

Composition of the earth's upper mantle—II: Volatile trace elements in ultramafic xenoliths

J. W. Morgan¹, G. A. Wandless¹, R. K. Petrie¹, and A. J. Irving²

¹U.S. Geological Survey, Reston, Virginia 22092 ²University of Washington, Seattle,
Washington 98195

Abstract—Nine volatile elements (Ag, Bi, Cd, In, Sb, Se, Te, Tl and Zn) were determined by means of radiochemical neutron activation analysis in 19 ultramafic rocks; mainly spinel lherzolites from North and Central America, Hawaii and Australia, and garnet lherzolites from Lesotho in southern Africa.

A sheared garnet lherzolite PHN 1611 may approximate undepleted mantle material and tends to be higher in volatile elements than is depleted mantle material represented by spinel lherzolites. Granular garnet lherzolites show dual effects of loss by partial melting and enrichment by metasomatism.

Comparisons of continental basalts with PHN 1611, on the one hand, and of oceanic ridge basalts with spinel lherzolites, on the other, show similar basalt: (source material) partition factors for 8 of the 9 volatile elements (Sb being the exception).

The Cl chondrite normalized abundances of the predominantly lithophile volatile elements in PHN 1611 suggest that the well-known depletion of Ge relative to Ni and Co in ultramafic rocks is simply a reflection of the earth's depleted volatile complement.

The strong depletion of Se and Te in the mantle relative to lithophile elements of similar volatility suggests that 97% of the earth S, Se and Te may be in the outer core. The corresponding amount of FeS (9%) in the outer core seems insufficient to lower the density to that inferred geophysically and may require the presence of another light element, possibly O. The abundances of Te in ultramafic rocks are similar to those of the highly siderophile elements and suggest that the population of planetesimals bombarding the earth in the first 600 m.y. of its history may have resembled the C2 chondrites in volatile content; about 10^{25} g of planetesimals of this composition would provide the H₂O present on the earth.

INTRODUCTION

The distribution of volatile elements in the earth's mantle has been the topic of considerable recent interest, particularly in terms of similarity to or contrast with the bulk composition of the moon (Ringwood and Kesson, 1976; Wolf and Anders, 1979). Compared with Cl-chondrite (~cosmic) abundances, the terrestrial complement of moderately volatile (K, Rb, Cs, Pb) and highly volatile (e.g., Tl) elements relative to refractory elements (U, Th, Sr) is depleted, as shown by isotopic and geochemical studies of crustal rocks (Gast, 1960; Anders, 1968; Wasserburg *et al.*, 1964; Ringwood, 1966). Most of the elements listed are in-

compatible large-ion lithophile elements that are strongly fractionated into the crust of a differentiated planet; the relatively invariant K/U and Tl/U ratios (for example) in crustal rocks are probably fair approximations for these ratios in the bulk earth. Much less is known of the relative and absolute abundances of the more compatible volatile elements in the bulk earth and particularly in material from the upper mantle. Recent discussion of the volatile distribution in the earth's mantle have relied upon compilation of often sketchy data gathered from many different sources for a variety of rock types: komatiites, alpine peridotites, and ultramafic inclusions (Ringwood and Kesson, 1976). However, a more unified data base is now available. An extensive collection of spinel and garnet lherzolites has been analyzed by means of instrumental neutron activation analysis (INAA) for major, minor and some lithophile trace elements as part of the NASA sponsored Basaltic Volcanism Study Project (Irving, 1980). Eighteen of these rocks have now been analysed by radiochemical neutron activation analysis (RNAA) for 7 siderophile elements (Au, Ge, Ir, Ni, Os, Pd, and Re) and 9 volatile elements (Ag, Bi, Cd, In, Sb, Se, Te, Tl, and Zn). In addition, RNAA has been applied to the important sheared garnet lherzolite PHN 1611, which apparently was derived from depths ≥ 150 km and which has a composition suggesting that it may represent relatively undepleted mantle. The siderophile data have been discussed in the first paper of this series (Morgan *et al.*, 1980a). In the present paper, we publish the volatile-element results and discuss them in terms of the fractionation between crust and mantle. We will then briefly recapitulate the implications of the siderophile element results and suggest a possible scenario for the formation of the earth.

METHODS AND MATERIALS

Ultramafic inclusions

Brief descriptions of the 19 ultramafic nodules analyzed were given in the companion paper (Morgan *et al.*, 1980a). Petrology and major, minor and lithophile trace-element geochemistry of most of these rocks have been summarized and discussed by Irving (1980).

Analytical procedures

Powders were specially prepared by one of us (AJI) for several studies associated with the Basaltic Volcanism Study Project. Aliquants weighing 100 to 200 mg were sealed in high-purity fused-silica vials. The samples were packaged in two batches, each containing appropriate standards and a control sample (BCR-1), and were irradiated for 10 days in a thermal flux of 2×10^{14} n.cm⁻² sec⁻¹ the U.S. National Bureau of Standards research reactor, Gaithersburg, Md.

Irradiated samples were allowed to cool for from 2 to 4 days before being opened for chemical processing. Radiochemical separation methods have evolved from those described by Keays *et al.* (1974) and, for Os and Pd, by Gros *et al.* (1976), with considerable streamlining devised by Anders and co-workers (unpublished data).

A systematic error exists in the Te monitors used for these determinations and for some lunar materials analysed recently (Morgan and Petrie, 1979). The monitor specific activities agree well between runs, but results for BCR-1 and Apollo 17 black glass soils are higher by almost exactly a factor of 3 than results from other labs (Krähenbuhl *et al.*, 1979; Morgan *et al.*, 1974). No other determinations of Te in ultramafic nodules are available, and rather than abandon the Te analyses entirely, we normalized our ultramafic nodule analyses to be compatible with data from other labs by using results for the lunar black glass soil 74001, in which Te was high enough to be precisely determined. Systematic errors in the determination of Te by radio-chemical neutron activation were discussed recently by Wolf *et al.* (1980).

RESULTS

The analytical data are summarized in Table 1. Note that the Tl value of 4.2 ppb listed for PHN 1611 in our preliminary report (Morgan *et al.*, 1980b) was incorrect owing to a transcription error. In addition to the ultramafic xenoliths, an oceanic-ridge basalt DR-10 (Juan de Fuca Ridge; Melson, 1969) and a continental flood basalt BCR-1 (Columbia River, Oregon; Flanagan, 1976) were analyzed as controls. The new results can be compared with (1) BCR-1 for which there is a considerable body of data; (2) other analyses of ultramafic xenoliths; and (3) recent compilations. These comparisons are shown in Table 2.

Basalt BCR-1

A large number of analyses of BCR-1 for volatile elements have been reported by Anders and co-workers in many publications, and have been summarized by Keays *et al.* (1974) and Morgan (1977). To make such a comparison may be presumptuous as the papers cited and the present work have an author in common. The results used in the comparison, however, represent the work of 10 analysts rotated over a period of 8 years work in which 5 different reactors and many variants of analytical procedure were used. As can be seen from Table 2, BCR-1 is a very good control sample for the volatile elements, unlike most of the siderophile elements (Morgan *et al.*, 1980a), and no appreciable systematic error is apparent in the analyses reported in Table 1. In particular, the Te values now agree well with those of previous analyses and suggest that the accuracy (at least relative to other labs) is probably as good as the precision.

