PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Metallogenesis in Relation to Mantle Heterogeneity [and Discussion]

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Metallogenesis in relation to mantle heterogeneity

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Regional variations in the type and abundance of metalliferous mineral deposits formed at a given time depend on environmental factors operating not only at the sites of deposition but also in the source regions supplying the metals. The extent to which chemical heterogeneities in the mantle may have helped to determine such patterns of variation can be most effectively explored by concentrating on types of ore deposit that are genetically related to magmatism originating in the mantle. Attention is focused particularly on regions where phases of mineralization involving the same metal or group of metals have been repeated over a long time-span and/or in widely different tectonic settings. Chromium, platinum, nickel, tin and uranium are of interest in this context. Although the two latter elements are often considered to have crustal sources, it is suggested that mantle-derived volatiles have played a part in the processes leading to their enrichment in certain acid magmas.

1. Introduction

The distribution of metalliferous mineral deposits is worth considering in the context of mantle inhomogeneity for two reasons: first, because the metals that are concentrated in certain types of deposit are thought to have been derived, directly or at only one or two removes, from sources in the mantle; and secondly, because regional variations in the abundance of certain types of deposit do not seem to be readily explicable by reference to tectonic setting or crustal processes. The accumulation of evidence that variations in the compositions of igneous assemblages may reflect the influence of inhomogeneities in the mantle (see, for example, other papers in this volume) raises the possibility that irregularities in the distribution of ore deposits related to mantle-derived magmatism may reflect the same influence.

The formation of economic concentrations of any metal involves the interplay of processes operating in the source region, in the crustal environments through which the metal is transported, and at the ultimate sites of mineralization. Under most circumstances, variations in the conditions of transport and deposition probably mask effects related to inhomogeneity of mantle source regions. The discussion which follows is therefore focused on styles of mineralization that do not involve extensive recycling of metals by crustal processes such as weathering, sedimentation or the circulation of groundwaters or hydrothermal fluids. Deposits of orthomagmatic and pneumatolytic origin, formed by processes inseparable from those responsible for the differentiation of the associated igneous rocks, provide the most suitable material for investigation in the present context. Two groups of such deposits are discussed below. The first includes deposits associated with basic and ultrabasic igneous suites which are almost universally accepted as derivatives of partial melts formed in the mantle. The second includes deposits associated with certain types of acid intrusives whose relation with mantle sources is more questionable.

† Elected F.R.S. 15 March 1979.

2. Chromium and nickel in basic–ultrabasic igneous assemblages

Chromium, platinum, nickel and a number of related metals characteristically form concentrations in or adjacent to igneous complexes dominated by basic and ultrabasic rocks. Most of these concentrations appear to have been formed as by-products of differentiation of the parent magma. The principal factors that govern their distribution are therefore those concerned either with partial melting in the mantle or with the course of crystallization at the site of intrusion or extrusion. Differentiated basic–ultrabasic complexes are among the commonest products of igneous activity and have been formed through the entire span of geological time in a variety of tectonic environments; only a minority of these complexes contain mineral deposits of economic importance.

The idea that the abundance of chromite deposits in basic–ultrabasic complexes varies in relation to the composition of the underlying mantle was outlined by Anhaeusser (1974, 1976) in discussions of the significance of mineralization in southern Africa. An area of about 200000 km^2 extending from Rhodesia to the Transvaal (South Africa) contains the World's largest known concentration of chromite. The mineral, occurring mainly in stratiform layers segregated during crystallization, is associated with igneous bodies that vary widely in tectonic setting, intrusion form and bulk composition. Archaean deposits are associated with ultramafic sheets intercalated in a typical greenstone-belt (Selukwe, Rhodesia) with intensely deformed stratiform anorthosite–gabbro complexes of the Limpopo belt and with the unusual Mashaba complex (Rhodesia) emplaced in a relatively stable environment. Proterozoic deposits occur in the gravity-stratified lopolithic complexes of the Great Dyke and Bushveld complex, both of which were emplaced in cratonic crustal massifs. Anhaeusser has pointed out that these chromite-bearing intrusions were emplaced at intervals through a time-span of about 1500 Ma and has inferred that throughout this period the crustal region concerned was situated above a mantle area enriched in chromium. An alternative possibility (Watson 1978) is that the mantle was anomalous with respect to an element such as oxygen which is capable of influencing the behaviour of chromium during partial melting or crystallization differentiation.

