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Mean crustal velocity: a critical parameter for interpreting crustal structure and crustal growth

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Mean crustal velocity is a critical parameter for genesis of continental crystalline crust because it is a function of mean crustal composition and therefore may be used to resolve continental crustal growth in space and time. Although the best values of mean crustal velocity are determined from wide-angle reflection measurements, most studied here necessarily come from vertical averages in crustal refraction determinations. The mode of 158 values of mean crustal velocity is 6.3 km/s, a velocity which corresponds to a mean crustal composition of granodiorite to felsic quartz diorite; Archean crust may be slightly more mafic. Mean crustal velocities range from 5.8 to 7.0 km/s. The lowest values invariably are found in thermally disturbed rift zones and the highest values correspond to velocities in gabbro. Velocities in island arcs may be as low as 6.0 km/s but are typically 6.5–6.9 km/s which corresponds to andesitic composition; estimates of island arc composition are andesitic. If values of mean crustal velocity are not biased, this observation suggests that continental crust did not grow simply by addition of island arc material. Possibilities are that crust formed from fusion of island arcs and was later changed to more felsic composition by addition of material from the mantle or that the late Archean episode of major crustal growth did not involve processes similar to younger island arcs. Some crustal blocks might be changed in composition and thickness by such processes as underplating, interthrusting, necking and sub-crustal erosion. Specially designed experiments are suggested to determine this parameter so critical for understanding genesis of continental crust.

1. Introduction

The compositional variation of continental crust in space and time is a critical parameter for the study of crustal genesis. We would, therefore, like to know crustal composition and how it varies from one region to another. Seismic velocity is commonly used to estimate composition of unexposed portions of the earth and, though composition cannot be determined uniquely from velocity, velocity measurements offer our only chance, short of drilling or unusual exposures such as the Ivrea zone, to determine overall crustal composition. Mean crustal velocity ($\bar{V}$) may, therefore, be used to estimate mean crustal composition in any given area leading to estimates of overall continental crustal composition and may be determined from velocity measurements in crustal refraction or reflection studies. Although these data have not been collected specifically to attack this problem, they may be used to place constraints on crustal genesis such as mean composition of the material derived from the mantle to form the crust and spatial and temporal variations in crustal composition, i.e., does crustal composition change from Archean continental nuclei through progressively younger belts?

2. Methods to determine mean crustal velocity

Almost all crustal velocity determinations are based on refraction methods [1–3]. This has the two following disadvantages: (1) the method does not readily detect velocity reversals which must be present in the crust, (2) the method averages crustal properties over a wide area on horizontal paths along a slant section through the crust (greater depths are sampled at greater distances from the source). The ability of the seismic reflection method to measure velocity variations including velocity reversals is well known [4,5] and is regularly used and developed to a fine degree in seismic exploration. Not many seismic reflection determinations of crustal velocity are available except for Soviet DSS-type surveys whose interpretation is based on wide-angle reflections as well as refractions so that deep reflection velocity measurements may be produced [6,7]. Most modern refraction interpretations also utilize reflections, particularly to resolve velocity reversals [3,7,8] if the surveys were recorded with enough detail. Most of the mean crustal velocities presented will, of necessity, be based on the value averaged from a number of layers below the sedimentary section interpreted from refraction data or, in some cases, directly from published values of mean crustal velocity. Most of the published refraction velocities for layers are boundary velocities and do not include velocity variations within each layer. When reflection surveys are designed to measure crustal velocities in specific areas to resolve certain problems, more significant conclusions may be drawn.