Ultramafic nodules

Very few data are available on volatile elements in ultramafic nodules (this fact, of course, was a major stimulus for carrying out the present analyses). In their study of the distribution of 49 major, minor and trace elements in 6 carefully

Table 1. Abundances of volatile trace elements in ultramafic rocks of possible upper mantle origin (in ppb, except for Zn in ppm).

| Sample | Type* | Locality | Sb | Ag | Zn | In | Cd | Bi | Ti | Se | Te |
|---------|-----------|-----------------------------------|-------|-------|------|------|------|------|------|-------|-----|
| UM1 | amp sp lz | Nunivak Is., Alaska, USA | | 3.2a | 47a | 10a | 43a | 1.6c | 4.2a | 10.7a | 8c |
| UM3 | gr sp lz | Kilbourne Hole, New Mexico, USA | | 4.8a | 43a | 10a | | 1.5a | 1.0a | 38a | 11c |
| UM4 | gr sp lz | Kilbourne Hole, New Mexico, USA | | 18.4a | 30a | 12a | 33b | 1.8a | 2.2a | 28a | 13c |
| UM5 | ff sp lz | Kilbourne Hole, New Mexico, USA | 1.6a+ | 9.6a | 67a | 15a | 57a | 2.0a | 1.1b | 51a | 10c |
| UM6 | gr sp lz | Kilbourne Hole, New Mexico, USA | | 6.3a | 20a | 14a | | 1.3a | 0.9a | 47a | 10c |
| UM7 | ff sp lz | Kilbourne Hole, New Mexico, USA | 4.9a | 8.1a | 60a | 7a | 48a | 2.9a | 1.3a | 61a | 9b |
| UM8 | ff sp lz | Kilbourne Hole, New Mexico, USA | | 3.9a | 35a | 13a | 47a | 1.2a | 0.6a | 25a | 10c |
| UM9 | gr sp lz | Kilbourne Hole, New Mexico, USA | 1.3a | 6.3a | 53a | 13a | 61a | 1.0a | 0.8b | 61a | 18c |
| UM10 | sp lz | San Carlos, Arizona, USA | | 0.5a | 31a | 7a | 49c | 0.9a | 0.3b | 1.3b | ≤2 |
| UM11 | sp lz | San Carlos, Arizona, USA | 3.2a | 0.5a | 54a | 5b | 30a | 1.0a | 0.5b | 1.3a | ≤8 |
| UM12 | sp lz | Cochise Crater, Arizona, USA | 0.7a | 6.9a | 62a | 6b | 68a | 2.3a | 0.7b | 63a | 14c |
| UM13 | sp lz | Salt Lake Crater, Hawaii, USA | | 9.6a | 42a | 9a | 49b | 2.2a | 2.5a | 15.2a | 8c |
| UM14 | sp lz | San Quintin, Mexico | | 2.9a | 29a | 13a | 33c | 3.0a | 0.4b | 17.0a | 14b |
| UM15 | sp lz | Mt. Quincan, Australia | | 1.7a | 52a | 12b | 50a | 2.0a | 0.5b | 7.1a | 14d |
| UM16 | gr g lz | Matsoku, Lesotho, Africa | 9.1a | 3.6a | 34a | ≤1 | 67a | 3.4a | 4.4a | 8.2a | |
| UM17 | gr g lz | Matsoku, Lesotho, Africa | | 2.7a | 22a | 3a | 29d | 2.4a | 12a | 7.6a | 3d |
| UM19 | gr g lz | Matsoku, Lesotho, Africa | | 3.4a | 30a | 2a | | 5.0a | 22a | 9.8a | 5d |
| UM19 | gr g lz | Matsoku, Lesotho, Africa | 2.8a | 10.6a | 38a | 2c | 143a | 11a | 23a | 8.4a | 4d |
| PHN1611 | sh g lz | Thaba Putsoa, Lesotho, Africa | 25a | 19.1a | 81a | 18a | 40a | 10a | 66a | 40a | 22b |
| UM20 | g sp hz | Lashaine, Tanzania, Africa | | 1.3a | 30a | 2a | 9c | 1.0a | 4.2a | 2.2a | ≤2 |
| DR-10 | oc bst | Juan de Fuca Ridge, Pacific Ocean | 18a | 104a | 99a | 100a | 152a | 9a | 50a | 180a | |
| BCR-1 | cn bst | Columbia R., Oregon, USA | 570a | 24a | 135a | 95a | 137a | 45a | 300a | 80a | 5d |
| BCR-1 | cn bst | Columbia R., Oregon, USA | 610a | 23a | 134a | 95a | 134a | 45a | 280a | 78a | 6d |

*amp = amphibole g = garnet sp = spinel ff = fine grained foliated gr = granular sh = sheared bst = basalt hz = harzburgite
 lz = lherzolite cn = continental oc = oceanic

+ Errors based on counting statistics alone; a, 5%; b, 5–10%; c, 10–25%; d, 25–50%.

Table 2. Comparison of volatile element abundances in ultramafic rocks and BCR-1 with previous analyses and with compiled values (in ppb, except for Zn in ppm).

| Element | Ringwood and Kesson (1977) | Chou (1978) | Jagoutz <i>et al.</i> (1979) | This Work | | | Keays <i>et al.</i> (1974) | Morgan (1977) | |
|---------|-------------------------------|----------------|---------------------------------|-----------------|---------|---------|-------------------------------|------------------|-----|
| | Compiled Values | | sp lz* | sp lz | gr g lz | sh g lz | BCR-1 | BCR-1 | |
| Sb | | 100 | | 2 | 6 | 25 | 590 | 550 | 580 |
| Ag | 50 | 50 | | 6 | 5 | 19 | 23 | 27 | 24 |
| Zn | 40 | | 50 | 45 | 31 | 81 | 134 | 131 | 129 |
| In | 3 | | | 8 | 2 | 18 | 85 | 93 | 92 |
| Cd | 14 | | | 47 | 80 | 40 | 136 | 137 | 135 |
| Bi | 6 | | | 1.8 | 5 | 10 | 45 | 46 | 45 |
| Tl | | | | 1.3 | 15 | 66 | 290 | 300 | 280 |
| Se | 50 | | 40 ^a | 47 ^b | 9 | 40 | 79 | 85 | 78 |
| | | | | 9 ^c | | | | | |
| Te | | | | 11 | 4 | 22 | 5 | 6 | 5 |

^aKilbourne Hole and San Carlos only

^bKilbourne Hole and Cochise Crater

^cother localities

*abbreviations as in Table 1.

selected spinel lherzolites, Jagoutz *et al.* (1979) determined only two of our suite of volatile elements: Zn and Se. The agreement for Zn is very good and presumably reflects the compatible nature of this element and also the ease with which it is determined. Comparisons for Se are complicated by the variability of this element in both collections of ultramafic nodules. In our suite of spinel lherzolites, Se appears to be bimodally distributed; a group consisting of the Kilbourne Hole peridotites and UM12 (Cochise Crater) average 47 ppb, the remaining nodules average 9 ppb Se. The high Se abundances in the Kilbourne Hole rocks are presumably associated with the possibly secondary enrichment of sulfide in lherzolites from this locality (Irving, 1980). Of the 6 nodules analyzed by Jagoutz *et al.* (1979), two from southwestern U.S.A. (Kilbourne Hole and San Carlos) average 40 ppb Se and agree reasonably well with ours from proximate localities.

Compiled values

Ringwood and Kesson (1976) have gleaned the sparse data for trace-element abundances in ultramafic rocks from all available sources, and have presented estimates for all the elements listed in Table 1 except for Sb and Tl. Chou (1978) has included Sb and Ag in his estimates of the abundances of siderophile elements in ultramafic rocks. Taking a positive attitude, we look first for those elements for which there is good agreement. Again, Zn is clearly well determined, and the value for Se agrees well with our higher group of values. The compiled values for Bi, Cd and In are based on analyses of harzburgite PCC-1 and dunite DTS-1 and insofar as these rocks are representative of any mantle material, they might be expected to be significantly depleted in many elements. We find indeed that Cd is much lower than our Cd values, but In and Bi fall within the range of our analyses. The estimates for Ag and Sb were based on older analyses, and this may be the reason for the rather large discrepancies.

More recently, the chemical composition and origin of the primitive earth mantle has been reconsidered, and a new table of mantle abundances has been assembled (Sun, 1980). We have not compared our analyses with this new compilation, because Sun's estimates rely heavily on data from a preliminary version (Morgan and Wandless, 1979) of this paper and its companion (Morgan *et al.* (1980a); such a comparison would involve a high degree of circularity.

