other major point of view, the continents have grown throughout geological time, being derived from the material in the earth's mantle.

These two points of view, in their extreme form, reflect the division of the geological world into those workers who appeal to sudden or catastrophic processes as opposed to those who wish to account for the observations "by reference to causes now in operation" (Lyell, 1830). Gilvarry (1961) and Harrison (1960) proposed that the ocean basins formed by asteroidal impact based on analogy with the preferred theories for formation of the lunar maria. The continental material was piled up around the ocean basins and subsequently sank due to isostatic compensation. The depth-diameter relations for the initial ocean basins fitted the curves based on terrestrial and lunar craters. The origin of the continental material was not specified. More recently Donn et al. (1965) have suggested that the continents were derived from the infall of sialic meteorites early in the history of the earth. The place of origin of these meteorites was not specified.

There are of course many older theories postulating an initial sialic crust for the earth.

In contrast, theories of gradual growth of the continents by geological processes associated with orogenic activity, have been frequently proposed, and are associated with the names of Wilson (1952), Rubey (1951), Gilluly (1955), Engel (1963) and MacDonald (1963) to name a few of the more recent advocates of this general hypothesis.

THE GEOPHYSICAL EVIDENCE

The mass of the whole crust \((2.4 \times 10^{25} \text{ g})\) is 0.40% of the mass of the earth, divided into oceanic crust \((\text{mass} = 0.6 \times 10^{25} \text{ g})\) comprising about 0.10% of the mass of the earth and continental crust comprising about 0.30\%(\(1.8 \times 10^{25} \text{ g}\)) of the mass of the earth \((6 \times 10^{27} \text{ g})\). The strong upward concentration of many elements in the earth gives the crust a geochemical importance out of proportion to its mass. Typical crustal thickness in shield areas
is 40-45 km (Pakiser and Robinson, 1966) with seismic velocities ranging from 6 to 7.2 km/sec and underlain by mantle with seismic velocities of about 8.2 km/sec. The broad structure is not agreed on. The existence of the Conrad discontinuity separating an upper acidic from a lower basic crust is currently in debate.

On a broad scale the masses of continental and oceanic sections are equal, implying that the subcontinental mantle must be denser at depth than the suboceanic mantle. This is consistent with a vertical segregation model for continental growth.

### TABLE I

Average heat-flow values from Lee and Uyeda (1965)

<table>
<thead>
<tr>
<th>Area</th>
<th>μ cal/cm² sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continent: (average)</td>
<td>1.43 ± 0.56</td>
</tr>
<tr>
<td>Precambrian shields</td>
<td>0.92 ± 0.17</td>
</tr>
<tr>
<td>Post-Precambrian non-orogenic areas</td>
<td>1.54 ± 0.38</td>
</tr>
<tr>
<td>Palaeozoic orogenic areas</td>
<td>1.23 ± 0.4</td>
</tr>
<tr>
<td>Mesozoic-Tertiary orogenic areas</td>
<td>1.92 ± 0.49</td>
</tr>
<tr>
<td>Oceans: (average)</td>
<td>1.60 ± 1.18</td>
</tr>
<tr>
<td>Basins</td>
<td>1.28 ± 0.53</td>
</tr>
<tr>
<td>Trenches</td>
<td>0.99 ± 0.61</td>
</tr>
<tr>
<td>Ridges</td>
<td>1.82 ± 1.56</td>
</tr>
</tbody>
</table>

The latest review by Lee and Uyeda (1965) shows that the mean heat flow is 1.5-8 μcal./cm²/sec. Table I gives data for various major crustal areas. The strong upward concentration of radioactive elements in the continental areas and the general similarity of the heat flow indicates that the distribution of radioactivity down to probably 500 km is unequal beneath oceans and continents. This results in lateral temperature gradations in the upper mantle and provides an explanation for the concentration of earthquake activity and for the localisation of orogenic areas at continental margins. MacDonald (1963) states that 70% of the earthquake energy is released in the upper 60 km, 27% in the range 60-300 km, and 3% in the range 300-700 km. The energy release is 10²⁵ ergs/year compared with 10²⁶ ergs/year from volcanic activity and 10²⁸ ergs/year from heat flow. There is thus adequate thermal energy to account for volcanic and earthquake activity (MacDonald, 1963, p.601).

