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57. I thank my past and present colleagues in the laboratory, whose investigations are described in this paper; and especially B. M. Cox, who has made the major contributions to our work on endorphin. These studies were supported by grants from the National Institute on Drug Abuse (DA-972 and DA-1199) and the Drug Abuse Council.

Ancient Lithosphere: Its Role in Young Continental Volcanism

Continental volcanic rocks inherit strontium isotopic compositions from old subcontinental lithosphere.

C. Brooks, D. E. James, S. R. Hart

The world's volcanic rocks may be classed as oceanic or continental; because the tectonic environment leading to volcanism differs both between and within these classes, a common exercise in the study of mantle-derived volcanic rocks is to correlate the mode of formation with a distinctive geochemical imprint. This has not been particularly successful in major-element studies, but differences have been observed both for certain trace elements (for example, K/Ba ratios) and for Sr isotopic compositions. Thus, continental volcanics commonly possess higher and more variable $^{87}Sr/^{86}Sr$ ratios than oceanic volcanics (1).

The Sr isotope values for oceanic volcanic rocks are believed to reflect the isotopic compositions of the mantle [asthenosphere in the case of ridge basalts, asthenosphere or mesosphere in the case of oceanic (nonarc) island basalts (2)]; however, because mantle-derived magmas in continental areas have traversed some 30 to 40 kilometers of ancient, radiogenic sialic crust, the high and variable Sr isotopic ratios observed in these magmas are commonly ascribed to crustal contamination (3–10). Alternatively, these higher Sr ratios may be inherited directly from suncontinental mantle possessing anomalous Sr isotopic compositions. The observed range in values would reflect lateral or vertical heterogeneities within this mantle. The recent literature increasingly favors the latter possibility, mostly on the basis of studies of alkalic rocks (11) and volcanics of the western United States, where subcontinental lithosphere and asthenosphere are apparently playing a major role in surface-reaching magmatism (12–16).

An important but commonly overlooked isotopic property of volcanic

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rocks is that they often show Sr isotopic compositions that correlate with Rb/Sr ratios to form pseudoisochrons which give ages grossly in excess of the true age of volcanism [11, 17]. It is our contention that these pseudoisochrons are a key to the understanding of mantle processes both in continental and oceanic [18] regions, and that for the former they furnish evidence for the participation of ancient lithosphere in continental magmatism. The high and variable $^{87}Sr/^{86}Sr$ ratios are, following this contention, the direct result of (i) large-scale "primary" heterogeneities frozen into the ancient lithosphere and (ii) small-scale "secondary" heterogeneities resulting from disequilibrium accumulation of radiogenic daughter products in mineral phases guarded at subsolidus temperatures throughout their existence. We believe that the pseudoisochrons contain significant age information and are in reality mantle isochrons. It is the purpose of this article to elucidate this precept, and show that Sr isotopic study of young mafic volcanics provides windows through which the chronologic evolution of subcontinental mantle can be viewed, and regional variations mapped.

Pseudoisochrons and Mantle Isochrons

Before discussing the data on which this article is based, it is essential to distinguish between the simple isochron plot [17] and the pseudoisochron plot utilized throughout our data presentation.

In the isochron diagram for a group of igneous rocks their individual $^{87}Sr/^{86}Sr$ compositions as measured today (termed present-day ratios) are plotted against their respective Rb/Sr ratios. In the pseudoisochron diagram, however, the initial $^{87}Sr/^{86}Sr$ ratios of the samples are plotted against their respective Rb/Sr ratios. In other words, on a pseudoisochron diagram the $^{87}Sr/^{86}Sr$ ratios of the samples already have been individually "corrected back" to their time of crystallization by using independent information for the age of crystallization. When a plot of initial $^{87}Sr/^{86}Sr$ against Rb/Sr does not define a horizontal array on the pseudoisochron diagram, then there is a hint that some precrystallization history in $^{87}Sr/^{86}Sr$ has been preserved in the rocks. If the data actually define a good linear array, the hint is strengthened and there is a strong possibility that the information given in the pseudoisochron plot pertains directly to the source region of the volcanics [19]. For many volcanic rock associations of continental regimes

this source region is the mantle: therefore, we searched the literature for pseudoisochrons with the aim of evaluating the possible preservation of mantle isotopic properties in surface-reaching igneous rocks.

The results of the literature survey are given in Table 1. Here, each measured $^{87}Sr/^{86}Sr$ ratio has been corrected for the true age of the rock and the whole-rock initial $^{87}Sr/^{86}Sr$ ratios have then been plotted against Rb/Sr on a pseudoisochron diagram. Correlation theory and regression analysis indicate that most of these pseudoisochrons have slopes significantly different from zero at confidence levels up to 95 percent (in some cases up to 99.9 percent) and that they define excess "ages" ranging from 70 million years to more than 3000 million years [20]. Some examples are shown in Fig. 1.

For the most part the pseudoisochrons come from young volcanic terranes in which no age correction of the measured present-day Sr isotopic composition is necessary. Noteworthy are the numerous examples from the western United States, where pseudoisochrons are observed in rock associations of widely differing chemical composition. Furthermore, pseudoisochrons are not restricted to young volcanics. Examples are also encountered in plutonic and hypabyssal rocks of Mesozoic age (the California batholith and the Jurassic dolerites of Antarctica); Caledonian basic igneous rocks of Scotland (the Haddo House mass); and ancient, layered, mafic intrusions (the Usushwana Complex of South Africa).

A variety of mechanisms could produce the pseudoisochrons given in Table 1. These mechanisms can be divided into crustal and mantle types. The crustal processes simply involve mixing of mantle-derived magmas with crustal material of higher $^{87}Sr/^{86}Sr$ (crustal contamination). The criteria for evaluating such a process as a potential means of raising the $^{87}Sr/^{86}Sr$ of mantle-derived magmas are well illustrated in studies of young island arc volcanics [5, 9]. In these studies, a hyperbolic relation between $^{87}Sr/^{86}Sr$ and Sr concentration is taken to be indicative of contamination. Clearly, however, many forms of disequilibrium melting or mixing of heterogeneous mantle may produce similar curves and may otherwise be indistinguishable from crustal contamination. Hence such relations cannot be considered diagnostic.

On the other hand, there is usually independent evidence against crustal contamination of mafic continental vol-

canic rocks. We include in this category such pertinent features as the following.