VOLATILE ELEMENTS IN THE UPPER MANTLE

Elemental abundances in xenoliths as a reflection of upper mantle composition

Fractionation in the upper mantle

The composition of ultramafic nodules has been derived from that of the "primary" (i.e., unfractionated) upper mantle material by means of two major processes; partial melting and metasomatism. The removal of a few percent of

basaltic magma from previously unfractionated mantle rock will leave a residual ultramafic rock that has a higher Mg number and is depleted in such large-ion lithophile (LIL) elements as alkali elements (K, Rb, Cs and Tl; Tl often behaves as an honorary alkali metal) and light rare-earth elements (LREE). Metasomatism by a fluid rich in LIL minor and trace elements may enhance the abundances of these elements in a refractory residual rock (or, for that matter, a previously unfractionated rock) without significantly affecting major-element composition. Therefore, approximately chondritic REE patterns, or even those enriched in LREE, do not necessarily ensure that an ultramafic xenolith is not residual material.

Most of the rocks analyzed in the present work probably represent depleted mantle material, particularly the spinel lherzolites. In our study of the siderophile elements in the same suite of rocks (Morgan *et al.*, 1980a), Ni, Co, Ge and Pt metals generally showed little effect from the combined processes of partial melting and metasomatism. The significant depletions of Re and Au relative to the Pt metals, however, were apparently due to partitioning into basaltic liquid. No substantial enrichments of Re and Au could be ascribed to metasomatism, even in the highly metasomatized amphibole spinel lherzolite UM1. The apparently worldwide uniformity of siderophile abundances in spinel lherzolites strongly indicates, too, that little fractionation of these elements has taken place (Jagoutz *et al.*, 1979; Mitchell and Keays, 1979). Fractionation effects, particularly those involving partial melting, may be far more significant for the lithophile volatile elements listed in Table 1. At least some of these elements seem to have been substantially depleted in spinel lherzolites.

Sheared garnet lherzolite PHN 1611

The key that may help decipher the abundance pattern of volatile elements in the undepleted mantle is the sheared garnet lherzolite PHN 1611, from Thaba Putsoa, Lesotho in Southern Africa. Major element evidence suggests that the sheared garnet lherzolites in general are less refractory than the granular variety, being less depleted in Na, Ti, Fe and Ca. Pyroxene geothermometry and geobarometry suggest that the sheared garnet lherzolites may have originated at depths greater than 150 km (Boyd and Nixon, 1975), and experimental petrology shows that PHN 1611 melts at 10–15 kbar to yield a liquid of quartz tholeiitic composition, and at 20 kbar to produce an olivine tholeiitic magma (Kushiro, 1973). The REE are approximately chondritic in both pattern and abundance (Morgan *et al.*, 1980b), and although Sun (1980) pointed out some deviations from an ideal theoretical mantle composition, the available evidence does suggest that PHN 1611 is reasonably representative of unfractionated mantle material. The distribution of the lithophile volatile elements in PHN 1611 appears to support this conclusion.

Lithophile volatile element patterns

The distribution of lithophile volatile elements in spinel and garnet lherzolites show considerable scatter when normalized to CI chondrites. The variation is evident both between samples and between elements (Fig. 1; readers who find

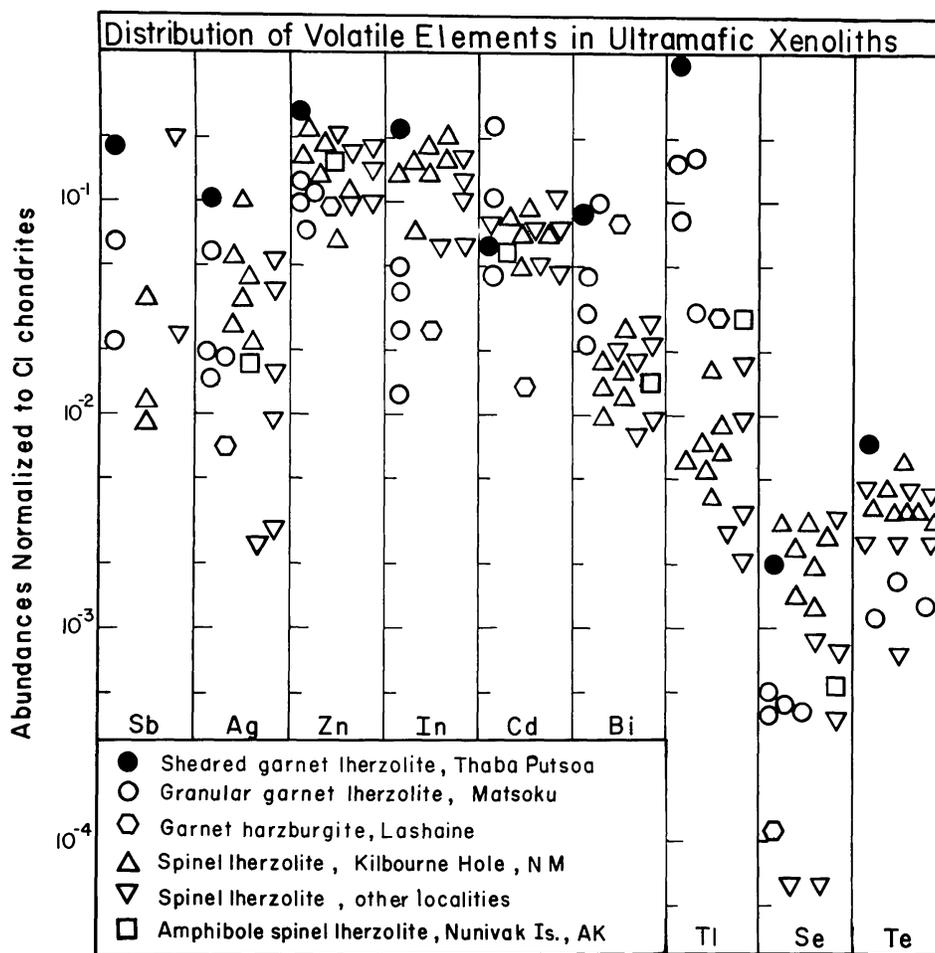


Fig. 1. The distribution of volatile elements in ultramafic xenoliths. Data are normalized to CI chondrite abundances. Elements Sb through Tl are arranged in approximately ascending order of volatility. The highly chalcophile elements Se and Te are quite strongly depleted geochemically and are plotted last. The sheared garnet lherzolite PHN 1611 may be fairly representative of undepleted mantle material.

the large number of data points difficult to assimilate may refer to the central part of Fig. 4 where averaged data are plotted). The data for PHN 1611 are notable for two reasons. First, the fact that most of the absolute abundances are higher than other lherzolites suggests that PHN 1611 may indeed be more representative of undepleted mantle than our other samples. The higher volatile-element abundances (with a possible exception of Tl) seem unlikely to be due predominantly to metasomatic enrichment because we found no corresponding enhancement of LREE content. In addition, the sheared garnet lherzolites generally have been affected far less by metasomatic enrichment processes than has the granular variety (Irving, 1980). Second, when the elements are arranged in order of increasing volatility (as in Fig. 1, where the highly chalcophile elements are also included, but placed last for largely aesthetic reasons), the PHN 1611 abundances tend to suggest a carbonaceous chondrite-like distribution (averaging 0.2 CI chon-

drite abundances) although the scatter about the average is so large that it precludes identification with any particular chondrite group. The volatile elements in PHN 1611 retain at least a trace of their cosmochemical origin, but this origin has been completely obscured by geochemical processes in other more fractionated rocks. Clearly many more samples that are possibly derived from unfractionated mantle must be collected and analyzed.

Depletion of highly chalcophile elements

The abundances of Te and particularly Se are markedly depleted relative to elements of similar volatility in all our ultramafic rock suite, and in all but one of those reported by Jagoutz *et al.* (1979). Of these two elements, Te is more uniform in the spinel lherzolites and is apparently partitioned poorly into the basaltic fraction on partial melting. The very low Te/Se ratios in ocean-ridge basalts (Hertogen *et al.*, 1980) reflect the retention of Te in the mantle and probably are not an indication of severe Te depletion relative to Se in the earth as a whole. These two highly chalcophile elements are only about as volatile as Zn [50% condensation temperatures from a gas of solar composition at 10^{-5} atm are: Zn, 684 K; Se, 684 K; Te, 634 K (Wolf *et al.*, 1979)] and we can find no valid cosmochemical reason for Se (or Te) to be so depleted relative to Zn. In addition, the S/Se ratio is almost invariant over the range of chondritic meteorite types (Mason, 1979); this uniformity suggests that the ratio is rather insensitive to the state of oxidation and the effects of Fe-FeS buffering. To a first approximation, the Se abundance could be used as an indicator for S, but Te may be better because it appears to be far less variable in mantle materials. In PHN 1611, the Cl chondrite-normalized Te/Zn ratio is 0.027 and has a similar value in spinel lherzolites. From this we infer that ~97% of the earth's budget of Te, Se and S has been removed from crust and mantle, and now resides in the outer core. If Zn, S, Se and Te are equally present (on a Cl chondrite-normalized basis) in the bulk earth, we estimate that 9.3% FeS is in solution in the outer core [mass of outer core 0.308 total mass of the earth, Ito (1976).] This appears insufficient to lower the density of the outer core to that inferred geophysically and may require another light element to be present, perhaps O (Ringwood, 1977).