The most outstanding recent advance in the interpretation of the gravity and seismic data has been the demonstration of a thinner crust in orogenic areas, with an anomalous low density upper mantle beneath them. Notable contributions have been made by Press (1961), Cook (1962), MacDonald (1963), Nuttli (1963), Pakiser (1963, 1965), Pakiser and Zietz (1965) and Thompson and Talwani (1965). The most detailed information is available for the United States. In the Pacific coastal region of California, the crust is about 20 km thick deepening to 34 km under the Basin and Range province and to 44 km to the east (Pakiser and Robinson, 1966). Underlying the thin crustal area is low density (3.3) upper mantle, compared with the standard mantle density of 3.4 under the eastern United States. Fedotov (1965) has shown that the crustal structure in the Kuriles is similar, with a 20 km crust underlain by mantle with $V_p = 7.7$ km/sec.
The geophysical evidence may be summarised as follows:

1. The overall mass and composition of the earth to a depth of 500 km is the same on a broad scale beneath continents and oceans.

2. The heat flow in shield areas is less and in orogenic areas is greater than the overall average.

3. The mantle under shield areas is cooler than under the oceans.

4. The crust in orogenic areas is thinner than average continental crustal thicknesses of 40 km. No thick root of crustal rocks exists in orogenic areas.

THE GEOLOGICAL EVIDENCE

Rates of erosion

Many geologists have been impressed by the rapid destruction of land areas by erosion, but others have called for slower rates. Geologists working in recent orogenic areas are commonly enthusiastic supporters of a rapid rate of erosion and of orogenic processes in general. Gilluly (1965) has suggested that estimates be confined to areas greater than 200 m in height. This suggestion would help to reconcile the conflicting views. Judson and Ritter (1964) have made new estimates of the rates of denudation for the United States. They find an average rate of 6 cm/1,000 years, which would remove a volume equivalent to that of the United States above sea level in 11 or 12 million years. Other factors must be considered, such as isostatic uplift and the slowing of rates of erosion as base level is approached. Allowing for these factors, a period of about 30–50 million years would remove the mountainous areas. There is some agreement that the present rates are anomalously high, accounting, for example, for the young age of the oceans by the measured rates of accumulation of sodium. But even allowing a factor of ten in the calculations, the destruction of mountainous areas occurs in periods brief compared with geological time.

Since these areas are now widespread, the material above sea level removed from the continents must be continually replaced. Because of the loss of material to the deep-ocean basins, a simple recycling of the material is not sufficient, for we would see a slow decrease in continental areas with time.

An interesting point is the survival of the stable shield areas. Once erosion has levelled the land to near base level, the rate slows to vanishing point and we see the survival of ancient areas, as in Western Australia where portions of the shield retain a thin cover of old marine sediments. There is ample geological evidence that the Canadian and Australian Shields have been stable for long periods of time, with the only tectonic activity being slow epeirogenic movements.

Continental growth

In general, the case for continental growth has been strengthened by
recent investigations. The North American and Australian examples are well documented through recent work on geological ages.

In North America, there is a well established sequence from the ancient Superior (3300–2300×10⁶ years) and Slave (2900–2200×10⁶ years) Provinces down to the young Appalachian (600–200×10⁶ years) and Cordilleran (350–0×10⁶ years) provinces. These provinces appear to have been more extensive than are clearly exposed at present, and the concept of concentric growth is an oversimplification, but the geochronological evidence of increase in lateral extent with time seems clear.

In Australia, there is a sequence from 2900–2300×10⁶ years in Western Australia, through areas with ages of 1800×10⁶ years to the Palaeozoic sequences in eastern Australia. If another 500×10⁶ years is allowed to account for the geological evidence of an orogenic cycle occurring before the oldest dated granites, the familiar geological processes can be extrapolated back to 3.5 or 4×10⁹ years (Donn et al., 1965).

Several hundred million years seem required for the production of continental crust and its ultimate stabilisation as continental shield. The uncertainty about the areal extent of the older provinces makes it difficult to decide whether the process has been slowing down or speeding up. Hurley et al. (1962) have postulated an areal growth rate of 7,000 km²/10⁶ years.

