GEOCHEMISTRY

Early Evolution of Continents

A. W. Hofmann

Geochemists have been trying to unravel the earliest history of Earth ever since the discovery of radioactivity provided us with clocks built into rocks. This has turned out to be an extraordinarily difficult quest. Were it not for the occasional fall of meteorites, which are remnants of planetesimals dating back to the formation of the solar system, we would not have been able to measure the age of Earth itself. Earth underwent a highly complex evolution that has obscured the first half billion years of its history. Thus, although we know that Earth is 4.5 billion years old, the oldest crustal rocks we can find are less than 4.0 billion years old, and consequently, we have no direct evidence of any geological record of the first 500 million years of our planet. Nevertheless, geochemical methods are beginning to give answers to some questions about the early evolution of continental crust and the mantle beneath. On page 521 of this issue, for instance, Sylvester *et al.* (*1*) analyze 2.7-billion-year old volcanic rocks from Australia to show that the amount of ancient continental crust then in existence is the same as today.

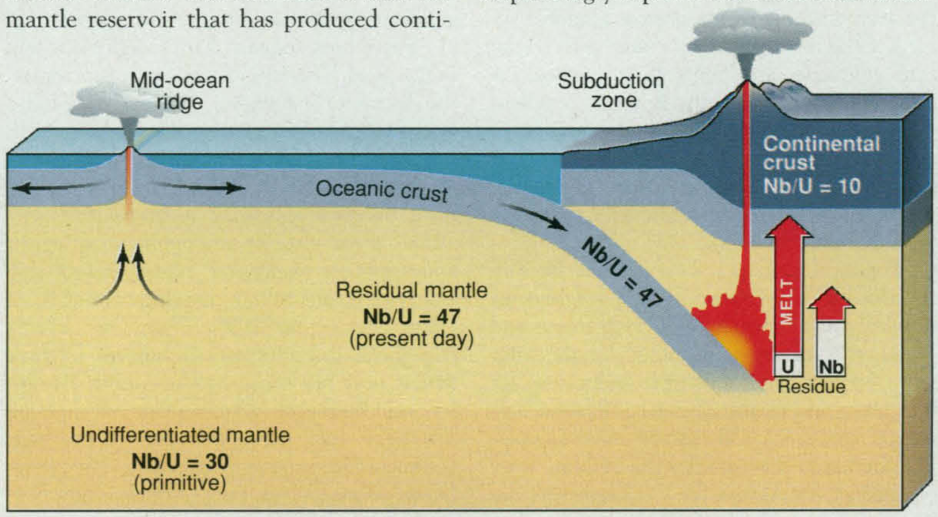
A debate about the evolution of the continents has gone on for nearly 30 years. Did continents of mass and area similar to those of today exist during the early period only to be destroyed by erosion and subduction in the course of plate tectonic processes? Or was continental crust first formed about 4 billion years ago, with gradual, and more or less irreversible, growth in volume and area ever since (*2*)?

In principle, this debate can be resolved by measuring the abundance of the neodymium isotope ^{143}Nd, the decay product of the radioactive samarium isotope ^{147}Sm, in crustal rocks of different ages. Because the crust has a systematically lower Sm/Nd ratio than the mantle from which it is formed, the ratio of radiogenic to nonradiogenic Nd, $^{143}Nd/^{144}Nd$, is also lower in sedimentary rocks than in the mantle. This relation can be used to calculate a "crustal residence" age, which is the average length of time the source rocks of the sediments have resided in continental crust (as opposed to Earth's mantle).

Present-day sediments yield crustal residence ages of about 1.5 billion years, but sediments deposited more than 3 billion years ago have crustal residence ages not much greater than their deposition age. This difference indicates that at the time, all of the continental material in existence was quite young and that much older continents simply did not exist. An alternative explanation is that the continental crust has been in a steady state, with rapid formation and destruction in the first 500 million years and a gradual slowdown of this creation-destruction process ever since. As a result of this early rapid recycling, ancient crust would simply have had a short life cycle, but there would nevertheless be just as much continental crust in existence as there is today. The upshot is that isotope studies have so far not provided a clear answer to the question of whether the mass of the continental crust has irreversibly grown over geological history or whether it has maintained an approximately constant mass in a steady-state process of creation and destruction.