Crust-mantle fractionation of volatile elements

Estimates of the volatile elements in the upper mantle now allow the distribution of these elements in basalts to be considered in terms of partition processes. Fresh oceanic-ridge basaltic glasses are generally considered to be relatively unfractionated partial-melt products from the underlying oceanic mantle. The tendency towards depletion of LREE in these basalts, as well as isotopic evidence, indicates derivation from a depleted source region. Recently, analyses for volatile

trace elements in a specially selected suite of fresh oceanic ridge basaltic glasses have been reported (Hertogen *et al.*, 1980). The earlier work by Laul *et al.* (1972), values for DR-10 reported in the present work, and the new results afford an homogeneous data set. The oceanic basalt abundances can be compared with those in our suite of spinel lherzolites, which are representative of depleted mantle material. The spinel lherzolite samples are from continental, not oceanic, locations, but there is no *a priori* reason to suppose that the depleted segments of the mantle beneath the continents should differ much in composition from those underlying oceanic regions; rare gas isotopic evidence suggests a genetic relationship between oceanic ridge tholeiites and at least the spinel lherzolite from Salt Lake Crater, Hawaii (Kaneoka and Takaoka, 1980). Thus, to a first approximation, some useful insight into the processes of crust-mantle partitioning of volatile elements may be gained by a comparison between oceanic basalts and spinel lherzolites. A similar comparison between continental basalts and undepleted garnet lherzolites should in principle be equally rewarding but is complicated by two factors. First, very few recent data are available for the suite of volatile elements in continental basalts. Second, the effects of magmatic fractionation (and possibly crustal contamination) appear greater for continental basalts than for basalts from oceanic spreading centers.

Continental basalts and garnet lherzolites

For only Columbia River basalt BCR-1 is there a wealth of analyses for the full range of our suite of elements (Keays *et al.*, 1974; Morgan, 1977). A more restricted range of elements has been determined by means of a variety of methods in a large number of samples from the Great Lake (Tasmania) dolerite sheet (Greenland and Campbell, 1977; Greenland and Fones, 1971; Greenland *et al.*, 1973). Considerable fractionation is present throughout the dolerite sheet, and the chilled margin is not entirely representative of the composition of the initial magma because of deuteric alteration (Greenland *et al.*, 1973). The measured concentrations down the section were averaged, weighted according to thickness, to approximate the trace-element composition of the unfractionated magma. In order to make a valid comparison with BCR-1 data, we renormalized the Great Lakes Ag value to correct for a significant difference in the BCR-1 results [36 ppb Ag found by Greenland and Fones (1971) as compared with 23 ppb found in the present work]. No Sb abundances were reported for the Great Lake rocks but a very fresh chilled margin sample M 172 from the related Red Hill intrusion was analyzed for Sb by Tanner and Ehmann (1967). The volatile-element abundances for the two continental basalt occurrences are compared with those of garnet lherzolites in Fig. 2. BCR-1 is an unusually fractionated basalt, approaching an andesite in composition, and may not be entirely representative of the flood basalts from the Columbia River province. The Great Lake intrusion appears fairly typical, however, of the Tasmania-Antarctic Jurassic tholeiites (Greenland *et al.*, 1973). Nevertheless, the trace-element patterns of the two basalt occurrences show virtually the same features. The ratio of basalt abundance to that in PHN 1611 gives a crude estimate of the degree of fractionation

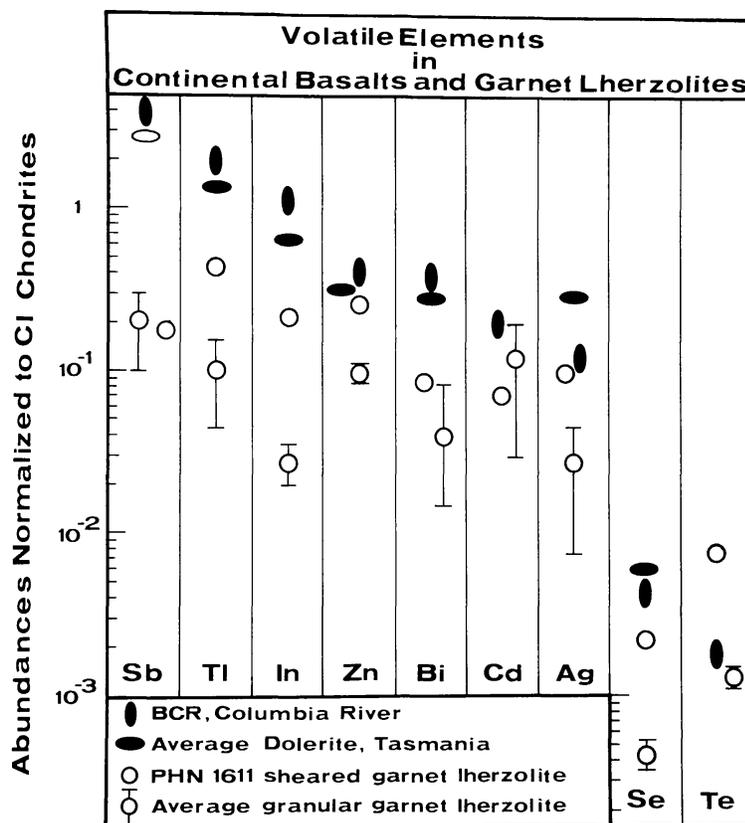


Fig. 2. Comparison of volatile element abundances in 2 continental basalts with those in garnet lherzolites. Data are normalized to CI chondrite abundances and arranged in descending order of their abundances in BCR-1. The Tasmanian dolerite values are section-weighted means of samples from a drill core through the Great Lake dyke. The open symbol for Sb represents a very fresh chilled margin from a related intrusion at Red Hill.

involved in magma production. Now let us compare these ratios with the apparent partition factors between oceanic ridge basalts and spinel lherzolites.

Oceanic ridge basalts and spinel lherzolites

The pattern of basaltic enrichment over probable source region material is seen much more clearly in the oceanic ridge basalts (Fig. 3) than in continental basalts. Again, elements are arranged in decreasing order of abundance, and this order differs from that of the continental basalts in some important respects. Thallium in the putative source region material is rather strongly depleted, and though it is still quite strongly partitioned into the oceanic ridge basalt, the resulting content remains quite low (as is generally the case for K-related elements in these rocks). Antimony which was the most abundant in continental basalts (on a CI chondrite-normalized basis) is now amongst the least enriched. Not only is the source material apparently depleted in Sb, but the degree of enhancement in most oceanic basalts seems considerably less than in the continental basalts. (There are several oceanic ridge samples, however, that are unusually high in Sb.) For