**Source of continental material**

If the continents are growing, then the question of the source of the material arises. Sedimentation from the older areas can contribute, but it is clearly a self-limiting process which would result in the decrease in the rate of continental growth with time. If it was the dominant process, we would see a large continental nucleus surrounded by successively smaller areas of younger rocks. The conclusion seems inescapable that material is being added to the continents. The three alternative sources of supply are from space, laterally from the ocean floor (indirectly from the mantle) or by vertical segregation from the mantle.

The crustal masses are as follows: ocean crust (0.6×10²⁵ g) + continental crust (1.8×10²⁵ g) = total: 2.4×10²⁵ g. If the continental crust has grown over 4×10⁹ years a nett increase of 4.5×10¹⁵ g/year is needed.

**Meteoritic contribution**

The earth receives material from space in the form of meteorites, micrometeorites and cosmic dust. Recent studies have been made by Hunter and Parkin (1960), Crozier (1962), Schmidt (1963), Fredriksson and Martin (1963) and Wright et al. (1963). Wright et al. (1963) estimate the total accretion of cosmic material as 10⁶ metric tons or 10¹² g/year. There is much dispute about these estimates and the figure quoted is likely to be an extreme upper limit (Fredriksson and Martin, 1963). More recent studies suggest that the total is probably much less than 1,000 tons/day or less than 4×10¹¹ g/year (J.R. Arnold, personal communication). The amount in any event is insignificant in comparison with the amount required. The cosmic increment falls on ocean and continent alike so that the amount added to the
Continents is $3 \cdot 10^{11}$ g at most, a factor of $10^4$ less than required. The composition of this material is entirely unsuitable.

**Lateral accretion**

The second source is by lateral accretion from the oceanic crust.

**TABLE II**

Typical oceanic crustal structure (excluding mid-ocean ridges)

| Layer | P-wave velocity (km/sec) | Depth (km) |  |
|-------|--------------------------|------------|
| 1     | <4                      | 1.0        |
| 2     | 4-6                      | 1.7        |
| 3     | 6.7                      | 4.9        |
| 4     | 8.2                      | -          |

The structure of the oceanic crust is reasonably well known from seismic evidence (Table II). Layer 3 of the oceanic crust and appears to be universally observed in oceanic areas. It is characterised by very uniform P-wave velocities and this argues for uniform composition. Present geological processes on the ocean floor will give rise to a non-uniform mixture of basic volcanic material and pelagic sediment. Possibly this layer is primitive crust.

The material in layer 2 is much less uniform, and there are wide variations in the seismic velocities observed. There is some doubt as to whether it is present universally although Ewing and Nafe (1963) interpret the seismic data as generally indicating its presence. The observed range in seismic velocities covers many rock types and Raitt (1963) concludes that it is not a uniform layer. Hamilton (1959, 1960) has argued from data on sediment compaction (using techniques developed in soil mechanics) that layer 2 is sedimentary. Ewing and Nafe (1963) conclude from the observed thickening near volcanic islands that it is in part volcanic. The question is of interest for the age of the ocean basins, total amount of sedimentation, rates of erosion and geochemical balance calculations generally. However, the attempts to estimate the age of the ocean basins by sediment accumulation are subject to many variable factors, difficult to evaluate.

The interpretation of layer 1 as unconsolidated sediment seems to be generally accepted. There is a marked variation between the Pacific with about 0.5 km and the Atlantic with about double the thickness. If the Atlantic Basin is younger, this needs an explanation. The rate of sedimentation on the ocean floor has been extensively studied and the figure corrected for compaction, is about 1.0 mm/1,000 years. If layer 2 is volcanic material, then layer 1 represents the total accumulation of sediment on the ocean floor. An important observation is that the deep-ocean sediments are smooth, flat lying and undisturbed (Ewing and Ewing, 1965). If the sea floor is being moved laterally, no apparent large scale folding or crumpling seems to have occurred.
Talwani et al. (1965), and Le Pichon et al. (1965) have shown that the crust does no thicken under the mid-ocean ridges but thins slightly and that they are underlain by anomalous low-density material. Various interpretations of the gravity and seismic data are possible, but a layer of density 2.6 underlain by material with density 3.15 extending to 40 km is consistent with the data. Layer 2 is present over the axis of the ridge but layer 3 thins out and disappears.