1) Limited range of Sr isotopic composition of the volcanic rocks despite the very large range in isotopic composition of the supposed contaminating materials.

2) Limited range of Sr isotopic composition in many volcanic associations despite a wide range in Sr concentrations.

3) Persistence of normal rock compositions (for example, tholeiites) despite significant variability in isotopic composition and hence presumed wide variation in the nature and quantity of contaminant required.

4) Constancy of composition of mafic to intermediate differentiates, irrespective of the nature and amount of the supposed contaminant.

5) High initial $^{87}Sr/^{86}Sr$ ratios, associated with pseudoisochrons, which ought not to be influenced by crustal contamination [21], assuming linear mixing relations (that is, the uncontaminated magma should form one end of a mixing line).

6) Lack of geographic correlation of isotopic compositions for many tectonic environments [15, 21].

7) Lack of correlation between Sr and Pb isotopic ratios [15].

8) The same range of values for $^{206}Pb/^{204}Pb$ ratios in basalts and rhyolites [15].

9) Volumetric paucity of included material such as crustal xenocrysts and xenoliths.

In a detailed study to find the cause of the high $^{87}Sr/^{86}Sr$ ratios in Cenozoic andesites and dacites of southern Peru, criteria of this nature led us to reject crustal contamination as a plausible mechanism for either the high $^{87}Sr/^{86}Sr$ ratios or the pseudoisochrons observed there [5, 9]. This conclusion is especially remarkable when it is noted that the Andean crust through which these magmas have passed is about 70 km thick, thicker than any other known crustal section in the world save that of the Himalayas.

On the basis of this synthesis, we consider the crustal contamination explanation for high $^{87}Sr/^{86}Sr$ ratios in mafic to intermediate continental volcanic rocks improbable, and advocate that other possible mechanisms leading to the observed isotopic compositions be evaluated. We believe that these mechanisms are all mantle-related, implying that both the high Sr ratios and the pseudoisochrons are the result of mantle processes. This viewpoint is supported by the observation that some pseudoisochrons and high $^{87}Sr/^{86}Sr$ ratios are observed in oceanic regions, where little or no possibility of sialic contamination exists [18].

Mantle-related processes that could

lead to Rb-Sr pseudoisochrons include the following.

1) Mixing of heterogeneous mantle material.

2) Selective melting of heterogeneous mantle material of the same age or different ages.

3) Disequilibrium melting of homogeneous mantle in which individual mineral phases are in isotopic disequilibrium (22).

Distinguishing between these possibilities is difficult as none of the proposed mechanisms leads to a uniquely identifiable compositional property in the rocks, other than that of Pb and Sr isotopic variation; nonetheless, it is important to inquire whether the pseudoisochrons do contain meaningful age and isotopic information about the mantle.

One means of evaluating pseudoisochrons is to determine whether they involve identifiable mixing-line chemistry. Rubidium-strontium variation diagrams and plots of $^{87}Sr/^{86}Sr$ against $1/Sr$ can be used for this purpose (23). Examination of such plots for the data used to construct Table 1 reveals that a good pseudoisochron is commonly accompanied by a good positive correlation between $^{87}Sr/^{86}Sr$ and $1/Sr$, but no correlation at all between Rb and Sr. The absence of an Rb-Sr correlation is inconsistent with simple mixing. Thus, while we cannot discount mixing of heterogeneous mantle material, the data in general seem to preclude simple two-component magma mixing as an important factor in most pseudoisochrons. The volcanics of Peru are among the few examples where good correlations are found between both $^{87}Sr/^{86}Sr$ and $1/Sr$ and Rb and Sr (5, 9). In this case, the pseudoisochrons could result either from mixing of magma or selective melting of a heterogeneous source region of uniform age or from disequilibrium melting of homogeneous mantle.

Selective withdrawal of magma from mantle material that is heterogeneous (and of uniform or nonuniform age) will result in the generation of pseudoisochrons that do not necessarily reflect the average age of the source region, although the degree of data scatter could reflect age variation at the source. We cannot avoid the conclusion, however, that such pseudoisochrons reflect a long history of isolated isotopic evolution of the subcontinental mantle (24). Thus, whatever the specific origin of pseudoisochrons (save those that can be shown to be due to crustal effects) they do imply a significant age for mantle heterogeneities, and for this reason we refer to them as mantle isochrons, a general term designed to emphasize the unique nature of the ancient isotopic imprint borne to the surface in mantle-derived magmas.

In cases where pseudoisochrons can be shown to be mantle isochrons, major constraints can be placed on the nature of the mantle source regions. First, the age information embodied in mantle isochrons implies the existence of mantle that has long preserved a distinct chemical identity. This in turn indicates that the mantle source region is sufficiently immobile as to be static and resistant to reworking and mixing processes during most of its history. Second, the elevated Sr isotopic ratios indicated by the mantle isochrons suggest that the mantle source region is not chemically depleted. Third, the wide range in observed Sr isotopic composition requires that the mantle be grossly heterogeneous, probably on both regional and local scales (25, 26). What sort of mantle fits these requirements? Asthenosphere most probably does not

Table 1. Pseudoisochron data for some igneous associations of continental affinity. Unless stated, volcanic associations are Tertiary or younger. For details of the regression analysis, see (20); errors quoted are at 1 standard deviation. Abbreviations: N, number of samples included in the regression (the numbers in parentheses are the numbers of excluded samples); r, Pearson correlation coefficient (the numbers in parentheses are increments of the standard deviation and indicate the level of confidence at which the slope of the fitted regression line differs from zero).