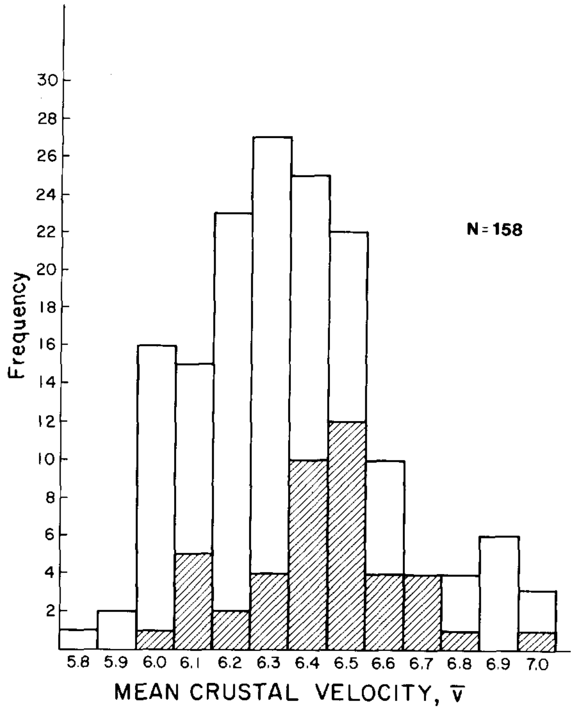

Fig. 1. Histogram showing frequency of occurrence of mean crustal velocity values. Note preponderance of low mean velocities that would correspond to quartzofeldspathic rocks. 158 samples of which 44 are from Archean terrains. Open bars represent all terrains; lined bars represent Archean terrains only. Archean terrains show slightly higher values of mean crustal velocity; therefore, seem to be slightly more mafic.

3. Mean crustal velocity

A total of 158 mean crustal velocities are calculated from a wide range of sources, primarily references 1–3,6, and appear in Fig. 1. Of these, 34% come from North America, 33% from Europe, 20% from Asia, 4% from Africa, 4% from Australia, 3% from South America and 2% from Antarctica.

Velocities range from 5.8 to 7.0 km/s and are skewed toward the low values; the most common value is 6.3 km/s with most values in the range 6.2–6.5 km/s. One 7.0 km/s value, appropriately enough, comes from Iceland where crust is basaltic, and another comes from Africa. Crustal velocities in Precambrian shields are variable and show high velocities of 6.5–6.8 km/s in the Canadian shield and low values of 6.1 km/s in the Indian, South African and Fennoscandian shields. Mean crustal velocities of orogenic areas have wide ranges. The Alps have a mean velocity of 6.25 km/s [3] conditioned by a low-velocity mid-crustal zone that may be partially melted and by lower-crustal velocities distinctly greater than 7 km/s.

Mean velocity is high (6.5–6.9 km/s) in Alaska, Puget Sound and Peru. High velocities are found in the stable eastern U.S. and low velocities occur in the tectonically active western U.S. [9]. Areas of high heat flow associated with rifting and mantle diapirism have low crustal velocities of 6.0–6.2 km/s which accounts for the relatively large number of values around 6.0 km/s; these velocities are a function of temperature as well as composition. The Hercynian orogenic areas of Western Europe are characterized by rather low crustal velocities ranging from 6.1 to 6.3 km/s; this may be related to the relative detail of the data in this area where interpretations commonly include crustal low-velocity zones [3]. Low velocities around 6.0–6.3 km/s are found in the Japanese island arc [1], but most parts of island arcs such as the Aleutians, Tonga, Puerto Rico, Sakhalin and Japan may have high velocities [10–12] of 6.7–7.1 km/s indicating that crust formed from a basaltic to andesitic pile. Thermal effects could bias velocities in island arcs toward the low side by 0.1–0.2 km/s [13]. Mean crustal velocity shows great variation but is usually less than 6.5 km/s.