*Deep-sea clays*

The extent of the deep-sea clays is large and they probably make up the bulk of layer 1. The geochemical interest in these sediments is that they contain very great concentrations of certain elements. Compared to normal shales, these clays contain more Mn, Mo, B, Co, Ni, Cu, Zn, Y and the rare earths Ba and Pb (Goldberg and Arrhenius, 1958; Wedepohl, 1960; Turekian and Wedepohl, 1961). Portions of these elements, e.g., Mn, Ni, Co, Zn, Cu, may be contributed by basic volcanic activity, and in addition some Ni and Co may be derived from meteoritic sources, but the high concentrations of lead and the rare earths are probably derived from weathering of continental rocks. The rare-earth pattern is similar to that of other sedimentary rocks (Haskin et al., 1965). If there is 1.0 km of this material on the ocean floor, it represents the accumulation of these elements from several kilometres of continental rocks. The high concentration of these elements points to long continued stability in the ocean basins. These clays have a Rb/Sr ratio of about 0.6 (Rb = 110, Sr = 180 p.p.m.).

Simple lateral movement of the dominantly basic oceanic crust beneath the continents does not solve the chemical problems of forming the more siliceous continental crust. In addition to simple accretion, chemical processing to give an overall composition of an intermediate igneous rock, is required. The volume of clay from layer 1 is too small to provide more than a small fraction of silicic rock. This material is mainly derived from weathering of continental rocks and the process is self limiting.

Production of andesitic rocks by partial melting of basaltic rocks in the mantle in orogenic areas would solve some of the chemical problems, and lateral movement of basaltic rocks in the mantle might thus provide a source for continental material, as suggested by Pakiser and Zietz (1965). The very low abundances of K, U, and Th in common oceanic basalts (Engel et al., 1965) are a serious difficulty for this hypothesis.

The second variation of lateral growth is the accumulation of sediment derived from the continents in areas adjacent to the continental margin. Typical present day examples are on the Atlantic coast of the United States and the Mississippi delta. This is also self limiting since the sediments are derived from the continents but undoubtedly this process makes a contribution, through recycling, to continental material.

*Vertical accretion*

The addition of material from beneath the continents will now be examined. Igneous activity suggests a mechanism in keeping with a Lyellian approach. The four main types of igneous activity are:

(a) Basaltic volcanism.
(b) Calc-alkaline volcanism, mainly andesitic.
(c) Formation of acid plutonic rocks such as granodiorites and granites.
(d) Acid volcanism, producing ignimbrites, and rhyolites.

Basalts are derived from the mantle and there is increasing evidence that andesites likewise originate in the upper mantle in orogenic areas (Taylor and White, 1965, 1966). It is not possible to derive the continents from weathering of basalts which occur in oceanic and continental regions alike.

Gilluly (1965) notes that there has been a nearly continuous record of orogenic sedimentation and volcanism in the western United States since the Cambrian: "Throughout most of Phanerozoic time the western part of the United States has been the site of orogenetic sedimentation and volcanism... Basaltic and andesitic volcanics are represented in every system and in most series... in general no direct connection with plutons can be demonstrated... The great batholiths of the west do not coincide areally with the belts of... thrusting... nor do they conform in time. Many orogenic belts active in Palaeozoic and Early Mesozoic time... have no associated granites... volcanism and tectonism have been more or less continuous in the Cordillera throughout Phanerozoic time but plutonism has been essentially independent of both processes in place and catastrophic in time." Gilluly (1963) states that the "vast masses of silicic plutonic and volcanic rock now occupying the former eugeosynclinal area near the Pacific cannot have formed by mobilising merely the material of the geosyncline, and its basement; they demand accretion from a differentiating mantle or from former sialic lands to the west".