Location	Association	Apparent age (million years)	$\left(\dfrac{^{87}Sr}{^{86}Sr}\right)_0$	N	r	Reference
United States	Absaroka volcanic field; andesites	3340 ± 1540	0.6987 ± 0.0033	4	0.84(2)	(73)
United States	Western Grand Canyon; hawaiites	1300 ± 290	0.7025 ± 0.0004	12	0.86(3)	(12)
United States	Western Grand Canyon; alkali basalt series	1100 ± 240	0.7025 ± 0.0003	20	0.75(4)	(12)
Scotland	Haddo House mass; Cambrian quartz and olivine norites	1160 ± 210	0.7049 ± 0.0011	9	0.90(3)	(71)
Brazil	Paraná basin; Mesozoic basalts and dolerites	1020 ± 280	0.7011 ± 0.0016	4	0.93(4)	(8)
United States	Colorado Plateau; basalts	960 ± 240	0.7028 ± 0.0003	9	0.84(3)	(69)
United States	Snake River plain; King Hill basalts	940 ± 210	0.7089 ± 0.0010	6	0.92(3)	(13)
Scotland	Arnage mass; Cambrian quartz and olivine norites	830 ± 180	0.7054 ± 0.0008	8	0.89(3)	(71)
South Africa	Archean Usushwana Complex; mafic rocks	815 ± 390	0.7014 ± 0.0008	10	0.59(2)	(62)
Spain	Jumilla, alkalic complex; jumillites	780 ± 390	0.7117 ± 0.0016	6	0.70(1)	(74)
United States	Snake River plain; Crater of the Moon basalts	620 ± 60	0.7055 ± 0.0003	10	0.97(4)	(13)
Gondwanaland	Tasmania, Africa, Antarctica; Jurassic dolerites	520 ± 80	0.7059 ± 0.0008	30	0.75(4)	(4,7,66)
Antarctica	Jurassic dolerites	470 ± 90	0.7064 ± 0.0010	25	0.73(4)	(4,7)
United States	Absaroka volcanic field; shoshonites	470 ± 50	0.7032 ± 0.0002	6	0.98(2)	(73)
Peru	Arequipa volcanics; andesites, dacites	440 ± 70	0.7061 ± 0.0002	16	0.82(4)	(67)
Uganda	Napak alkalic complex; nephelinites, ijolites	380 ± 340	0.7031 ± 0.0001	8(1)	0.41(1)	(3)
Peru	Barroso volcanics; andesites, dacites	310 ± 50	0.7045 ± 0.0003	8	0.91(4)	(67)
United States	Columbia River group; basalts, andesites, dacites	290 ± 80	0.7032 ± 0.0004	6	0.86(3)	(65)
United States	California; Mesozoic granites ($^{87}Sr/^{86}Sr)_0 < 0.706$	277 ± 47	0.7030 ± 0.0003	9(2)	0.91(4)	(68)
United States	Basin and Range; basalts	200 ± 70	0.7029 ± 0.0004	11	0.54(1)	(69)
United States	Northwest Great Basin; basalts, andesites	190 ± 80	0.7033 ± 0.0002	13(1)	0.58(2)	(70)
United States	Navajo alkalic province; trachybasalts, lamprophyres	170 ± 110	0.7062 ± 0.0006	11	0.44(1)	(74)
United States	Leucite Hills; lamproites, orendites	150 ± 80	0.7056 ± 0.0004	17	0.41(1)	(74)
United States	California; Mesozoic granites ($^{87}Sr/^{86}Sr)_0 > 0.706$	115 ± 29	0.7055 ± 0.0004	11	0.80(3)	(68)
New Zealand	East arc, North Island; basalts, andesites	110 ± 20	0.7046 ± 0.0002	35	0.71(4)	(5,75)
United States	Cascades, Glacier Peak; basalt, andesites	110 ± 90	0.7034 ± 0.0003	6	0.49(1)	(64,65)
United States	Cascades, Mt. Lassen; basalts, andesites, dacites	100 ± 50	0.7036 ± 0.0002	10	0.58(2)	(64,65,72)
Uganda	Budeda alkalic complex; ijolite series	80 ± 50	0.7032 ± 0.0002	8(1)	0.57(1)	(3)
United States	Bearpaw Mountains alkalic complex; syenites, etc.	80 ± 40	0.7069 ± 0.0004	7(1)	0.64(2)	(74)
Uganda	Toror alkalic complex; phonolites, nephelinites, etc.	70 ± 5	0.7034 ± 0.0001	4(1)	0.99(4)	(3)

(26, 27), leaving either subcontinental lithosphere or mesosphere as the likely source region. Because mantle isochrons are observed in continental arc volcanics, which are shielded from the mesosphere by the downgoing plate (21), the mesosphere is not a likely direct source, even though its nature and composition are probably compatible with the mantle isochrons. Is continental lithsophere compatible with the data, however? In the following section we will show that there is a substantial amount of evidence that allows an independent case to be built for thick, ancient, heterogeneous and chemically undepleted continental lithosphere with an isotopic composition consistent with that implied by mantle isochrons.

Nature of Continental Lithosphere

Most of our knowledge concerning the nature of continental lithosphere comes from three sources: seismic studies, heat-flow measurements, and the analysis of ultramafic nodules believed to be samples of lithosphere rafted to the earth's accessible regions in mantle-derived magmas. These broad areas are so interdependent that it is impractical to isolate the individual contributions originating in each. Consequently, in this discussion we synthesize the evidence from these sources by treating successively the thickness of continental lithosphere, its chemical composition (and the resulting implications for heat flow), its isotopic heterogeneity, and finally its age.