4. Velocity and composition

Mean crustal velocities exhibit a mode of 6.3 km/s, and 45% of the values range from 6.2 to 6.4 km/s. The chemical composition corresponding to this velocity, even though it cannot be determined uniquely, represents a good estimate for mean crustal composition. We must consider other factors besides composition that affect velocity; these are pressure, temperature, fluids and anisotropy. Seismic P-wave velocity increases rapidly with depth in the upper crust as cracks are closed by increased pressure [14], but the effect of temperature is to decrease velocity with increasing depth. Estimates of the temperature effect in stable crust where the temperature at the Moho is about 400°C [15,16] suggest that below around 20 km depth the effect of temperature and pressure on P-wave velocity approximately cancel each other and in the lower (> 30 km) crust temperature effects could cause velocity to decrease by about 0.1 km/s below values determined at high pressure alone [13,17], so that measured velocities in rocks at several kilobars pressure may be used to estimate composition. The biggest unknown is the presence of overpressured fluids in zones of the crystalline crust which might cause dramatic decreases in velocity [18] that are unrelated to changes in composition; this might account for the upper-crustal low-velocity zones [19] reported from some areas [2,3,8]. The effect of dehydration as a rock passes from amphibolite- to granulite-facies mineralogy could be to increase the seismic velocity by 0.1–0.2 km/s [20] without changing composition except for H_2O. Anisotropy, particularly in metamorphic rocks, could result in variations of about 2–15% between slowest and fastest directions in rocks such as granulite and amphibolite [17,21] and 5% is a plausible value for a typical sequence of rocks with constant attitude. If structures in the deep crust are highly contorted, effects of anisotropy probably average out. But, if subhorizontal structures are common in the deep crust [22], then velocities could be 0.2–0.3 km/s higher in one horizontal direction than in the vertical direction and refraction methods could be sensing higher velocities than reflection methods. Because of our lack of detailed knowledge of the crust, the importance of the above effects is difficult to judge quantitatively. To some extent, these various effects tend to cancel each other. Probably none of the above factors would affect the overall conclusions of this study with the exception of a thick overpressured zone about which we have little knowledge at present.

Another approach would be to extract detailed composition information from reflection coefficients [23] or from imaging velocities [24,25]. This could ultimately produce a much higher resolution picture of crustal compositional variation. This approach based on numerous deep reflections has been used qualitatively to infer that lower crustal composition must be more felsic than gabbro [26].

Velocities measured in laboratories range from 6.0–6.2 km/s for granites to 7.0–7.4 km/s for gabbros and pyroxene granulites [13,20,27]; therefore, a mean crustal velocity of 6.3 km/s correspond to quartzofeldspathic rocks, granodiorite or possible relatively felsic quartz diorite. A charnockite (anhydrous garnet- and/or pyroxene-bearing granite) might have a slightly more felsic composition for the same velocity [20] and charnockites are probably common in the deep crust along with other granulites.

A reasonable estimate of mean crustal composition [22] is shown in Table 1. A mixture containing 50% granite (6.1 km/s) and 50% gabbro (7.1 km/s) would have a mean crustal velocity of about 6.6 km/s, distinctly higher than that suggested by this compilation. This result is expected because lower crustal velocities are commonly around 6.7 km/s corresponding to diorite (andesite) not gabbro. Another approach to mean crustal composition is

TABLE 1

Estimates of composition (%)