Other workers have measured Nd isotopes in volcanic rocks derived directly from the ancient mantle. The idea here is that the mantle reservoir that has produced continental crust with low Sm/Nd ratios will have a correspondingly higher Sm/Nd ratio. Therefore, this reservoir should generate higher $^{143}Nd/^{144}Nd$ ratios than an undifferentiated reservoir. Such high ratios have indeed been found in many Archean volcanic rocks. This finding is at least consistent with the hypothesis that a sufficient mass of continental crust existed before the eruption of the volcanics to generate a mantle reservoir with a high Sm/Nd ratio. Nevertheless, these results have been controversial, in part because the same increase in $^{143}Nd/^{144}Nd$ can be produced by a high Sm/Nd ratio over a short time span or by a much lower Sm/Nd ratio over a longer time span. In addition, the initial $^{143}Nd/^{144}Nd$ ratios of these rocks must be calculated back from present-day measured ratios (using the known or assumed age and the Sm/Nd ratio), and this extrapolation amounts to wagging a rather large dog by a small tail, particularly when the rocks have been affected by younger metamorphic episodes (which can subtly change Sm/Nd ratios).

An alternative approach to the above isotope studies is to look at the chemical composition of the mantle from which the continental crust was formed. Many trace elements, such as thorium, uranium, niobium, tantalum, and barium, are highly concentrated in the continental crust and highly depleted in the mantle reservoir from which this crust has been extracted. Therefore, if there was a large volume of continental crust in existence in ancient times, there must also have been an extensive mantle reservoir correspondingly depleted in the same elements.



Rock of ages. Major reservoirs of niobium and uranium in Earth. (**Left**) Mid-ocean ridge model in which the lower mantle has not been significantly differentiated and has retained its "primitive" Nb/U ratio. The upper mantle has produced continental crust, a process that extracts U much more efficiently than it does Nb; thus, the crust has a much lower Nb/U ratio than the primitive value of 30. (**Right**) Melt generation and crustal growth in a subduction zone, which ultimately produces new crust. The boxes with arrows labeled U and Nb illustrate the more efficient extraction of U through the melt, whereas a greater fraction of Nb remains in the solid residue and mantle. The Nb is retained in the mantle by minerals that are stable, especially in subduction regions of mantle melting. These minerals are generally not stable in other mantle melting environments such as the mid-ocean ridge or oceanic islands. Therefore, Nb and U are taken up by the normal mantle melts with equal efficiency, so that the Nb/U ratio in the melt remains the same.

The author is at the Max-Planck-Institut für Chemie, Postfach 3060, 55020 Mainz, Germany, and is a visiting investigator at the Institut de Physique du Globe, 4 Place Jussieu, 75252 Paris, France. E-mail: hofmann@geobar.mpch-mainz.mpg.de

The difficulty here is that we cannot look at ancient mantle directly (since we have no samples of it); we must instead reconstruct the state of early mantle depletion from volcanic rocks, usually basalts, that were created by the melting of this mantle.

Although it is nearly impossible to infer the absolute concentrations of trace elements in a mantle region from the concentrations in the basalts formed in that region, it is comparatively easy to determine the concentration ratios of such elements in the melting region from the ratios measured in the basalts. The Nb/U ratio is particularly useful in this respect because its value has been changed from an original Nb/U = 30 in the mantle before continent formation (inferred from analyses of stony meteorites) to a value of Nb/U = 47 in the present-day mantle (3). This change is clearly related (and complementary) to the formation of the continental crust, which has a value of Nb/U = 10 (see figure).

Sylvester *et al.* (*1*) have used this "diagnostic" ratio to show that basaltic rocks from a 2.7-billion-year-old region of Western Australia were derived from a mantle source with a Nb/U ratio (= 47) that is indistinguishable from that of modern mantle rocks. The only previous attempt to study the Archean mantle in this fashion yielded rather ambiguous results, seemingly indicating that the mantle at that time had an Nb/U ratio closer to the value of the undifferentiated Earth (4). In that study, a wide variety of ancient volcanic rocks from various localities had been analyzed. Sylvester *et al.* adopted a different strategy and decided to do a very systematic study of a single formation. They found that the apparently scattered results were caused by small but variable amounts of contamination of the lavas by crustal rocks, which would tend to lower the Nb/U ratios and bring some of them close to the "primitive" value of Nb/U = 30. Nevertheless, their least contaminated samples have Nb/U ratios that are indistinguishable from the value (47) of the modern mantle, which provides a strong argument that 2.7 billion years ago, a similar amount of continental crust existed as today.