Although there is no consensus about the thickness of continental lithosphere among geophysicists, whose estimates range between about 200 and 400 km (28), the lack of agreement is largely one of definition and not substance. In particular, the lower estimates of lithosphere thickness are based on the determination of the minimum depth below which oceanic and continental velocity structures need not differ. But depths so calculated provide no information on the actual thickness of the lithosphere; that is determined by the depth at which shear wave velocities or Q (29) decrease rapidly or discontinuously to asthenospheric values. By this criterion, few seismic studies successfully identify the base of the lithosphere. They do show, however,
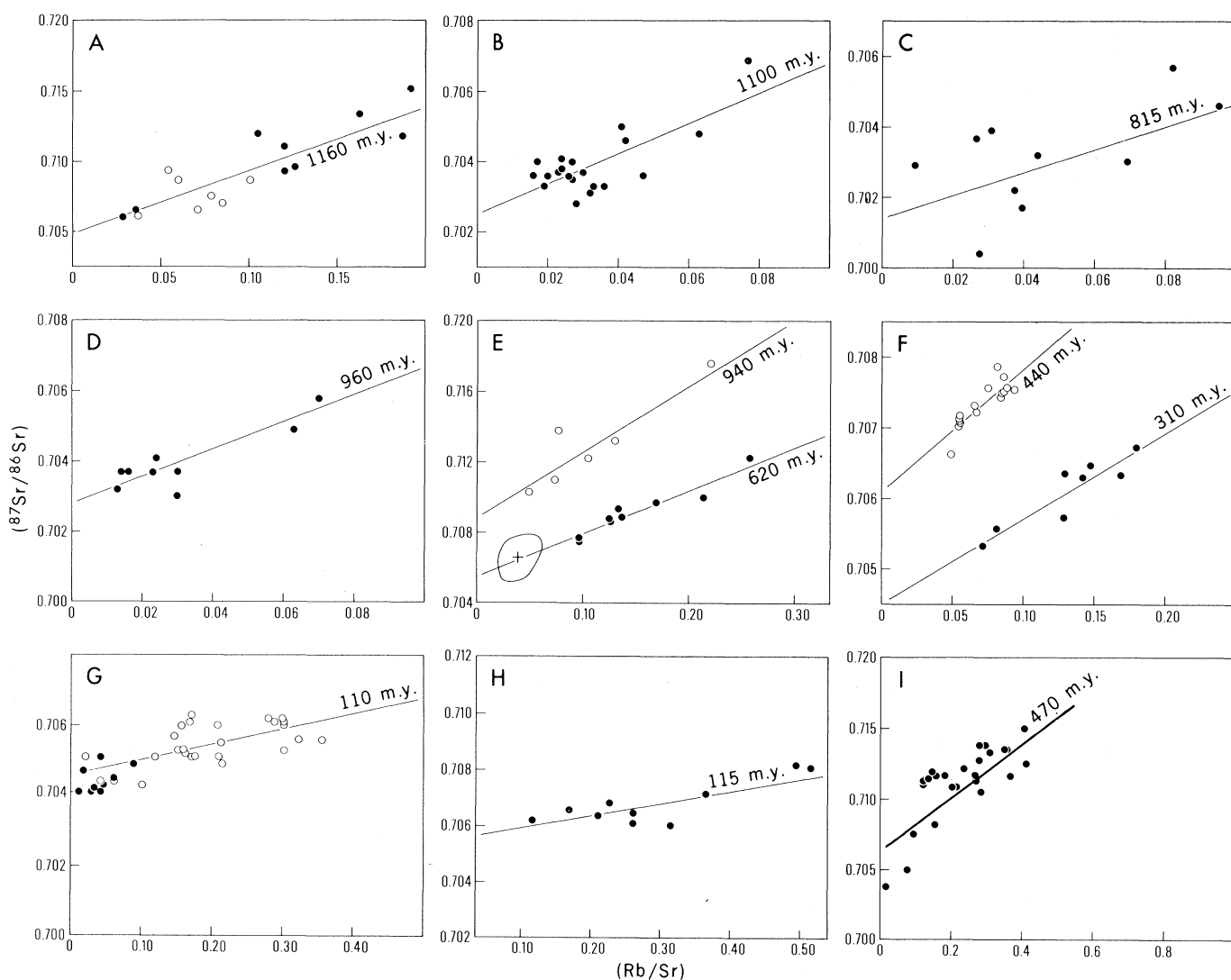

Fig. 1. Rubidium-strontium pseudoisochrons (initial $^{87}Sr/^{86}Sr$ ratios plotted against Rb/Sr) for some representative igneous rock associations of continental affinity (for more details see Table 1). (A) Quartz and olivine norites from the Arnage (○) and Haddo House (●) igneous masses, Scotland. The regression line is for the Haddo House mass. (B) Alkali basalt series of the western Grand Canyon, United States. (C) Mafic rocks of the Archean Usushwana Complex, South Africa. (D) Colorado Plateau basalts, United States. (E) Snake River basalts, United States: (●) Crater of the Moon basalts; (○) King Hill basalts. The field is for olivine tholeiites ($N = 34$), with the cross showing the average composition. (F) Peruvian Cenozoic andesitic volcanics, southern Peru; (●) Barroso volcanics; (○) Arequipa volcanics. (G) New Zealand east arc volcanics; (●) basalts; (○) andesites. (H) Mesozoic granites of California (initial $^{87}Sr/^{86}Sr > 0.706$). (I) Jurassic dolerites of Antarctica (includes the Ferrar Group and Queen Maud Land dolerites).

that lithosphere beneath cratons may be at least 300 to 400 km thick (30); that is, the continental mantle is subsolidus to that depth, exhibiting no significant low-velocity or low-Q zone at lesser depths. While there may be a low-velocity channel at greater depths, the poor resolving power of the seismic data precludes its unequivocal identification. One important study of Q beneath the Andes of South America, however, clearly demonstrates the existence of a low-rigidity (and probably low-velocity) channel at a depth of 350 km beneath a high-rigidity lithosphere (31). This result is of considerable general importance because the Andean orogen evolved atop the ancient South American shield and the integrity of the underlying lithosphere appears to be intact (32).

Additional evidence favoring thick continental lithosphere comes from an analysis of global heat flow data by Pollack and Chapman (33). Although the results of their study are not conclusive, they indicate that the lithosphere beneath ancient continental interiors may attain thicknesses in excess of 300 km. This estimate is based on regional variations in the geothermal gradient and the corresponding depths at which the geotherm intersects an empirically postulated temperature of incipient melting (34, 35). In this model, as in most previous thermal models (36, 37), it is assumed that the continental lithosphere is somewhat depleted in heat-producing elements. Yet, one of the principal conclusions to be drawn from the interpretation of mantle isochrons is that continental lithosphere is essentially undepleted. Since chemical composition provides the input to the thermal model, our conclusion must be consistent both with the observed heat flow data and with what is known about the composition of continental lithosphere as revealed by studies of ultramafic nodules found in kimberlites and basalt (38).

Kimberlites crystallize from volatile-rich magmas that appear to have originated at depths greater than 200 km (38, p. 101; 39; 40). They apparently ascended rapidly, and in so doing incorporated many ultramafic xenoliths which are believed to represent samplings of different depth zones of the mantle (39, 41, 42). Although there is debate as to the source region of the kimberlite magma, and no assurance that it lies in the lithosphere, there is a consensus that many of the xenoliths are subsolidus mantle fragments showing little reequilibration to lower temperature and pressure assemblages (39, 42–44). The nodule compositions can therefore be used as guides to real mantle compositions. Studies of nodules in kimberlites indicate that the subcontinental mantle has high Rb/Sr ratios and correspondingly high $^{87}Sr/^{86}Sr$ ratios, and is otherwise undepleted in its basaltic fraction (44–48). The undepleted character of the mantle from which the nodules were derived is attested to by the dominance of the fertile garnet peridotite (especially the sheared variety) over other more depleted nodules (44). Thus, nodule studies corroborate our conclusions based on Sr isotopic compositions and argue for the existence of a continental lithosphere that is far from depleted, and which, under favorable thermal conditions, would be a ready source of basaltic magma.