Dickinson (1962) stated that andesitic volcanism has been widespread along the Pacific margin of the United States since the mid-Palaeozoic. He notes (p.1242) that the geosynclinal volcanics in the western United States are dominantly andesitic rather than basaltic in composition. "The more mafic rocks of the Late Mesozoic granitic batholiths of the Frazer Belt are chemically similar to the geosynclinal Jurassic andesitic rocks. The less mafic batholithic rocks have compositions that could probably be attained in melts formed by partial fusion of andesitic rocks" (Dickinson, 1962, p.1253). Dott (1965) has also noted the dominance of "continental" type andesites in the Cordilleran. "The long-supposed trends of volcanic and plutonic rocks in eugeosynclines from initially very mafic to progressively more felsic, implying a possible crustal evolution, are illusory (and) since mid-Palaeozoic time, western North American igneous rocks reflect a constant average tendency for andesitic composition, closely comparable with continental Tertiary andesites" (Dott, 1965, p.4702; cf. Tyrrell, 1955).

The evidence from workers in the western United States appears to be that andesitic volcanism has made a major contribution to continental growth. The question whether the more acidic rocks have been formed by partial fusion within the crust, or have been at least partly derived from the mantle, remains an open question. The limited occurrence of granodiorites in parts of the Aleutian Arc, well removed from continental crustal thicknesses (e.g., Ilak Island: Frazer and Barnett, 1959; Adak Island: Frazer and Snyder, 1959) indicate probable mantle derivation of these particular acidic plutonic rocks. In the proposed model for continental growth presented later in this paper, the view is taken that most granodiorites and granites originate within the crust and that direct derivation from the mantle is a minor source. This
view is based on extensive geological evidence for the crustal origin of these rocks (Tuttle and Bowen, 1958; Winkler, 1965).

Taylor and White (1965, 1966) suggested, from a study of geochemical and geological data, that andesites were derived from anomalous upper mantle in orogenic areas. The occurrence of andesites in island-arc environments such as the Aleutians (Coats, 1962) Marianas (Schmidt, 1957) and Solomons where sialic crust is thin or absent points to a mantle origin for these voluminous eruptive rocks. Sapper (1928) estimated that the yearly increment of volcanic material, mainly from orogenic areas, was about 1 km$^3$. This amount of $2-3 \cdot 10^{15}$ g is within a factor of two of the amount needed for continental growth.

The geological evidence may be summarized as follows:

1. Mountainous areas are destroyed by erosion in periods of a few million years.
2. Shield areas, once eroded to near base level, remain stable for long periods of time ($\sim 10^9$ years).
3. Continents have grown throughout geological time and are now more extensive than previously.
4. Calc-alkaline, mainly andesitic, volcanism is typical of orogenic areas.

**THE GEOCHEMICAL EVIDENCE**

*Crustal composition*

Recently Eade et al. (1966) have given an average composition of 200,000 sq. miles of the Superior province of the Canadian Shield. They used the samples collected during helicopter reconnaissance surveys and combined them into about 80 representative samples. About 2/3 of the area was amphibolite facies and 1/3 low granulite facies. Little difference in

**TABLE III**

Composition of crystalline shield rocks

<table>
<thead>
<tr>
<th></th>
<th>after Poldervaart (1955)</th>
<th>after Eade et al. (1966)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>66.4</td>
<td>65.8</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>15.5</td>
<td>16.4</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td>FeO</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>MgO</td>
<td>2.0</td>
<td>2.3</td>
</tr>
<tr>
<td>CaO</td>
<td>3.8</td>
<td>3.4</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>3.5</td>
<td>4.1</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>3.3</td>
<td>2.9</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.6</td>
<td>0.49</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>99.7</strong></td>
<td><strong>99.89</strong></td>
</tr>
</tbody>
</table>