Regional anomalies in the distribution of sulphide nickel deposits with respect to that of the types of igneous complex most often associated with nickel mineralization have also been tentatively interpreted in terms of mantle inhomogeneity, possibly involving sulphur which influences the partitioning of nickel between sulphide and silicate minerals (Watson 1978). Well over half of the World's known reserves of nickel are contained in an area of 1500 km × 1000 km in Canada and northern U.S.A. The parent igneous bodies, emplaced over a time-span of more than 1500 Ma, are very diverse in tectonic relations and compositions. They include ultramafic sheets incorporated in Archaean greenstone belts, ultramafic bodies in a deep shear zone (the Thompson lineament), the Sudbury lopolith, possibly generated by meteoritic impact, and the Duluth stratiform complex emplaced in a continental rift structure. As with the southern Africa chromite deposits, the common factor linking these occurrences is their spatial association. The wide range of ages, characters and settings of the parent igneous bodies seems to rule out the possibility that the segregation of nickel sulphides took place because partial melting and subsequent differentiation occurred under uniformly favourable conditions. The favourable anomaly may therefore have been connected with the composition of the mantle underlying the area.

3. Tin-bearing and uranium-bearing acid intrusives

Tin, with elements such as tungsten and niobium, is consistently associated with acid plutonic to subvolcanic igneous rocks and pegmatites or with detrital sediments derived from these rocks. The parent igneous assemblages fall within a rather narrow chemical range and are commonly enriched in elements such as Li, Be, B or F. The distribution of economic concentrations of tin is unusual in terms of tectonic setting and age, for while ore deposits are associated with igneous bodies emplaced in both mobile and cratonic crustal provinces, they are almost confined to late Proterozoic and Phanerozoic rocks, the great majority being less than 400 Ma in age. Their spatial distribution is notoriously patchy with respect to the related tectonic provinces and many authorities (e.g. Schuiling 1967) have delineated tin provinces or tin belts in which mineralization is thought to have been favoured by the occurrence of anomalous concentrations of tin and/or some of the associated elements in the magma source regions. The persistence of anomalies favouring tin mineralization in some provinces is demonstrated by the recurrence of deposits of widely different ages (*ca.* 1000 to *ca.* 15 Ma in the western Brazil–Bolivia belt of South America; *ca.* 500 to *ca.* 160 Ma in Nigeria).

The extent to which the mantle has contributed to the generation of tin-bearing granites is disputed. A strong body of opinion holds that both granites and associated metals are derived, by partial melting or by a process of scavenging, from crustal sources enriched in tin (for discussion see Hunter (1973) and Hutchison & Chakraborty (1978)). Tischendorf (1973) and Moreau (1976) see Hercynian tin in Europe as having its origin in thick geosynclinal welts subjected to anatexis. Granites of the 1000 Ma Rondônia province in Brazil or the Mesozoic 'newer granite' province of Nigeria, which were emplaced in stabilized cratonic crust composed of high-grade metamorphic rocks and older granites, can, however, have had no connection with geosynclinal processes or thickening of the crust, and although partial melting at sites of anomalously high heat flow provides a possible mechanism for their formation it seems unlikely that the tight, structurally complex basement rocks traversed by the rising magma could provide channels for scavenging by volatiles of the type which may be effective in lower-grade, well layered geosynclinal sedimentary sequences.

The common arrangement of tin-bearing complexes in linear zones some of which correspond to old-established structural features (Wright 1970), and the fact that most such igneous bodies carry unusual amounts of Be, Li, F or P, has focused attention on the role of volatiles in mineralization and especially on the activity of fluorine which is thought to form mobile complexes with tin at depth. Mitchell & Garson (1972) suggest that mineralization above subduction zones is facilitated by release from the downgoing crustal plate of volatiles that mobilize tin from the lithospheric mantle or lower crust during their passage upward. Hunter (1973) envisages a deep source for volatiles associated with mineralization in the cratonic setting of the Bushveld complex, in contrast to the view (Wilson 1978) that these volatiles were mobilized from the crust itself.

In view of the uncertainties concerning the derivation of fluorine and other volatiles in tin provinces, it is interesting to examine evidence relating to analogous igneous assemblages of two other types. First, Bailey (1977 and this symposium) has argued strongly that alkaline magmatism in intraplate environments is facilitated by the segregation of volatiles from the mantle as part of a continuous process of outgassing of the Earth. Igneous complexes of this type tend to be enriched in volatile elements and are commonly located along linear zones that correspond to deep fractures. Secondly, granites that carry high uranium and rare earth elements resemble tin-bearing granites in many geochemical features – indeed, tin-granites such as those of Cornwall are themselves frequently enriched in uranium. Studies of late-orogenic Caledonian granites and syenites in northern Scotland (Simpson *et al.* 1979) show that the majority of pre-Devonian plutons that are commonly regarded as products of crustal anatexis do not have high concentrations of uranium; in general, their trace element contents differ only by small amounts from those of the late Precambrian metasediments by which they are surrounded (Watson & Plant 1979). On the other hand, early Devonian intrusions such as the Cairngorm granite in the same area are enriched in uranium and show values of Be, Li and light rare earths well above background values for the region and comparable with those of Hercynian tin granites in southwest England. Simpson *et al.* (1979) and Watson & Plant (1979) attribute this geochemical contrast to the effects of deep fracturing which released volatiles (especially fluorine) from mantle material underplated on the crust during earlier orogenic phases. The mechanism envisaged has much in common with that proposed by Bailey (this symposium) for intraplate magmatism. The 'exotic' trace elements introduced to the stabilizing Caledonian orogen include Be, Li and U, which are characteristically enriched in many tin granites. As has already been mentioned, deep fracturing appears to have played a part in the magmatic activity giving rise to such granites.