Steady-state thermal models based on undepleted mantle compositions can be constructed that are entirely consistent with measured heat flows and postulated geothermal gradients. Consider, for example, a surface heat flux for a continental craton of 1.05 heat flow units (HFU; microcalories per square centimeter per second), a standard 40-km crust which produces 0.43 HFU, and a lithospheric mantle 310 km thick that consists of undepleted peridotite containing 1000 parts per million (ppm) K, 0.06 ppm U, and 0.23 ppm Th (36, 37, 49). This mantle material will contribute 0.38 HFU to the steady-state heat flux, leaving 0.24 HFU to be derived from below 350 km, a deep-mantle contribution that is only about one-half the value assumed in the static earth model of Clark and Ringwood (37). Our thermal model, in which most surface heat flow originates in the lithosphere rather than at greater depth, results in slightly lower geothermal gradients for the same surface heat flux; this, in turn, forces the point of incipient melting to even greater depths, thereby making thick continental lithosphere even more feasible. This example illustrates that steady-state thermal models based on undepleted mantle compositions are entirely consistent with observed heat flows and postulated geothermal gradients.

The study of ultramafic nodules provides evidence not only that the continental lithosphere is chemically undepleted, but that it is ancient, isotopically enriched, and grossly heterogeneous. Kimberlite nodules typically show $^{87}Sr/^{86}Sr$ ratios that vary between 0.703 and 0.710 (average, 0.707) (46–48, 50, 51). The consistent and wide variation in isotopic ratio cannot be attributed to contamination and must reflect mantle inhomogeneity (46, 47). Furthermore, the existence of isotope disequilibrium between mineral phases in individual nodules suggests that the heterogeneity is present even on the scale of mineral grains (14, 35, 46, 51–56).

The high average $^{87}Sr/^{86}Sr$ ratio suggests a significant prehistory for continental lithosphere, long isolated from less enriched asthenosphere. More direct evidence that the subcontinental mantle is very old comes from studies of Sr and Pb isotopes in ultramafic nodules. Measurements of isotopic ratios give apparent ages up to 3 billion years or more (51, 52, 55–57). Other studies showing a wide variation in Sr isotopic ratios between nodules provide indirect evidence that parts of the mantle have remained in isotopic isolation over very long periods of time (35, 46, 53). Thus, while no single geochemical study yet provides definitive evidence for an ancient mantle, the integrated result of all studies strongly suggests an aged and heterogeneous subcontinental lithosphere.

Implications

Because continental lithosphere exists at relatively low, subsolidus temperatures, it is protected from transport into subduction zones by the buoyancy of the overlying continental capping; as a result, parts of the lithosphere may be as old as the coupled sialic crust (for instance, early Precambrian for continental cratons). Any sections of lithosphere that are not depleted will, by virtue of their sheltered existence, possess distinctive isotopic compositions that result from both regional and local variations in Rb/Sr ratios. If this ancient lithosphere participates in younger magmatism, then the volcanic products will contain isotopic evidence of the "prehistory" of the source region. This evidence, manifest as mantle isochrons, raises two major questions: first, how does this lithosphere form, and second, how does this lithosphere, isolated for long periods of time, become involved in young magmatism?

While discussion of these questions aims at explaining mantle isochrons of continental regions, and indeed the existence of ancient lithosphere is central to that theme, mantle isochrons are observed in oceanic regions as well (18), where such lithosphere is nonexistent. In evaluating models of the development of continental lithosphere we use these oceanic mantle isochrons as a constraint, and derive a model that provides a unified explanation of both continental and oceanic regions.

The range in initial $^{87}Sr/^{86}Sr$ ratios of

mantle-derived magmas (Table 1 and Fig. 1) provides strong evidence that the continental lithosphere is characterized by a degree of regional isotopic heterogeneity that is more pronounced than that observed in other mantle provinces. Specifically, the subcontinental mantle has Sr isotopic ratios from as low as 0.703 to more than 0.710, a range of values nearly identical to that found for mantle-derived ultramafic nodules. By comparison, ocean-ridge basalts, taken to represent oceanic asthenosphere, have a quite limited range of values about 0.7027 (26, 27), indicating that this asthenosphere is comparatively homogeneous isotopically, as might be expected in rapidly convecting, partially molten material. On the other hand, oceanic islands, derived at least in part from the mesosphere, exhibit a considerable range in Sr isotopic values (from about 0.703 to 0.706), which suggests that the mesosphere has substantial regional isotopic heterogeneities, although not as pronounced as those of continental lithosphere (18).

The upper limits of these ranges in $^{87}Sr/^{86}Sr$ ratios lead to an important inference concerning the relative enrichment of the different mantle provinces. Continental lithosphere consistently displays Sr isotopic values that are significantly higher than those of oceanic asthenosphere, indicating that some parts of the subcontinental mantle are considerably more enriched in radiogenic components and LIL (large-ion-lithophile) elements than suboceanic mantle. Mesosphere, as manifest in oceanic islands, can be regarded as a nondepleted base to both oceanic and continental regions alike, locally possessing a degree of enrichment in radiogenic components comparable to but possibly somewhat smaller than that of continental lithosphere.

Our review of mantle isochrons and related Sr isotopic data indicates that continental lithosphere is in part both more enriched and more heterogeneous in its radiogenic components (and LIL elements) than other mantle provinces. Such lithosphere enrichment and heterogeneity could result from a variety of processes operating either individually or in concert. Some possible models are outlined below.

1) Thermal accretion by "freezing" of enriched asthenosphere. Since lithosphere begins to form soon after the formation of crust, the lithosphere under old continental areas may have started to form at a time when the asthenosphere was enriched or nondepleted (as contrasted with its present state of chemical depletion).

2) Trapping of an enriched layer of asthenosphere at the base of the lithosphere (as the lithosphere progressively crystallizes, LIL elements are concentrated into the partial-melt zone of the asthenosphere directly beneath the boundary of the lithosphere).

3) Upward percolation of a phase rich in LIL elements and volatiles (which is not miscible with the silicate partial melt) from mesosphere or asthenosphere into the subcontinental lithosphere.