*Direct sampling of 200,000 sq. miles, New Quebec area, Canadian Shield.*

Tectonophysics, 4(1) (1967) 17–34
### TABLE IV

Abundances of major elements in continental crust

<table>
<thead>
<tr>
<th>Composition* (%)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>60.18</td>
<td>61.90</td>
<td>63.1</td>
<td>59.4</td>
<td>60.3</td>
</tr>
<tr>
<td>Al2O3</td>
<td>15.61</td>
<td>16.66</td>
<td>15.2</td>
<td>15.6</td>
<td>15.6</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>3.14</td>
<td>3.44</td>
<td>-</td>
<td>2.3</td>
<td>-</td>
</tr>
<tr>
<td>FeO</td>
<td>3.88</td>
<td>3.87</td>
<td>6.0**</td>
<td>5.0</td>
<td>7.2**</td>
</tr>
<tr>
<td>MgO</td>
<td>3.56</td>
<td>3.50</td>
<td>3.1</td>
<td>4.2</td>
<td>3.9</td>
</tr>
<tr>
<td>CaO</td>
<td>5.17</td>
<td>5.35</td>
<td>4.1</td>
<td>6.6</td>
<td>5.8</td>
</tr>
<tr>
<td>Na2O</td>
<td>3.91</td>
<td>2.15</td>
<td>3.4</td>
<td>3.1</td>
<td>3.2</td>
</tr>
<tr>
<td>K2O</td>
<td>3.19</td>
<td>4.15</td>
<td>3.0</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td>TiO2</td>
<td>1.06</td>
<td>0.83</td>
<td>0.8</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Σ</td>
<td>99.70</td>
<td>99.85</td>
<td>98.7</td>
<td>99.7</td>
<td>98.8</td>
</tr>
<tr>
<td>FeO**</td>
<td>6.71</td>
<td>6.97</td>
<td>6.0</td>
<td>7.1</td>
<td>7.2</td>
</tr>
</tbody>
</table>


**All iron as FeO.

Composition was noted. The average is rather close to Poldervaart's (1955) estimate of the composition of crystalline-shield rocks based on several earlier estimates (Table III). There is accordingly a reasonable case to be made for the upper half of the crust in shield areas having a composition close to that of granodiorite.

The overall estimates point to a more basic composition. Estimates of the major elements based on different approaches are consistent with a value of about 60% SiO2 (Table IV).

Various additional lines of evidence point to an overall crustal composition consistent with these estimates. This is apparently unique to the continents and differs widely from both oceanic crust and mantle.

**The rare earths**

Recent studies of the rare-earth elements (Haskin et al., 1965) have confirmed the existence of two major patterns, one characteristic of the chondritic meteorites, and one of sedimentary rocks (Fig. 1).

The presence of the chondritic rare-earth pattern in some oceanic basalts (Haskin et al., 1965) may be interpreted as indicating that the overall rare-earth pattern is the same in the earth and the chondrites. The evidence that the composition of the earth for non-volatile elements, is similar to that of the type I carbonaceous chondrites, has been extensively discussed by Ringwood (1966a). Formation of basalts results generally in less severe fractionation than shown by the sedimentary pattern. Granites generally display a greater degree of fractionation than shown by the sedimentary pat-
Andesites and granodiorites commonly show rare-earth patterns close to the sedimentary pattern.

The latter pattern, which is typical of nearly all sediments, including the deep-sea clays, is apparently the result of mixing of the diverse patterns formed during crustal evolution and this represents the average pattern of the crustal rocks exposed to weathering. It is such a constant pattern that it is reasonable to suppose that it might be typical of the whole crust. The origin of such a distinctive rare-earth pattern must lie in the chemical processes producing new crustal material. The rare-earth pattern highlights the chemical problem of producing such fractionated material. It does not seem possible to produce such patterns by processes operating within the crust on chondritic type patterns unless the lower crust has rare-earth patterns complementary to the sedimentary patterns.

The strontium-isotope data

Some useful relevant data has been provided by the study of the strontium isotopes. The Rb–Sr decay is particularly useful because of the wide separation of Rb and Sr in many crustal processes as was pointed out by Ahrens (1948). The young oceanic basalts have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.702–0.704 indicating that they have been in a region with a Rb/Sr ratio of about 0.03 during geological time. Their observed ratios of 0.04–0.06 indicate recent fractionation of Rb relative to Sr as would be predicted in crystal chemical grounds. Hurley et al. (1965) at the Massachusetts Institute of Technology have measured a large number of ratios of continental rocks and they state that: "Continental volcanic rocks show initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios at the time of eruption, slightly higher than those in oceanic volcanics". The strong enrichment of Rb in crustal rocks, where Rb/Sr ratios of 0.25 are common, restrict the amount of remixing of crustal material with high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (> 0.710). The overall Sr data indicate that
Fig. 2. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, obtained by isochron plot of continental crustal rocks plotted against age. The lower line represents the enrichment of $^{87}\text{Sr}$ with time in the parent material of young oceanic basalts. (After Hurley et al., 1965.)

there is a major continuing addition to the near surface continental crust of material not enriched in radiogenic $^{87}\text{Sr}$. This evidence is consistent with an origin of continental material by accretion from the mantle and various estimates of the rate of growth have been made, including the areal growth of 7,000 km$^2$/10$^6$ years (Hurley et al., 1962).