	Mean crustal composition (Smithson [22])	Mean crustal composition (Ronov and Yaroshevsky [30])	Mean crustal composition (Pakiser and Robinson [9])	Mean island arc (Jakeš [31])	Weighted average Little Sitkin Island, Aleutians (Dickinson [32])	Kurile Islands (Dickinson [32])
SiO_2	63.0	61.9	57.8	58.8	57.1	59.3
TiO_2	0.7	0.8	1.2	0.8	0.8	0.8
Al_2O_3	15.8	15.6	15.2	15.6	17.3	17.4
Fe_2O_3	2.0	2.6	2.3	2.6	3.2	3.5
FeO	3.4	3.9	5.5	5.0	4.7	4.2
MnO	0.1	0.1	0.2	0.1	–	–
MgO	2.8	3.1	5.6	4.6	4.3	3.5
CaO	4.6	5.7	7.5	8.0	8.4	7.2
Na_2O	4.0	3.1	3.0	3.4	3.1	2.9
K_2O	2.7	2.9	2.0	0.8	1.1	1.2
	Kamchatka (Dickinson [32])	Sierra Nevada Batholith (Dickinson [32])	Southern California Batholith (Dickinson [32])	Volcanoclastic sandstone, Oregon (Dickinson [32])	Quartzo-feldspathic graywacke, Franciscan, California (Dickinson [32])	Lower crust (Smithson [22])
SiO_2	56.5	69.3	64.6	58.3	72.5	59.0
TiO_2	0.8	0.4	0.6	0.8	0.5	0.8
Al_2O_3	18.0	15.5	16.7	18.1	13.9	17.1
Fe_2O_3	4.2	1.4	1.3	2.3	1.2	2.0
FeO	4.6	1.9	3.8	4.6	2.8	4.1
MnO	–	–	–	–	–	0.1
MgO	3.4	1.2	2.4	3.4	2.2	3.4
CaO	8.1	3.2	5.3	5.9	1.5	7.0
Na_2O	3.1	3.4	3.3	4.0	3.6	3.9
K_2O	1.3	3.7	2.0	2.6	1.8	1.9

to study the Ivrea zone, a probable section through the crust where quartzofeldspathic rocks predominate in the upper crust and where lower crust consists of alternating granitic and gabbroic gneisses [28]. Only the lowermost several kilometers are gabbroic. The Ivrea zone would have a mean velocity of about 6.3 km/s [29] and a quartzofeldspathic mean composition. The mean crustal composition, proposed in this study based on mean velocities, is slightly more felsic than that proposed by Ronov and Yaroshevsky ([30] and Table 1) and much more so than that suggested by Pakiser and Robinson ([9] and Table 1).

Equally important as the mean crustal composition is the variation in composition which is reflected in velocities that range from 6.0 to 7.0 km/s. The lower value represents a crustal section of granite and the higher values represent a gabbroic crust such as Iceland. A velocity of 6.7–6.8 km/s represents an andesitic composition. A compilation restricted to Archean crustal velocity determinations (where at least one half of the profile lies in Archean crust) shows that mean crustal velocities are 6.4–6.5 km/s (Fig. 1). Rogers [33] suggested that Archean granitic terrains were more mafic than Proterozoic ones. This difference is supported by this compilation, but some studies in Canada [34] suggest that younger crust is more mafic. On the other hand, the Hercynian crust of Western Europe has low mean crustal velocities of 6.1–6.4 km/s, and such a low velocity implies an essentially granitic mean composition. These low values, however, may be influenced by the method of velocity determination because European workers use wide-angle reflections and detailed refraction interpretations that commonly involve low-velocity layers. Spatial variations of crustal velocity might reflect important differences in generation of crustal material such as crustal differentiation to form granitic batholiths, underplating, or obduction of ophiolites. Hence, spatial and temporal variations in crustal composition derived from crustal velocities are clearly decisive parameters for crustal growth.

5. Velocity and composition of island arcs

Numerous authors [32,35] have suggested that continents expand by addition and fusion of material from island arcs; information on velocity and composition of rocks from island arcs is essential to evaluate this hypothesis. Compositional estimates are difficult and will clearly be influenced by depth of exposure. Compositional estimates of island arcs, fore-arc sedimentary rocks, arc andesites and arc intrusives appear in Table 1 together with our average proposed crustal and lower crustal compositions. The first point observed from Table 1 is that mean compositions estimated for island arcs are essentially the same as andesite. A comparable mean crustal velocity would range from 6.7 to 6.8 km/s [27]. Mean velocity in the Japanese arc ranges from 6.0 to 6.7 [1,10] and most values fall between 6.0 and 6.3 km/s which would correspond to felsic granitic rocks if not greatly thermally disturbed; some studies show this range in a single profile. The high value is on the western flank of the arc. Velocities on the south flank of Sumatra are 6.5–6.8 km/s [12,36] for crystalline rocks; in Melanesian arcs the velocity is 6.7–7.1 km/s [12,37] and for Puerto Rico the velocity is 6.9 km/s [12]. In the Hokkaido-Kamchatka-Sakhalin-Kurile region, velocities are higher and more variable ranging from 6.2 to 6.7 km/s; the higher velocity is appropriate for andesitic mean composition. Mean velocity in 50-km-thick crust of the Sierra Nevada, a presumed former island arc is 6.6 km/s [38] where granitic rocks (of composition given in Table 1) crop out. Abnormally low-heat flow in this area could result in slightly higher velocity (about 0.1 km/s) relative to the mean composition for this area. After 10 km of erosion to more normal crustal thickness of 40 km, mean crustal velocity would be 6.8 km/s, a value appropriate for the large volume of mafic rocks inferred below the Sierra Nevada batholith from refraction interpretation [38].