4) Diapiric rise of LIL element–enriched mantle diapirs or blobs (58) from the mesosphere, which underplate and become incorporated into the thickening subcontinental lithosphere.

Model 1 would produce a zoned lithosphere, grading from enriched at the top to depleted at the base (since present-day asthenosphere is depleted). Derivation of continental magmas from such a lithosphere might reflect this zoning, with magmas formed at the greatest depths (youngest lithosphere) carrying a depleted signature. There is no convincing evidence, however, for the existence of significant quantities of "depleted" magmas in continental regions, and hence this model requires either that no magmas are derived from this depleted zone of the continental lithosphere, or that such magmas reequilibrate with shallower, more enriched, lithosphere.

Model 2 has been proposed by Kay (59) for the formation of heterogeneities in the suboceanic mantle; however, consideration of the rates of diffusion of LIL elements in silicate melts (25, 26) shows that any such enriched, nonconvecting, boundary-melt layer will be very thin ($\sim$ 10 m) and quantitatively insignificant for the later production of enriched magmas. The main difficulty in this model (for both oceanic and continental regions) arises because lithosphere accretes at a velocity that is higher than the rate of LIL element diffusion in silicate melts, so that its steady-state composition would be close to that of the asthenosphere from which it forms, and only trivial amounts of "enriched" partial melt could result from this process.

Model 3 requires a mobile phase that is not miscible with the partial-melt phase of the asthenosphere at the pressures and temperatures characteristic of the asthenosphere. Such a phase might be a hydrous, carbonate-rich fluid, which separates from the mesosphere and rises buoyantly through the asthenosphere, to be trapped against the advancing lithospheric front. Later partial melting of lithosphere containing this enriched phase could produce magmas showing enriched characteristics. In extreme cas-

es, this enriched phase might progress directly through the lithosphere, forming members of the kimberlite-carbonatite suite at the surface. While this model has many plausible characteristics (and is closely related to model 4, with which it could operate in conjunction) we note that it also implies the presence of kimberlite-carbonatite magmas throughout the geologic record. They are, in fact, rare in Precambrian time, a time when presumably thinner crust and lithosphere would have greatly enhanced the likelihood of such magmas reaching the surface.

Model 4 involves a convecting mesosphere containing thermal or chemical heterogeneities (60) such that blobs or plumes of material can become separated, rise through the asthenosphere, and become plastered on and slowly incorporated into the thickening subcontinental lithosphere. This mesospheric material is presumed to be enriched in the LIL elements relative to asthenosphere, so that the resulting subcontinental lithosphere will be a heterogeneous combination of frozen-out asthenosphere and included, mesosphere-derived blobs. This model is attractive because it can be applied equally well in oceanic regions to explain the existence of oceanic islands (variously related to hot spots or plumes), which invariably are built of volcanic material enriched in LIL elements and Sr and Pb isotopes relative to the depleted, asthenosphere-derived, spreading-ridge basalts.

In oceanic regions, the mesospheric blobs or plumes [a plume may be simply a more or less continuous train of blobs (58)] do not necessarily go through a two-stage process of lithosphere underplating and subsequent remelting. Instead, they may diapirically penetrate the thinner oceanic lithosphere and directly supply the partial melt leading to oceanic island volcanism. If the blobs do not penetrate the lower boundary of oceanic lithosphere, they will produce heterogeneity similar to that of the continental lithosphere. By this concept, then, oceanic regions provide us with a recent record ($<$ 200 million years) of the continuous upward migration of enriched blobs from the mesosphere, a process that has been going on under continents for billions of years.

The main difference between mantle isochrons of oceanic and continental regimes is that higher Rb/Sr and $^{87}Sr/^{86}Sr$ ratios are found for continental volcanics. This implies that there must be an additional fractionation (increase of Rb/Sr ratio) associated with the two-stage continental case (underplating and sub-

sequent remelting) relative to the single-stage oceanic case (direct penetration). We explain this as follows: At some point in the rise of mesospheric blobs, they become partially molten; this silicate melt, with a higher Rb/Sr ratio than the initial value of the blob, becomes

partially segregated from the crystalline residue as the blob ascends and is plated onto the bottom of the continental lithosphere. Later partial melting of this material will favor the previously partially segregated melt, leading to a second stage of enrichment of Rb with respect to

Sr. The relatively high $^{87}Sr/^{86}Sr$ ratios observed in continental volcanics (relative to oceanic island volcanics) arise because of the isotopic aging that follows the initial Rb/Sr fractionation. Cases of more or less complete melt-crystal segregation prior to or during the underplating stage would result, on further cooling, in an eclogite solid (frozen melt) and ultramafic residue. The eclogite nodules commonly brought to the surface in kimberlitic rocks may be evidence for such a segregation process.

Taken together, the evidence discussed in this article suggests that continental lithosphere accretes through a combination of processes 1 and 4. Such a model provides a satisfactory explanation for mantle isochrons from both continental and oceanic regions. A schematic view of this model is given in Fig. 2A, and although it is recognized that some aspects of the other models discussed may be of local importance, we have restricted ourselves to a portrayal of the main features of lithospheric growth beneath a continental craton, excluding lateral accretion for simplicity.

The data of Table 1 must be examined on a case-by-case basis to determine which pseudoisochrons may be considered mantle isochrons. A significant number of these pseudoisochrons have been interpreted by us and others to be mantle-related, although some (for example, those of the California Mesozoic batholiths and Haddo House and Arnage masses) have been interpreted differently. In many instances the data require further scrutiny. In all cases, Rb-Sr data are not themselves sufficient to provide a clear interpretation but must be considered in conjunction with other field and petrologic data. Insofar as the data in Table 1 construe mantle isochrons we observe that they are associated with a number of specific tectonic environments where ancient lithosphere can become reactivated and involved in partial melting processes. These environments are created where (i) subcontinental lithosphere overlying a subduction zone is activated by proximity to that zone, (ii) continental-scale rifting forms fractures that penetrate deep, unloaded lithosphere, and (iii) a continent-bearing plate overrides an oceanic rise or plume. A schematic representation of these various reactivation environments is given in Fig. 2B.