The initial ratios observed for material erupted from the mantle place useful restrictions on the amount of Rb in the upper mantle. Hurley et al. (1965) have shown that: "Most continental crustal rocks have originated from a source region slightly richer in radiogenic $^{87}\text{Sr}$ than the mantle source of oceanic basalts but not nearly as rich in $^{87}\text{Sr}$ as the average continental crust itself" (Hurley et al., 1965, pp.191–192).

The figure published by Hurley et al. (1965) indicates average initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.706–0.710. These ratios would develop from Rb/Sr ratios of 0.04–0.06 in times of the order of 4·10$^9$ years. Thus the Sr-isotope data restrict the average Rb/Sr ratio of the source region for upper crustal material to about 0.05. If we assume a chondritic earth with about 10 p.p.m. Sr and if all this is concentrated initially in the upper 400 km (10%) then the maximum Rb content in this region cannot exceed 5 p.p.m. If all this Rb is subsequently concentrated in the crust this gives an overall crustal average of 50 p.p.m. This is sufficient only for about 20 km of granodiorite (100 p.p.m. Rb, 2.5% K) with no Rb in the lower crust. These figures are close to maximum estimates, and indicate that the overall continental crust is probably more basic than granodiorite.

One further consequence of the Sr-isotope data may be noted. Hurley's data from the continental rocks indicates that initial ratios of about 0.708 have been rather uniform with time (Fig. 2). This indicates that source regions of progressively lower Rb/Sr ratios have been sampled. The alternative model of crustal contamination to explain the high ratios should show an increase with time, as suggested by Hedge and Walthall (1963). The time plot in Fig. 2 is also a distance scale since in this North American example progressively younger areas are being sampled. This indicates the possibility that there is an inhomogeneous distribution of Rb relative to Sr in the uppermost mantle. If there was an original variation in the distribution of rubidium in the uppermost mantle, then reasonable geochemical arguments can be made for similar concentrations of other elements. The discussion in the next section indicates that elements such as barium, cesium, the rare earths, lead, and
Fig. 3. Postulated initial distribution of Rb and Sr in the uppermost mantle resulting from primitive geochemical fractionation. The distribution of K, U, Th, Ba, Cs and the rare earths is similar. Depletion of these elements during continental growth reverses this element distribution. In particular the heat producing elements, potassium, uranium and thorium would be expected to follow the rubidium distribution (Fig.3). Such lateral variations provide possible sites for the initiation of continental growth.

The heat-flow data limit these variations probably to less than a factor of two (Table I) but do not exclude such differences in the upper 100 km.

Chemical evidence for vertical segregation

The crustal rocks, the solar surface, and the meteorites are the only components of the solar system which we can directly analyse. There is some agreement that the overall composition of the non-volatile elements in the solar system is not very different from the composition of the type I carbonaceous chondrites. These are similar in composition to the ordinary or common chondrites for many elements. This gives us data appropriate to the composition of the whole earth. Recent determinations of the alkali elements K and Rb, as well as U and Th in carbonaceous chondrites have improved the fit for the chondritic model - using the crustal composition and the chondrite data we find that there has been a very strong upward concentration of certain elements within the earth, based on crystal chemical properties (Fig.4). Elements such as Mn, Fe, Co, Ni, Mg, and Cr, are mainly retained in the deep mantle. Elements whose ionic size, or valency, is different from these elements are strongly concentrated in the upper mantle or in the crust. Included in these elements are the alkalies, notably K, Rb and Cs, Ba, U, Th, the lighter rare earths, Zr, Hf etc. Many of these elements are strongly concentrated in the continental crust (Taylor, 1964a,b). Fig.4 shows the strong control by ionic size and valency on the crustal enrichment.

It is important to note that the heat producing elements K, U and Th all have properties which will exclude them from entry into the deep mantle phases, where close packing of the elements O, Si, Fe and Mg probably occurs. The mineralogical composition of the mantle according to Ringwood (1966b) is given in Table V.