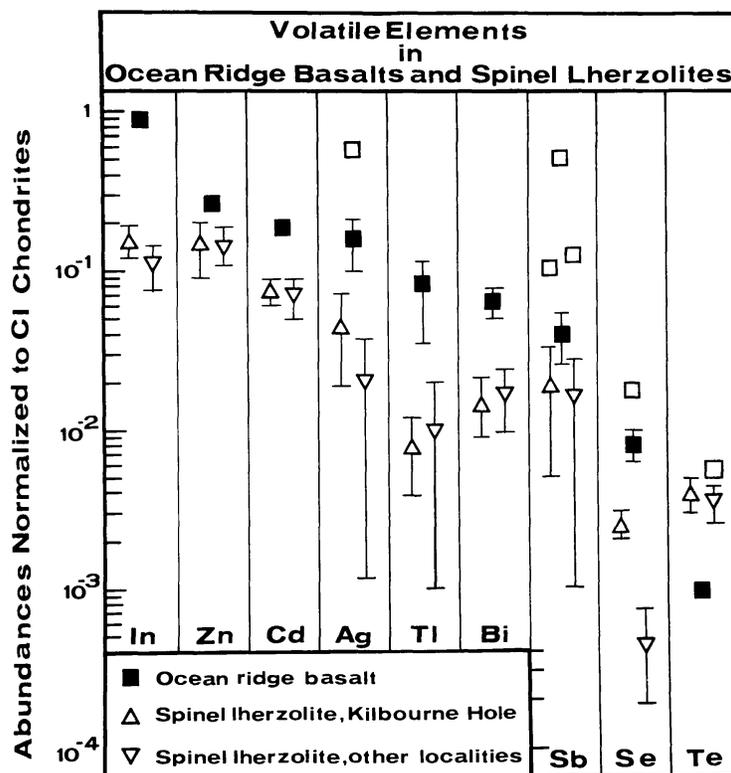


Fig. 3. Comparison of volatile-element abundances in oceanic ridge basalts with those in spinel lherzolites. Data are normalized to CI chondrite abundances and are arranged in decreasing order of their average abundance in oceanic-ridge basalts. Open squares represent basalts that have abundances very different from the average values.

most other elements, Table 3 shows a considerable similarity in enrichment factors between basalt and presumed source region for both oceanic and continental region.

Recently, Anderson (1980) has compared concentrations of lithophile elements in oceanic ridge basalts with those in continental tholeiites. The comparison suggests that the source region of oceanic basalts, while depleted in incompatible elements, has retained much of its complement of compatible elements. If the spinel lherzolites are indeed reasonably representative of a depleted source region, the present work indicates that this conclusion may be extended to the volatile elements.

LIMITATIONS ON TERRESTRIAL ACCRETION MODELS

Distribution of siderophile and volatile elements in upper mantle rocks

The abundances of volatile elements in the earth's upper mantle inferred from the present work, and those of siderophile elements reported previously (Morgan *et al.*, 1980a), place important new constraints on self-consistent historical earth models. The new data for five highly siderophile elements (Os, Re, Ir, Pd, Au),

three moderately siderophile elements (Ni, Co, Ge), seven lithophile volatile elements (Sb, Ag, Zn, In, Cd, Bi, Tl) and two chalcophile elements (Se, Te) are shown in Fig. 4.

The abundance patterns can be briefly summarized as follows. Highly siderophile elements: The Pt metals Os, Ir and Pd have uniform abundances and appear to retain chondritic mutual proportions. These elements average 0.008 CI chondrite abundances. The levels of Au and Re are more variable than those of the Pt metals, but the Au/Re ratios do not differ appreciably from the cosmic value. The fact that higher values of Au and Re have essentially cosmic ratios with respect to the Pt metals, suggests that originally all five of these highly siderophile elements described a chondritic pattern in undepleted mantle material.

Moderately siderophile elements: Abundances are extremely uniform in all our ultramafic rocks, averaging 0.20 ± 0.02 Ni, 0.22 ± 0.02 Co, but only 0.027 ± 0.004 Ge, all values normalized to CI chondrites.

Volatile elements: The four least volatile elements of this group (Sb, Ag, Zn, In) average 0.19 ± 0.07 in PHN 1611, and are roughly about as abundant as Ni and Co. This seems to be a geochemical coincidence, however, because in volatility, Sb and Ag closely resemble the far more depleted element Ge. The three most volatile elements (Cd, Bi, Tl) are much more variable, perhaps in part owing to metasomatic enrichment of Tl.

Table 3. Apparent enrichment factors between basalts and possible source regions.

| Element | Abundance ratio of basalt: source material | | | |
|---------|---|-----|---------|-----|
| | Continental | | Oceanic | |
| | 1 | 2 | 3 | 4 |
| Sb | 24 | 16 | 3 | 3 |
| Ag | 1.2 | 5 | 4 | 8 |
| Zn | 1.7 | 1.2 | 1.8 | 1.8 |
| In | 5 | 3 | 6 | 9 |
| Cd | 3 | — | 3 | 3 |
| Bi | 5 | 3 | 4 | 4 |
| Tl | 4 | 3 | 10 | 8 |
| Se | 2 | 3 | 4 | 19 |
| Te | .2 | — | .2 | .3 |

¹ Basalt BCR-1: sheared garnet lherzolite PHN 1611

² Tasmanian dolerite average: sheared garnet lherzolite PHN 1611

³ Oceanic basalt average: Kilbourne Hole spinel lherzolites

⁴ Oceanic basalt average: spinel lherzolites from other localities

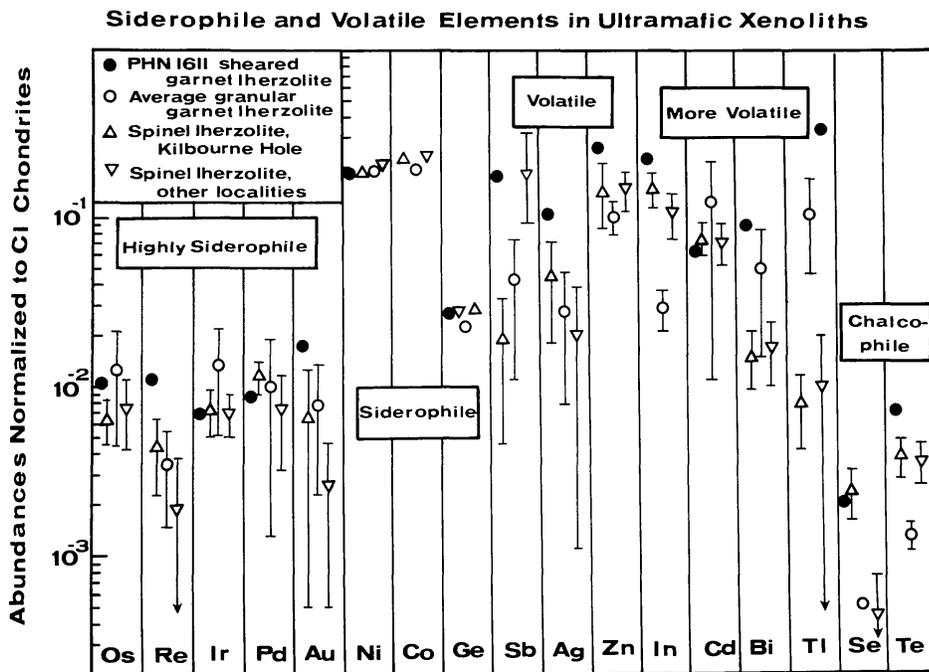


Fig. 4. Distribution of siderophile and volatile elements in ultramafic rocks. Data are normalized to CI chondrites; siderophile element analyses have been taken from Morgan *et al.* (1980a).

Chalcophile elements: Tellurium is much more uniformly distributed in ultramafic rocks than is Se and may be a better guide to the original abundance of this pair [of the chondrites, only the LL7 chondrite, Shaw, which has lost substantial metal and troilite (Takahashi *et al.*, 1978), has Se significantly depleted relative to Te.] In PHN 1611, Te, at $0.007 \times$ CI chondrites, is about as abundant as the highly siderophile elements, but Se is considerably lower (0.002 on the same scale).

These are the patterns that must be unified in terms of the accretionary history and geochemical evolution of the earth.

Volatile-element depletion and the earth's Ni, Co and Ge content

Simple two component models have been proposed to explain the composition of the earth. The most recent of these requires a mixture of 90% highly reduced, metal-rich material that is poor in volatile elements and 10% of an oxidized primordial component that is rich in volatile elements (Ringwood, 1977). A similar but more gradational model was earlier proposed by Clark *et al.* (1972). Such models provide Ni, Co and the Zn group of volatile elements in about the correct proportions. Some rather special circumstance is required to explain the large depletion of Ge relative to Ni, Co, Zn, etc. The new data on the highly siderophile

elements suggest that any addition of oxidized material cannot have been greater than about 1% (and probably much less if the mantle is not well mixed). Any attempt to explain the low abundances of the Pt metals by some partial extraction mechanism loses a great deal of plausibility in the face of the almost chondritic proportions of these elements.