Recognition that ancient lithosphere can play a major role in younger magmatism in these tectonic environments allows us to formulate new models of magma genesis. As an example of subduction zone reactivation, consider the well-
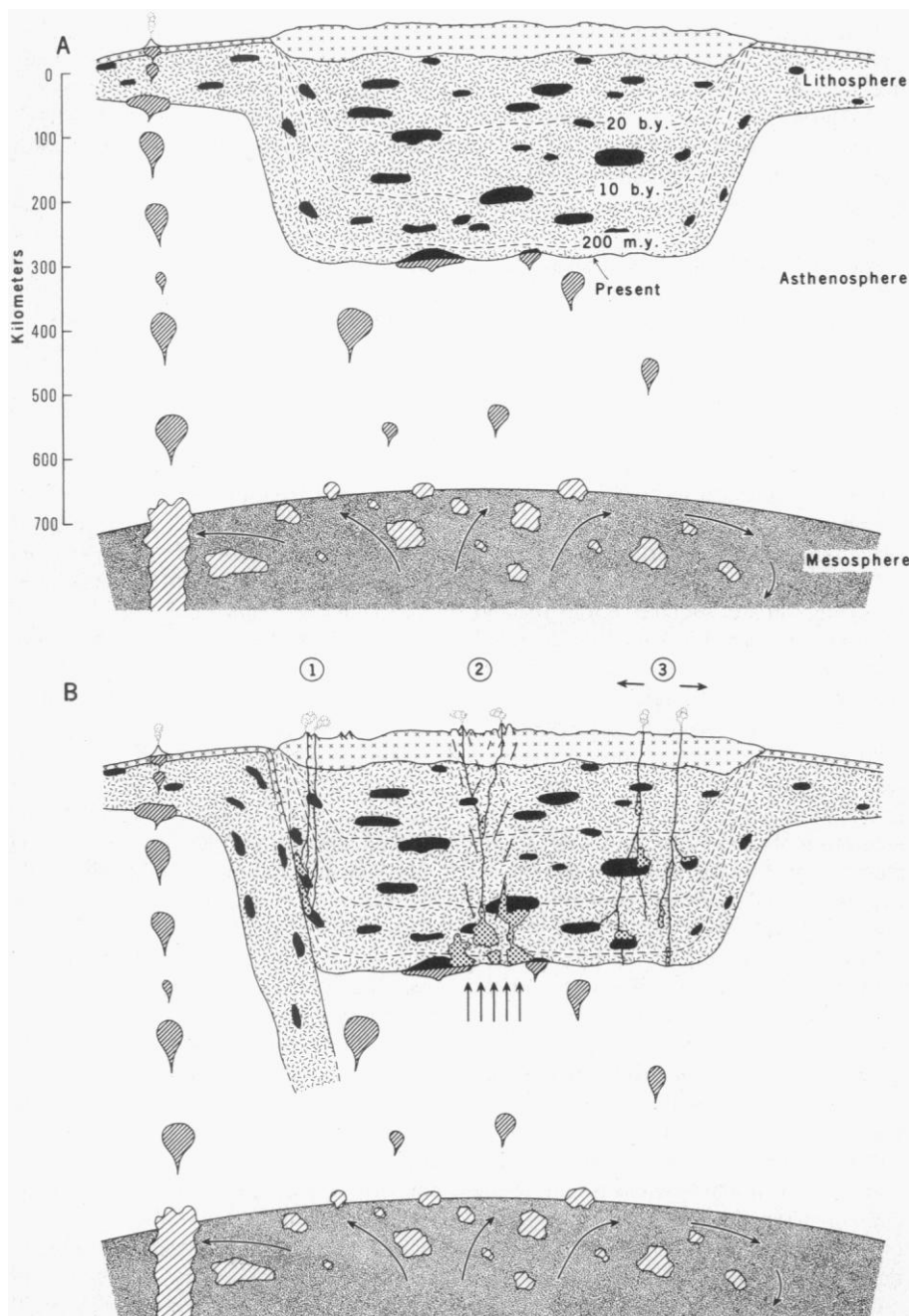

Fig. 2. Diagram showing development (A) and subsequent reactivation (B) of blob-enriched continental lithosphere (the vertical exaggeration is about 5 to 1). (A) Blobs are released from the mesosphere by buoyancy and convection, ascend through the convecting asthenosphere, and either underplate thickening continental lithosphere or penetrate through oceanic lithosphere. Ascending blobs (diagonally ruled pattern) may be partially molten, with some segregation of liquid occurring before they solidify in the lithosphere (solid pattern). Dashed age lines in the lithosphere represent, on a schematic linear scale, progressive positions of the boundary representing accretion of lithosphere from asthenosphere. Note that oceanic lithosphere is shown to be younger than 200 million years (m.y.). An oceanic "plume" is indicated schematically as a continuous train of blobs. (B) Various reactivation environments, where partial melts (stippled pattern) are formed in continental lithosphere; (1) above a subducting oceanic plate, (2) over a thermal or upwelling anomaly in the asthenosphere (plume or overridden ridge, arrows), and (3) during continental rifting (initial stage shown without causal mechanism).

studied Cenozoic volcanic rocks of the Andean region of southern Peru. These document the role of ancient continental lithosphere in producing both high $^{87}Sr/$ ^{86}Sr ratios and well-defined mantle isochrons in subduction zone environments (21). Here, the ancient lithosphere of the South American shield extends beneath the Andes to a depth of at least 200 to 300 km and forms, throughout the depth range over which magma is generated, a continuous lithosphere-lithosphere boundary with the descending Nazca plate. The model that most plausibly explains the isotopic and trace element data is one in which andesitic magma is produced by subduction zone melting of the ancient South American lithosphere. The isotopic imprint of that aged lithospheric mantle material is preserved in the mantle isochrons and anomalously high $^{87}Sr/^{86}Sr$ ratios of the young volcanics of the Andean region.

The rifting-related reactivation environment may be represented by the alkalic complexes of Africa and the Jurassic tholeiitic flood basalts (and dolerite sheets) associated with the breakup of Gondwanaland. The latter define mantle isochrons on both local (Antarctica) and regional (Antarctica, Tasmania, and Africa) scales (Table 1), and document the existence of very undepleted mantle in these regions. Mantle isochrons are also common in regions where a continent appears to have overridden an ocean rise or mantle plume. Our examples all come from the western United States, where many rock associations give mantle isochron ages in the range 600 to 1000 million years. This region is probably the most complex of those discussed, and despite numerous studies a definite pattern of ancient lithosphere consumption is not yet forthcoming. However, the possible participation of the lithosphere in the magmatism of the region is discussed in the literature (12–16).