4. Discussion

The regional distribution patterns of the metals discussed above are undoubtedly the end products of processes acting at many stages in the history of mineralization. Nevertheless, the relations between mantle processes leading to the generation of magmas and ore-forming processes in the crust seem close enough to allow one to regard these patterns as *prima facie* evidence in favour of the existence in the mantle of geochemical anomalies which have influenced the distribution of some, at least, of the ore deposits under consideration. If this inference proves to be correct, it would follow that the mantle is inhomogeneous on a scale measurable in hundreds of kilometres and that geochemical anomalies were already established in the Archaean mantle. Certain anomalies have persisted through time periods of 1000–2000 Ma, an observation which is in line with evidence that ancient structural lineaments penetrating the lithospheric mantle beneath cratonic regions have remained active over similar periods (Watterson 1975; Bailey 1977; Watson 1978). Finally, the possibility that variations in the relative abundance of volatile components in the upper mantle, by modifying the processes of partial melting or segregation of mobile fractions, have influenced the development of metalliferous mineral deposits is worth emphasizing in view of the more general interest in the subject of degassing of the mantle.

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Discussion

M. J. O'Hara (*Department of Geology, The University College of Wales, Aberystwyth, U.K.*). Many rocks that are garnet–lherzolites at low temperatures may be 'fertile harzburgites' when they undergo partial melting at high temperatures and intermediate pressures (O'Hara 1967, fig. 12.3*a*). Pressure (depth) control of the mineral assemblage in the residuum will be very strong.

Results presented by Professor Dawson clearly indicate that partial melting leading to the generation of barren harzburgite from fertile harzburgite will lead to a remarkable high concentration of chromium in the *liquid* fraction from an early stage, contrary to the situation that might be expected at higher pressures where a high chromium garnet might be conserved in the residuum until a late stage of partial melting.

There may thus have been a simple depth control affecting the amount of chromium entering the basic magmas of the South African geochemical province commented on by Professor Watson, in addition to any effects resulting from variations in oxygen fugacity. It is perhaps less easy to envisage a plausible explanation for a difference in depth of partial melting beneath S Africa compared with the rest of the world than to provide for a more reduced type of upper mantle beneath S Africa. However, the longevity of such geochemical provinces may either indicate closer coupling between continental crust and its underlying upper mantle than hitherto believed or may cast doubt upon the immediate mantle derivation of chromium and nickel, rather than the recycling of these elements within the continental crust, having been lodged there at an early stage.

Extending this point, it is evident that evolution of a continental crust in a high geothermal gradient, such as may have existed in the Archaean, would occur with the development of a dry residual crystalline layer at the base (the granulite basement) overlain by a wet partial melt layer (largely granitic) which could be expected to have solidified in the main *from the top downwards*. Incompatible elements may have become concentrated into a particular horizon within this early crust. Geochemical zones or belts characterized by relative abundances of U, Th or Sn mineralisation might reflect the present outcrop pattern of that horizon in the deeper crustal structure.

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J. Watson. The idea of depth control affecting the entry of chromium into mantle-derived magmas would be a satisfactory one in regions where chromite concentrations are associated with igneous bodies formed either during a single episode or during successive episodes in which conditions of partial melting were essentially similar. The example discussed in the paper is one in which mineralization was repeated (*a*) over a timespan of 1500 Ma and (*b*) in different tectonic settings. In these circumstances it seems unlikely that partial melting took place under the same conditions during all episodes and for this reason I have favoured the proposal that regional geochemical variations are involved in the control of mineralization. Professor O'Hara's

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second point, concerning the distribution of incompatible elements in the deep crust, implies that geochemical belts characterized by U, Th or Sn should correspond to structurally defined units and could be tested by reference to geophysical studies. Some of the geochemical boundaries seem to be independent of structural boundaries although many, of course, coincide with large structural features.