The models described above can be slightly modified to meet the new criteria. We have suggested (Morgan *et al.*, 1980a) that perhaps the bulk of the earth is indeed made of volatile-poor chondrite-like material (Ringwood, 1977), analogous to the "Mg silicate" of Ganapathy and Anders (1974). The material was highly reduced so that Ni, Co and Ge were predominantly in the Fe-Ni metallic phase, and even at this stage a low Ge:Ni ratio in the metal reflected the paucity of volatile elements in this major component. During accretion, apparently the metallic phase was partially oxidized, and Ni, Co and Ge entered the silicate, but the highly siderophile elements were retained in the relict metal phase and eventually entered the core. The process probably resembled the analytical technique of cupellation used in classical fire assay to concentrate Pt metals, Au and Ag after their extraction from ores in a Pb button (Beamish, 1966). In this technique the Pb is heated in air, whereupon Pb and base metals (including Fe and Ni) are oxidized and absorbed by the porous bone-ash crucible or "cupel"; the noble metals, however, are quantitatively retained in the residual phase. No information is available concerning the behavior of Ge in this process, but it is presumably oxidized in much the same fashion as Ni. Discussion in our previous paper (Morgan *et al.*, 1980a) indicates that the Ge:Ni ratio in the upper mantle is probably a reasonable approximation to that in the original accreting material. The new data for volatile elements tend to support this view. First, we can show that the whole Earth abundances of Ni, Co and Ge are consistent with a Ganapathy-Anders type calculation (Ganapathy and Anders, 1974; BVSP, 1981). In Fig. 5, we scale the model values of whole earth's Ni, Co and Ge to Ni = 0.2 × Cl chondrites to allow for the fraction of these elements oxidized. (Absolute abundance is a free parameter because the calculations do not predict this fraction *a priori*.) The fit of the calculated values to those observed is clearly very close. Second, we can reverse the argument and scale the moderately siderophile elements to the volatile elements by making the cosmochemically reasonable assumption that Ge is about as abundant as the moderately volatile elements Sb, Ag, Sn (and In) on a Cl chondrite normalized basis. Implicit in this assumption is a lack of metal-silicate fractionation of the proto-planetary material before accretion into the bulk earth. The earth's core is 0.325 of the total mass, and combined with an apparent terrestrial $\frac{\text{MgO}}{\text{MgO} + \text{FeO mol}}$ of 0.88, we can deduce a bulk (total Fe)/Si weight ratio of 1.62 (BSVP, 1981). Because the corresponding cosmic ratio is 1.65 (Cameron, 1973), we can accept the premise that little fractionation of Fe-Ni took place during the earth's accretion. By scaling Ge to Zn (a well determined compatible element), we calculate a bulk earth Ni content of 1.8%. This result is in good agreement with the value of 2.0% Ni given by Gan-

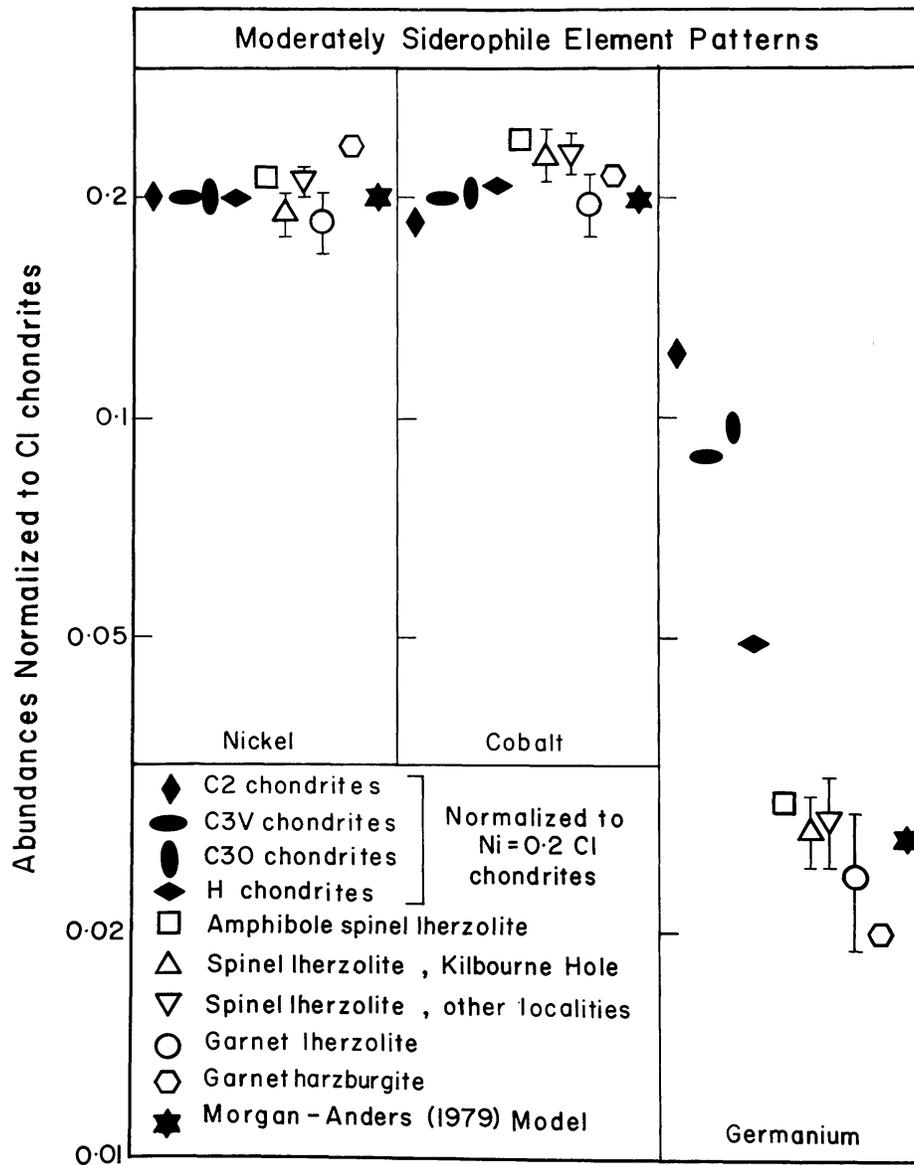


Fig. 5. Comparison of patterns of moderately siderophile elements in ultramafic rocks with chondrite patterns and with calculated abundances normalized to Ni. Results of the Morgan and Anders (1979) model have been incorporated in BVSP (1981).

apathy and Anders (1974) and of 1.9% Ni in a more recent calculation of a similar type (BVSP, 1981). Too much weight should not be given to the very close agreement, because variations in the ways of scaling Ge can give values as low as 1% Ni. The important point is that the values—those calculated theoretically from crustal elemental ratios, (e.g., Ganapathy and Anders, 1974) and those derived from the new empirical data obtained directly from rocks probably derived from the earth's upper mantle—agree to within less than a factor of 2 or 3 and are not an order of magnitude or more apart, as they well might be if our assumption contained a serious error.

Origin of highly siderophile elements and chalcophile elements in the upper mantle

The partial oxidation (or cupellation) process described in the preceding section would leave the earth's mantle virtually devoid of highly siderophile elements, owing to core formation. Metallic Fe and FeS form a low melting point eutectic (1250 K; Hansen and Anderko, 1958), and therefore sulfides would be efficiently stripped from a sulfide-poor medium. The abundances of such highly chalcophile elements as Te and Se might therefore be expected to be as severely depleted as the highly siderophile elements. That the moon received a heavy bombardment during the first 600 m.y. of its history is well established, and the earth would have collected material from this family of objects even more efficiently because of its greater gravitational potential. This bombardment is an extremely plausible source of highly siderophile elements, as pointed out in Kimura *et al.* (1974) and in more detail by Chou (1978). A quantitative treatment suggests that the earth may have collected 10^{25} g of material during the 600 m.y. bombardment, if the highly siderophile elements are confined to the upper mantle by the 670-km discontinuity (Anderson, 1979).