An important aspect of Table 1 is that pseudoisochrons are not restricted to young volcanics, but are also encountered in young hypabyssal and plutonic intrusives (Jurassic dolerites of Antarctica and California Mesozoic batholiths), metamorphosed basic rocks of early Palaeozoic age (Caledonian basic igneous province, Scotland), and an ancient layered intrusion [Usushwana Complex of South Africa (61, 62)]. These examples are encouraging since they demonstrate that pseudoisochrons are not necessarily masked by either differentiation or metamorphism, which extends their usefulness as petrogenetic indicators.

One serious consequence of the mantle isochron model is that crystalliza-

tion ages determined on basic igneous rocks by the Rb-Sr whole-rock technique can be greater than the true age by many hundreds of millions of years. This problem of inherited age is more serious for younger rocks, and there are well-documented instances of conflicts between stratigraphic age and Rb-Sr age in the literature (6, 63).

Effective use of the mantle isochron concept requires knowledge of actual crystallization ages (so that the measured isochron can be divided into its pre-and postcrystallization components) and determination of isochron parameters on rocks that have been subjected to minimal postmelting processes (fractional crystallization, wall rock contamination, and so forth). The concept of Rb-Sr mantle isochrons as we have presented it provides a new tool for understanding the petrogenesis of mantle-derived igneous rocks and for mapping the evolution of the various segments of the earth's mantle.

References and Notes

1. Because ^{87}Sr is partly radiogenic (produced by beta decay of ^{87}Rb) and ^{86}Sr is stable, the $^{87}Sr/$ ^{86}Sr ratio increases approximately proportionally to (i) the amount of Rb relative to Sr in the system (denoted by the Rb/Sr ratio) and (ii) the length of time that Rb/Sr ratio has existed.
2. The terminology adopted is as follows: the lithosphere is the rigid outer shell of the earth, which includes the crust and upper mantle; the asthenosphere is mobile (probably incipiently melted) mantle material underlying the lithosphere; and the mesosphere is the rigid mantle material underlying the asthenosphere and constituting the bulk of the mantle. Subcontinental mantle is a general term used primarily to mean lithospheric mantle, but not necessarily excluding asthenosphere and mesosphere. Undepleted refers to a mantle system with Rb/Sr and Sr isotopic ratios compatible with closed-system evolution for 4.5 billion years. Enriched and depleted refer to systems in which present Rb/Sr ratios are higher and lower, respectively, than those required for closed-system evolution. Thus, the typical midocean ridge tholeiite comes from partially depleted mantle and is therefore much lower in K, Rb, Sr, and Ba, and has a much lower Rb/Sr ratio than tholeiites of otherwise similar composition from oceanic islands and from continental regions. Homogeneous implies that chemical composition is uniform from place to place provided sample size is large enough to average out mineral-scale compositional variation. Heterogeneous is used to refer to compositional variations on any scale. A mantle age refers to the time of some geological event in the mantle, such as the development of large-scale heterogeneities.
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17. The time dependent change of $^{87}Sr/^{86}Sr$ with Rb/Sr can be portrayed graphically with the former as the ordinate and the latter as the abscissa. A genetically related group of igneous rocks of a certain age will plot along a straight line termed an isochron, whose slope is approximately proportional to that age, and whose intercept gives the Sr isotopic composition of those rocks at the time of formation [$(^{87}Sr/^{86}Sr)_0$; this composition is termed the initial Sr ratio]. For volcanic rocks this would be their value at the time of extrusion and crystallization, and under ideal conditions it would also be the isotopic composition of the source region for those volcanics at the time of their derivation.
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20. The data of Table 1 have been statistically evaluated by (i) calculating the Pearson correlation coefficient (r) which defines the "goodness of fit" of the data about a regression line, and (ii) testing the slope of the fitted line for significance against zero. The regression treatment used to obtain slopes and intercepts was that of D. York [Can. J. Phys. 44, 1079 (1966)] in which the errors in the age and initial ratio are calculated solely from the data scattering and are given at 1 standard deviation [following C. Brooks, S. R. Hart, I. Wendt, Rev. Geophys. Space Phys. 10, 551 (1972)].
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76. We acknowledge A. Hofmann for many stimulating and productive discussions and M. Strobel for generously providing statistical programs and assistance in evaluating the Rb-Sr data. The drafting assistance of M. Demidoff is greatly acknowledged. This study has been supported in part by the National Science Foundation (grant GA 36094) and the National Research Council of Canada (grant A 5581 to C.B.). One of us (C.B.) gratefully acknowledges the Carnegie Institution of Washington for providing financial support and research facilities during his sabbatical year.

Hyperlipidemia and Atherosclerosis

Chronic hyperlipidemia initiates and maintains lesions by endothelial cell desquamation and lipid accumulation.

Russell Ross and Laurence Harker

The lesions of atherosclerosis are characterized by intimal proliferation of smooth muscle cells, accumulation of large amounts of connective tissue matrix including collagen, elastic fibers, and proteoglycans, and deposition of intra- and extracellular lipid. Many factors are involved in this process.

One of the original concepts regarding the pathogenesis of atherosclerosis was proposed by Virchow (1) who suggested that endothelial cell injury initiates atherogenesis. In a recent modification

of this hypothesis (2), it was proposed that the endothelium normally influences the behavior of arterial smooth muscle cells by providing a barrier to the passage of plasma proteins, and that the major effect of hemodynamic or other factors that injure the endothelium is to reduce the effectiveness of the barrier. Moreover, the lesions of atherosclerosis were considered to be potentially reversible, depending upon the nature, duration, and chronic nature of the injury.

Many investigators have subsequently

confirmed the key role played by endothelial cell injury in atherogenesis. The various injurious factors that affect the endothelium somehow alter the threshold of endothelial stability so that local hemodynamic factors result in focal endothelial desquamation and exposure of subendothelial connective tissue. Recent evidence has also linked endothelial injury with platelet adhesion, aggregation, and release of platelet constituents at sites in the artery wall where endothelial cell desquamation has occurred.

Figure 1 illustrates the importance of endothelial injury and the resultant release and passage of platelet and plasma constituents into the artery wall in the genesis of the lesions of atherosclerosis. According to the injury hypothesis, everyone is potentially susceptible to many forms of endothelial damage as a result of mechanical (3), chemical (4), immunologic (5), or toxic sources of injury. Figure 1 shows that if the injury were a single event, the lesions would be revers-

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