Several important issues remain to be resolved. One of these concerns the volume of the mantle reservoir that has been sampled. One formation from Western Australia cannot constrain the Nb/U ratio of the entire mantle. Similar studies need to be done on other continents to confirm the inference that a general characteristic of the ancient mantle has been measured. Another issue concerns the relatively "young" age of the formation studied. The period around 2.7 billion years ago constitutes the end, not the beginning, of the so-called Archean period of Earth history. This time was marked by a particularly high rate of continental growth. At least, this is what numerous workers who have studied the ages and composition of Precambrian terrains on several continents (5) have concluded. Thus, even if the continental crust grew irreversibly from small beginnings about 4 billion years ago, it may have grown to more than half of its present mass by 2.7 billion years ago, and the complementary imprint on the trace element ratios of the residual mantle should have been already quite significant, although not as great as at present. This uncertainty means that similar studies must be done in even more ancient terrains and on different continents before the results of Sylvester *et al.* will be accepted as a general constraint on the evolution of the terrestrial continental mass. Nevertheless, a crack has been made in one of the more intractable problems of understanding the history of the ground we live on.

References

1. P. J. Sylvester, I. H. Campbell, D. A. Bowyer, *Science* **275**, 521 (1997).
2. R. L. Armstrong, *Rev. Geophys.* **6**, 175 (1968); *Aust. J. Earth Sci.* **38**, 613 (1991).
3. A. W. Hofmann, K.-P. Jochum, M. Seufert, W. M. White, *Earth Planet. Sci. Lett.* **79**, 33 (1986).
4. K. P. Jochum, N. T. Arndt, A. W. Hofmann, *ibid.* **107**, 272 (1991).
5. S. R. Taylor and S. M. McLennan, *The Continental Crust: Its Composition and Evolution* (Blackwell Scientific, Oxford, 1985), pp. 1–132.

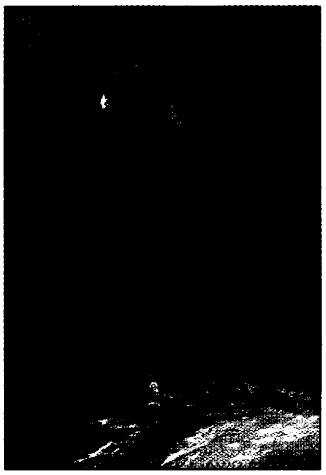
ECOLOGY

Science and the Protection of Endangered Species

H. Ronald Pulliam and Bruce Babbitt

Not all species are equally susceptible to extinction, and some species may actually benefit from land use and other changes caused by human activity. To accommodate both sustainable economic development and the protection of biological diversity, we need to know what kinds of species are most vulnerable and what kinds of human activities most threaten them.

On page 550 of this issue, Dobson *et al.* (*1*) demonstrate that "hot spots" for endangered species tend to occur where the ranges of many endemic species overlap with intensive urbanization and agriculture. Endemic species have, by definition, a restricted geographic distribution. As the size of the geographical area that a species occupies decreases, its local density in the occupied area also decreases (*2*). As Dobson *et al.* confirm, endemics are prone to extinction, especially in the face of rapid habitat loss or degradation.



California condor. An endangered species recently successfully reintroduced into its former range in Arizona.

Hawaii, Florida, and California have both the most endemic species and the most endangered species. The high number of Hawaiian endemics is a result of the small size of the islands and their extreme isolation. The Lake Wales Ridge and adjacent areas of central Florida are exceptionally rich in endemic plants, arthropods, and vertebrates. During much of the past 10 million years, coastal Florida has been submerged, isolating the higher ridges and providing ample opportunities for speciation. In California, it is the coastal Mediterranean climate and unusual habitat features—such as isolated patches of serpentine soils—that have resulted in high endemism. All three of these areas, especially California, Florida, and the Hawaiian island of Oahu, are experiencing exceptionally rapid population growth and economic development. In Florida, for example, the ridge tops that harbor so many endemic species also provide the right microclimatic conditions for citrus production, and large tracts have been converted from relatively natural vegetation to agricultural production in the past 20 years.

Urbanization and agriculture are not the only causes of the decline of native flora and fauna in the United States. Many recent ex-

H. R. Pulliam is on leave of absence from the University of Georgia and currently serves as Science Advisor to the Secretary of the Interior, Department of the Interior, Washington, DC 20240, USA. B. Babbitt is the Secretary of the Interior, Department of the Interior, Washington, DC 20240, USA. Correspondence should be addressed to H. R. Pulliam at the Institute of Ecology, University of Georgia, Athens, GA 30602, USA.