The abundances of Te in upper mantle material are remarkably constant, and are similar to those of the highly siderophile elements in equivalent types of rocks. Therefore, the possibility that Te was also added by the post accretionary bombardment is tempting to suggest. The Te:(Pt metal) ratio is 0.8 in PHN 1611 and 0.5 in the spinel lherzolites. If this ratio is indeed representative of the bombarding population, then the average composition of the population may have been as rich in volatile elements as were the C2 chondrites. The earth contains 1.6×10^{-4} of its planetary mass of H₂O. The C2 chondrites have $8.0 \pm 0.8\%$ of combined H₂O (Boata, 1954) and the earth's water could be provided by 0.2% of the planetary mass of such material. This mass fraction corresponds to 1.2×10^{25} g, and is clearly in very good agreement with a previous estimate for the aggregate mass of material required to account for the highly siderophile elements in the upper mantle.

Lest we be overwhelmed by euphoria, a major inconsistency should be mentioned and an alternative solution outlined. During the late bombardment, both earth and moon were presumably subjected to the same flux of planetesimals, yet *none* of the meteoritic components identified in ancient lunar breccias are as high in Te as the assumed *average* composition of the earth-impacting population. To be sure, we can contrive explanations—volatile-element loss during the impact process and gravitational sorting by geocentric velocity. Only the most recent basin-forming impacts on the moon may have been characterized, and these are restricted to the moon's nearside. Nevertheless, the assumption that Te is a better guide than Se may be incorrect. In the preceding discussion, we have tacitly assumed that low Se relative to Te was due to the demonstrated ease of fractionation of Se. Suppose, however, that the reverse were true, and that Te were incompletely extracted from the mantle during core formation; then Se might provide a better estimate of the volatile element content of the late-bombarding

planetesimal population. The Se/(Pt metals) ratios of PHN 1611 and the Kilbourne Hole spinel lherzolites are 0.23 and 0.27, respectively. These values ease the problem of the comparison with lunar meteoritic components but are still somewhat higher than the lunar component richest in volatile elements; Group 2 (Gros *et al.*, 1976). Admittedly, the Se/(Pt metal) ratios in granular garnet lherzolites and the remaining spinel lherzolites are much lower (0.036 and 0.060, respectively) and are more in the range of ratios in lunar meteoritic components, however the comparison is not really valid because of the significant fractionation effects shown by these terrestrial rocks. A Se/(Pt metal) ratio of 0.25 is similar to ratios found in C3 and H group chondrites and would imply that an insignificant amount of H₂O was provided by the late-bombarding population of planetesimals.

CONCLUSIONS

The new measurements of abundances of volatile elements in ultramafic nodules may be combined with the siderophile element data for the same rocks to put new constraints on evolutionary earth models. We briefly summarize below the observations and important first-order inferences relating to the development of the terrestrial upper mantle and the derivation hence of crustal mafic rocks.

Summary of data and inferences

Volatile-element content of ultramafic xenoliths

The sheared garnet lherzolite PHN 1611 may represent our best sample of undepleted mantle material. Abundances of lithophile volatile elements in PHN 1611 tend to be higher than those in granular garnet lherzolites and in spinel lherzolites. When normalized to C1 chondrites the 4 least volatile elements (Sb, Ag, Zn, In) lie within a factor of 2 of a mean value of 0.2. The 3 most volatile elements (Cd, Bi, Tl) are much more variable, possibly because of some metasomatic enrichment of Tl, a highly incompatible element.

Spinel lherzolite nodules probably represent depleted mantle, and generally contain lower abundances of volatile elements than does PHN 1611, particularly of the more incompatible elements. The granular garnet lherzolites have apparently been depleted by a partial-melting episode, but such highly incompatible elements as Tl and the LREE show evidence of subsequent metasomatic enrichment.

The highly chalcophile elements, Se and Te, are strongly depleted in mantle rocks relative to lithophile elements of similar volatility, such as Zn. From this we infer that ~97% of the earth's S, Se and Te now may reside in the outer core, corresponding to a maximum of about 9% FeS in solution in the liquid metal. This seems insufficient FeS to lower the density of the outer core to that inferred geophysically, and the presence of another light element may be required.

The observed abundances in mantle rocks of such moderately volatile elements as Zn suggest that the well-determined depletion of Ge relative to Ni and Co

requires no special circumstance but simply reflects the general depletion in the earth of elements of similar volatility.

Basalt-lherzolite fractionation of volatile elements

Oceanic-ridge basalts are derived from depleted mantle sources, which may compositionally resemble the spinel lherzolites. Continental tholeiites, in contrast, appear to originate in relatively undepleted mantle, for which PHN 1611 may be a reasonable approximation. Comparisons of oceanic ridge basalts and continental tholeiites with materials possibly representative of their source regions indicates that, with the exception of Sb, the degrees of fractionation are remarkably similar, particularly for the more compatible elements. This conclusion suggests that, in principle, source-region trace element composition may be estimated from basaltic abundances.

Possible accretion history

The bulk of the earth appears to have been formed from chondrite-like material poor in volatile elements, sufficiently reduced for Ni, Co and Ge to be in the metal phase. Partial oxidation during accretion allowed some Ni, Co and Ge to enter the silicate phase but the highly siderophile elements (Pt metals, Au, Re) were retained in the relict metal and, along with S and the highly chalcophile elements, were effectively removed from the mantle during core formation. The highly siderophile elements, and perhaps the highly chalcophile elements, were probably introduced into the mantle above the 670 km discontinuity by an influx of 10^{25} g of planetesimals during the first 600 m.y. of the earth's history. Depending upon the composition of the bombarding population, the earth's complement of H₂O may also have been introduced at this late stage.

Acknowledgments—We thank F. R. Boyd and R. Wendlandt for making a sample of PHN 1611 available for study. We also thank Edward Anders for useful suggestions; and D. L. Anderson, J. G. Arth, Anthony Finnerty and David Gottfried for helpful reviews. This work was supported in part by NASA contract T-4089F and is in part based upon activities supported by the National Science Foundation under agreement No. EAR-7911120. (Any opinions, findings and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.)

This paper constitutes contribution No. 44 of the Basaltic Volcanism Study Project. The project is organized and administered by the Lunar and Planetary Institute/Universities Space Research Association under Contract NASW-3389 with the National Aeronautics and Space Administration.

REFERENCES

- Anders E. (1968) Chemical processes in the early solar system, as inferred from meteorites. *Acc. Chem. Res.* **1**, 289–298.
- Anderson D. L. (1979) Chemical stratification of the mantle. *J. Geophys. Res.* **84**, 6297–1298.
- Anderson D. L. (1980) Hotspots and the evolution of the mantle. *Science*, In press.
- Beamish R. D. (1966) *The Analytical Chemistry of the Noble Metals*. Pergamon, Oxford. 609 pp.
- Boata G. (1954). The isotopic composition of hydrogen and carbon in the carbonaceous chondrites. *Geochim. Cosmochim. Acta* **6**, 209–220.