The following conclusions may be drawn: (1) mean velocities in island arcs suggest compositions ranging from granitic (6.2) to andesitic (6.7), (2) this same velocity (compositional) range may be present in one island arc and indicates significant lateral variation, (3) if the Sierra Nevada, a former island arc, were eroded about 10 km to a normal (cratonic) crustal thickness it would have a mean velocity of 6.8 km/s. This is far higher than mean velocities observed in most continental crust (Fig. 1), and either normal crust is more felsic than typical island arcs [22] or the overall composition of island arcs is actually less mafic than estimates quoted from different workers in Table 1.

6. Discussion

This study points out important conclusions about crustal genesis that may be drawn from mean crustal velocity, but we must remember that data necessary for the most important conclusions are not available in many cases. More wide-angle reflection measurements of crustal velocity, designed to resolve specific problems, are essential to answer many central questions about crustal genesis. Such measurements offer the advantage of sensing velocity reversals and of spanning a relatively restricted lateral extent of the crust so that lateral variations in velocity (composition) may be determined. Determining velocity to intermediate crustal reflectors would develop a much more detailed picture of crustal structure. These specifically designed studies could be planned to answer such questions as variations in crustal composition across suture zones, lateral variations of island arcs (granitic intrusives into a framework of mafic volcanic rocks), Archean crustal variations in granitic gneiss terrains and greenstone belts, crustal structure of granulite terrains, derivation of granitic gneisses by crustal anatexis leaving behind a garnet-pyroxene residuum, and crustal growth in general.

Two major questions involved are: (1) spatial variation of crustal composition, i.e., what are we dealing with; (2) temporal variation of crustal composition, i.e., crustal dynamics. The first leads to an understanding of the second. Lateral variations in crustal velocity and composition clearly exist. Some of these may be related to compositional change across a single island arc; others are related to crustal blocks of different ages.

Structural units of an island arc that might be expected to show different velocities and composition are the forearc basin, the andesitic pile, the axial intrusives [32] and the backarc basin so that velocity variations determined from island arcs may correspond to the different structural elements [10,11]. Seismic profiles across island arcs certainly show variations in the intrusive zone and the backarc basin [10]. Sedimentary rocks of the forearc basin show wide composition ranging from andesite to quartz monzonite [32, p. 819]. Buried dewatered sediments in modern forearc basins have velocities of 4.7–4.9 km/s. Once these rocks are recrystallized they might result in crustal velocities ranging from 6.1 to 6.7 km/s [29]. Franciscan crust in California shows velocities from 4.5 to 6.0 km/s [39,40] whereas the adjacent Sierran crust representing the core of an island arc has a distinctly higher velocity of 6.6 km/s [38]. Velocity along the intrusive axis of an island arc could range from 6.2 to 6.6 km/s and depends on the size of the mafic root (residuum?) underlying granodioritic intrusives. The Sierra Nevada granite axis shows a high mean crustal velocity and is underlain by a tremendous mafic root; if this is typical, the intrusive axis would be marked by a crustal velocity only slightly lower than an andesitic pile. Crust formed in a backarc basin could have a crustal velocity around 6.5 km/s if significant amounts of basaltic lava are extruded. Clearly overlap in velocity exists between the structural units of an island arc; the velocity found in any given area will depend on the specifics of genesis and on the depth of exposure.