The conclusion that this strong upward concentration has taken place is not very sensitive to the values used for the calculation, but appears as an overall systematic trend from consideration of crustal abundances in comparison with the overall composition of the earth based on a chondritic model.

In summary the geochemical evidence indicates that the continental crust has a composition of an intermediate igneous rock, that continental growth has occurred throughout geological time and that there has been strong upward concentration of the heat producing elements in the earth.
Fig. 4. Concentration of elements in the continental crust relative to the whole earth, assuming vertical segregation, an andesitic crustal composition (Taylor, in preparation) and a type I carbonaceous chondritic composition for the whole earth. The figures (3 - 8, etc.) refer to percentage concentration of the elements in the continental crust (see Taylor, 1964b). The elements depicted are the non-volatile elements which form mainly ionic bonds with oxygen. The strong dependence of upward concentration on the crystal chemical factors of valency and ionic size is striking. The elements in the "depleted" zone are those forming the major mineral phases in the mantle.

TABLE V

Mineralogical composition of the mantle, according to Ringwood (1966)

<table>
<thead>
<tr>
<th>Mantle regions</th>
<th>Depth (km)</th>
<th>Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper mantle</td>
<td>M-400</td>
<td>olivine, garnet pyroxene</td>
</tr>
<tr>
<td>Transition zone</td>
<td>400</td>
<td>Mg-pyroxene → forsterite + SiO₂ (stishovite)</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>forsterite → spinel structure</td>
</tr>
<tr>
<td></td>
<td>600-900</td>
<td>spinel → dense phases with octahedral coordination of Si</td>
</tr>
<tr>
<td>Lower mantle</td>
<td>900-2,900</td>
<td>close packing</td>
</tr>
</tbody>
</table>
The overall chemical evidence is suggestive of a crustal composition similar to intermediate igneous rocks. The low Rb concentrations, the overall rare-earth abundance pattern and the major element estimates are consistent with material of the composition of andesites. No single line of evidence points unequivocally to this composition, but such tests as are available are consistent with this suggestion.

MODEL FOR CONTINENTAL ORIGIN AND GROWTH

In conclusion, a simplified model consistent with the previous discussion, is presented:

1. The initial stage occurs during the final stages of separation of the core and the mantle. The large cations such as the alkali elements, U, Th, Pb and all the elements unable to enter the close packed deep mantle phases, accumulate in the upper 1,000 km. This stage constitutes the initial geochemical fractionation of the earth. All subsequent geological activity is concentrated in the upper mantle and crust.

2. The lateral distribution of the elements in the uppermost part of the mantle is not uniform. These differences are probably not large. Vertical as well as lateral variations are implied by the overall equality of the heat-flow data. The areas with the highest concentration of K, U and Th (and other associated elements) are the sites where continental nuclei develop. A complex cycle of vulcanism and degassing is initiated. This process depletes the upper mantle in radioactive and other elements, causing lateral chemical inhomogeneity, and further crustal growth.

3. Continental areas grow laterally mainly by the addition of andesites from the upper mantle in orogenic zones. Basalts and more silicic rocks (dacites, and possibly some rhyolites and granodiorites) are also derived from the mantle, and contribute to continental growth. The igneous rocks are weathered, go through a geosynclinal stage of sedimentation, deep burial, metamorphism and formation by partial melting of granodioritic and granitic plutonic rocks, and acid eruptives (ignimbrites and rhyolites), leaving a more basic residuum, which may approximate to anorthosite, in the lower crust. This process must take place within a few hundred million years to account for the evidence from strontium-isotope ratios.

The end product is a stable shield area, the upper portion approximating to granodiorite in composition with a gradual downward change. The mantle beneath the continental areas is depleted in the radioactive elements, causing differential heating and stress at the continental-oceanic boundary. Erosion removes thicknesses of several kilometers from the orogenic areas during their conversion to shield areas, thus reducing the concentration of radioactive elements and lowering the heat flow. The depletion of heat sources in the mantle beneath the shields results in a cessation of orogenic activity.

This proposed model of crustal origin and growth is much simplified but several aspects are open to geological and geochemical testing. A major purpose of the model is to draw attention to various geochemical problems in orogenic areas and to stimulate investigation of the composition of the continental crust.

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