- Boyd F. R. and Nixon P. H. (1975) Origin of the ultramafic nodules from some kimberlites of northern Lesotho and the Monastery mine, South Africa. In *Physics and Chemistry of the Earth*, Vol. 9 (L. H. Ahrens, J. B. Dawson, A. R. Duncan, and A. J. Erlank, eds.), p. 431–454. Pergamon, Oxford.
- BVSP (Basaltic Volcanism Study Project) (1981) Mantles of the terrestrial planets. In *Basaltic Volcanism on the Terrestrial Planets*, Chapter 4. Pergamon, N.Y. In press.
- Cameron A. G. W. (1973) Abundances of the elements in the solar system. *Space Sci. Rev.* **15**, 121–146.
- Chou C. L. (1978) Fractionation of siderophile elements in the earth's upper mantle. *Proc. Lunar Planet. Sci. Conf. 9th*, p. 219–230.
- Clark S. P., Turekian K. K., and Grossman L. (1972) Model for the early history of the Earth. In *The Nature of the Solid Earth* (E. C. Robertson, ed.), p. 3–18. McGraw-Hill, N.Y.
- Flanagan F. J. (1976) Descriptions and analyses of eight new U.S.G.S. rock standards. *U. S. Geol. Survey Prof. Paper 840*. 192 pp.
- Ganapathy R. and Anders E. (1974) Bulk compositions of the moon and earth, estimated from meteorites. *Proc. Lunar Sci. Conf. 5th*, p. 1181–1206.
- Gast P. W. (1960) Limitations on the composition of the upper mantle. *J. Geophys. Res.* **65**, 1287–1297.
- Greenland L. P. and Campbell E. Y. (1977) Variation of Se, Te, In, Tl and Zn with differentiation of tholeiitic magma. *Neues Jahrb. Mineral. Mh.* **1977**, 112–118.
- Greenland L. P. and Fones R. (1971) Geochemical behavior of silver in a differentiated tholeiitic dolerite sheet. *Neues Jahrb. Mineral. Mh.* **1971**, 393–398.
- Greenland L. P., Gottfried D., and Campbell E. Y. (1973) Aspects of the magmatic geochemistry of bismuth. *Geochim. Cosmochim. Acta* **37**, 283–295.
- Gros J., Takahashi H., Hertogen J., Morgan J. W., and Anders E. (1976) Composition of the projectiles that bombarded the lunar highlands. *Proc. Lunar Sci. Conf. 7th*, p. 2403–2425.
- Hansen M. and Anderko K. (1958) *Constitution of Binary Alloys*. McGraw-Hill, N.Y. 1305 pp.
- Hertogen J., Janssens M.-J., Palme H., and Anders E. (1980) Trace elements in ocean ridge basalt glasses: Implications for fractionations during mantle evolution and petrogenesis. *Geochim. Cosmochim. Acta*. In press.
- Irving A. J. (1980) Correlated major and lithophile trace element geochemistry of ultramafic xenoliths. *Tectonophys.* In press.
- Ito K. (1976) Outer cores of the terrestrial planets: Eutectic-melt hypothesis. *Geochem. J.* **10**, 59–64.
- Jagoutz E., Palme H., Baddenhausen H., Blum K., Cendales M., Dreibus G., Spettel B., Lorenz V., and Wänke H. (1979) The abundances of major, minor and trace elements in the earth's mantle as derived from primitive ultramafic rocks. *Proc. Lunar Planet. Sci. Conf. 10th*, p. 2031–2050.
- Kaneoka I. and Takaoka N. (1980) Rare gas isotopes in Hawaiian ultramafic nodules and volcanic rocks: Constraints on genetic relationships. *Science* **208**, 1366–1368.
- Keays R. R., Ganapathy R., Laul J. C., Krähenbühl U., and Morgan J. W. (1974) The simultaneous determination of 20 trace elements in terrestrial, lunar and meteoritic material by radiochemical neutron activation analysis. *Anal. Chim. Acta* **72**, 1–29.
- Kimura K., Lewis R. S., and Anders E. (1974) Distribution of gold and rhenium between nickel-iron and silicate melts: Implications for the abundance of siderophile elements on the Earth and Moon. *Geochim. Cosmochim. Acta.* **38**, 683–701.
- Krähenbühl U., von Gunten H. R., Jost D., Meyer G., and Wegmüller F. (1979) Trace and major elements in grain size fractions of two strata statura of drive tube 74001 (abstract). In *Lunar and Planetary Science X*, p. 668–690. Lunar and Planetary Institute, Houston.
- Kushiro I. (1973) Partial melting of garnet lherzolites from kimberlite at high pressures. In *Lesotho Kimberlites* (P. H. Nixon, ed.), p. 294–299. Cape and Transvaal, Capetown.
- Laul J. C., Keays, R. R., Ganapathy R., Anders E., and Morgan J. W. (1972) Chemical fractionations in meteorites—V. Volatile and siderophile elements in achondrites and ocean ridge basalts. *Geochim. Cosmochim. Acta* **36**, 329–345.
- Mason B. (1979) In *Data of Geochemistry Sixth Edition* Chapter B. Cosmochemistry Part 1. Meteorites. (M. Fleischer, ed). U.S. Geol. Survey Prof. Paper 440-B-1. U.S. Government Printing Office, Washington, D.C.

- Melson W. G. (1969) Preliminary results of a geophysical study of portions of the Juan de Fuca Ridge and Blanco fracture zone. *ESSA Technical Memorandum C and GSTMG*. U.S. Department of Commerce, Washington, D.C. 33 pp.
- Mitchell R. H. and Keays R. R. (1979) Palladium, gold and iridium in mantle minerals: Implications for models of magma genesis (abstract). In *Abstracts and Timetable for Inter-disciplinary Symposium*, p. 259. IUGG XVII General Assembly, Canberra, Australia.
- Morgan J. W. (1977) Chemical fractionation in the solar system. *J. Radioanal. Chem.* **37**, 79–118.
- Morgan J. W. and Petrie R. K. (1979) Siderophile and volatile trace elements in breccias 73215 and 73255 and in core 74001 (abstract). In *Lunar and Planetary Science X*, p. 852–854. Lunar and Planetary Institute, Houston.
- Morgan J. W. and Wandless G. A. (1979) Terrestrial upper mantle: Siderophile and volatile trace element abundances (abstract). In *Lunar and Planetary Science X*, p. 855–857. Lunar and Planetary Institute, Houston.
- Morgan J. W. and Anders E. (1979) Chemical composition of Mars. *Geochim. Cosmochim. Acta* **43**, 1601–1610.
- Morgan J. W., Ganapathy R., Higuchi H., Krähenbühl U., and Anders E. (1974) Lunar basins: Tentative characterization of projectiles, from meteoritic elements in Apollo 17 boulders. *Proc. Lunar Sci. Conf. 5th*, p. 1703–1736.
- Morgan J. W., Wandless G. A., Petrie R. K., and Irving A. J. (1980a) Composition of the Earth's upper mantle-I. Siderophile trace elements in ultramafic nodules. *Tectonophys.* In press.
- Morgan J. W., Wandless G. A., Petrie R. K., and Irving A. J. (1980b) Earth's upper mantle: Volatile element distribution and origin of siderophile element content (abstract). In *Lunar and Planetary Science XI*, p. 740–742. Lunar and Planetary Institute, Houston.
- Ringwood A. E. (1966) Chemical evolution of the terrestrial planets. *Geochim. Cosmochim. Acta* **30**, 41–104.
- Ringwood A. E. (1977) Composition of the core and implications for origin of the Earth. *Geochem. J.* **11**, 111–135.
- Ringwood A. E. and Kesson S. E. (1976) Basaltic magmatism and the composition of the Moon. Part II. Siderophile and volatile elements in Moon, Earth and chondrites: Implications for lunar origin. Publication No. 1222, Research School of Earth Sciences, Australian National University, Canberra. 58 pp.
- Sun S.-S. (1980) Chemical composition and origin of the primitive Earth mantle. *Earth Planet. Sci. Lett.* In press.
- Takahashi H., Gros J., Higuchi H., Morgan J. W., and Anders E. (1978) Volatile elements in chondrites: metamorphism or nebular fractionation. *Geochim. Cosmochim. Acta* **42**, 1859–1869.
- Tanner J. T. and Ehmann W. D. (1967) The abundance of antimony in meteorites, tektites and rocks by neutron activation analysis. *Geochim. Cosmochim. Acta* **31**, 2007–2026.
- Wasserburg F. J., McDonald G. J. F., Hoyle F., and Fowler W. A. (1964) Relative contributions of uranium, thorium and potassium to heat production in the Earth. *Science* **143**, 465–467.
- Wolf R. and Anders E. (1979) Moon and Earth: Compositional differences inferred from siderophiles, volatiles, and alkalis in basalts. *Geochim. Cosmochim. Acta*. In press.
- Wolf R., Woodrow A., and Anders E. (1979) Siderophile and volatile elements in the Earth and Moon: similar or not? (abstract). In *Lunar and Planetary Science X*, p. 1361–1363. Lunar and Planetary Institute, Houston.
- Wolf R., Richter G. R., Woodrow A. B., and Anders E. (1980) Chemical fractionations in meteorites—X1. C2 chondrites. *Geochim. Cosmochim. Acta* **44**, 717–717.