Composition and velocity of crustal blocks probably vary with age (history) as suggested for Canada [34], Antarctica [41] and for the western U.S. [42]. Whether a progressive change in composition becoming more felsic with decreasing age [24] takes place needs further study [34,42].

Considerable lateral variation in velocity (6.5–7.0 km/s) is present in the lower crust, especially in data based on DSS-type studies [6,7]. Deep reflections [43–46] are evidence for vertical variation in composition of the deep crust. Velocities of 7.3–7.5 km/s are reported sporadically for the lowermost crust [3,47]. This could represent mafic rocks from original oceanic crust metamorphosed in pyroxene-granulite facies similar to garnetiferous granulites found in the Ivrea zone [28,29]. In some areas along the Alpine chain, two Mohos separated by rock with a lower crustal velocity of 6.8 km/s have been found [48,49]. These are apparently formed by interthrusting along a collision zone.

Major questions concern the nature of crust beneath granulite terrains. Granulites may form by partial melting and differentiation in the lower crust [50]. Because the felsic components may be driven off in melt along with U and Th during the formation of granulites, they might be more mafic and exhibit higher velocities than other crustal rocks. In fact, some granulite terrains are mafic and others are essentially granitic and they are not necessarily depleted in large lithophile elements [51]. Granulitic rocks have slightly higher velocities than the similar rocks in lower metamorphic grade [20] so that, for a given velocity, a section of crust consisting of granulite-facies rocks is probably more felsic than for a similar velocity in other rocks.

How does velocity vary with crustal age? If Archean crust is more mafic as has been suggested [33], such a composition should be expressed as a higher mean crustal velocity (Fig. 1). Is the deep crust beneath old Archean gneisses in Greenland the same as crust beneath Archean gneisses in other areas such as Minnesota or South Africa? The work of Mooney and Prodehl [8] and Soviet DSS studies [6,7] show abruptly changing crustal velocity structure where adequate detail is available; therefore, well-planned high-resolution studies are suggested. Also, original velocity structure may be altered by later events. This study suggests that island arcs may have higher velocities than older continental crust, but the final answer to this question must await studies specifically designed to resolve the question.

Particularly interesting is the question of crustal dynamics. Once created, how does continental crust change through time? What are the roles of crustal thickening by underplating, crustal thickening by interthrusting, crustal thinning by subcrustal erosion, crustal thinning by crustal necking and intracrustal differentiation compared with mantle differentiation?

Clearly earlier crust must be thickened by later processes. This might occur by interthrusting associated with horizontal compression as has been suggested for the Archean of Greenland [52]. This process probably would not greatly change overall crustal composition and velocity. Thickening by ductile compression might have the same effect on a large scale. Continental collision could result in underthrusting of one continental block (and even two Mohos [3]) and result in crustal thickening such as has been suggested for the Alpine belt [53].

Crustal underplating with basaltic magma is another means suggested for crustal thickening [54]; e.g., if early Archean crust were thin [54], it could later be thickened by this mechanism. This is also one means of explaining sub-horizontal reflections that seem to be common in the deep crust [22], but underplating may be ruled out for depths at which complex reflection patterns are found [45]. This proposed mechanism may not generally be viable but underplating is an attractive mechanism for crustal thickening in at least several areas. These are the High Plains of eastern New Mexico and Krivoi Rog in the Ukraine. Both of these areas are stable craton with great crustal thickness of 50–55 km. High velocities appropriate for gabbro are found in thick zones in the lower crust and isostatic considerations require crust in these areas to be more mafic. This process allows for crustal thickening through time and would clearly result in relatively mafic crust with high mean crustal velocity.

As opposed to crustal underplating, subcrustal erosion might take place and has been suggested for the Pannonian Basin [55] where the lower crustal "layer" is thin. This process, associated with mantle diapirism and basin formation in this area, would result in thinner crust of more felsic composition and lower mean velocity (6.2 km/s). This raises a question whether crustal compositional (velocity) anomalies are related to basin formation or whether basin formation is solely related to deeper changes in the lithosphere.

Crustal thinning by necking accomplished through brittle deformation in the upper crust and ductile flow in the lower crust takes place in intracontinental rifts and Atlantic-type continental margins [56]. This process by itself probably is not associated with any significant change in crustal composition or velocity but these areas may be associated with basaltic magmatism which renders the crust more mafic. On the other hand, rift zones are marked by exceptionally low mean crustal velocities (5.9–6.2 km/s) which are transient phenomena caused by transient thermal effects. The mean crustal velocity and composition in these active zones depends on where one places the Moho because they are invariably underlain by anomalous mantle (or deep crust).

Mean crustal velocity measures mean composition of material differentiated from the mantle to form continental crust minus the continent-derived material in the oceans. More detailed seismic studies of intracrustal velocity (composition) structure integrated with geology and geochemistry can indicate the extent of intracrustal differentiation from the mantle or a multistage differentiation [48]; i.e., to what extent do metamorphism, metasomatism and ultrametamorphism (partial melting) affect crustal differentiation?

7. Conclusions

The point of this study is to stress the importance and potential of mean crustal velocity as an interpretative tool in understanding crustal composition rather than to make detailed interpretations from the data. Mean crustal velocity is our only widely applicable measure of mean crustal composition, and therefore, of continental crustal growth in space and time. Most of the data that must be used was not acquired in a manner designed to attack this problem; therefore, most effective use of this parameter is not presently realizable and must await wide-angle crustal reflection studies which are designed specifically to measure this parameter for particular tectonic regimes and age provinces. Conclusions based on this parameter will become more certain as measurements of crustal velocity are designed to attack specific questions.

The most common mean crustal velocity is 6.3 km/s; this corresponds to compositions ranging from granodiorite to felsic quartz diorite. Archean crust may be slightly more mafic. Such a felsic composition (low velocity) for many crustal blocks is further evidence that the lower crust is not basaltic but more andesitic in average composition [51,57] and that no widespread Conrad discontinuity exists even though some segments of deep crust are certainly basaltic. Based on these low mean velocity values, the mean composition of continental crust, including Archean crust, certainly cannot be andesitic [58]. Estimates of island arc composition which correspond to andesite (Table 1) are clearly far too mafic to correspond to this velocity. If the data are not biased, this suggests two possibilities: (1) estimates of island arc composition based on surface exposures are too mafic, (2) most continental crust grew by some means other than accretion of island arcs. In support of this first possibility, unexpected dioritic to granodioritic intrusives along the axis of the volcanic arc may well render these estimates somewhat too mafic. In support of the second, velocities in a former volcanic arc [38] of the Sierra Nevada are distinctly higher than common crustal velocities, crustal xenoliths in Japanese lavas are basaltic and primitive island arcs like the Aleutians are basaltic [59]. These facts leave us with the conclusion that, while some island arc surface-compositional estimates could be too mafic, island arc composition is still too mafic to correspond to much of the continental crust. Also, we should remember that erosion of the ediface of a former volcanic arc to normal crustal thickness could leave behind the more mafic deep part of the arc. Continents grow, in part, by accretion of a sedimentary wedge on the outside of the island arc [32] and sedimentary rocks are carried to great depths in the crust [60], but these sediments are derived from pre-existing crustal material, primarily in the magmatic arc. Most crust has a composition different from island arc composition. Neither basaltic nor andesitic magmatism alone can form continental crust. We must, consequently, consider the strong possibility that much of continental crust formed by different processes than those presently attributed to continental accretion or that early crust formed from island arcs has subsequently been altered in composition by addition of more felsic material from the mantle [22] or by other "secondary" processes (subcrustal erosion, underplating, etc.) discussed in this paper.

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