Zeitschrift: Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie

Band: 28 (1948)

Heft: 1: Festschrift P. Niggli zu seinem 60. Geburtstag den 26. Juni 1948

Artikel: Crustal Layers and the origin of ore deposits

Autor: Kennedy, W.Q.

DOI: https://doi.org/10.5169/seals-23036

Crustal Layers and the origin of ore deposits

by *W. Q. Kennedy,* Leeds

I. Introduction

That a fundamental relationship exists between ore deposits on the one hand and magmatic melts on the other, has long been recognised, and has been discussed by various geologists. NIGGLI has outlined the nature of the fundamental problem concisely in the following terms (Lit. I, pp. 1—2):

„Ore deposition, where it is connected with igneous rock formation, may be stated to be almost always the outcome of processes inevitably resulting from the presence of volatile components in the magma. Indeed, magmatic melts, volatile agents, igneous rocks, and ore deposits are so closely related to one another that it is impossible to study any one of them without considering the others... To follow the processes in which the magma may be involved, as far as the formation of the igneous rocks only, is to ignore a very vital part in the sequence of events, and entails separating phenomena which are genetically intimately related. The practice of studying rocks and ore deposits on quite separate lines tends to obscure the true relationships and should be substituted by a uniform treatment of mineral associations in the widest sense (minerocoenology). For whether a mineral deposit be of the nature of a rock, or constitute what is familiarly known as an ore deposit, has no essential bearing on the general principles underlying our investigations, and, in particular, a system of classification applicable to deposits of the one sort must also hold good for the other. This is no less true in questions of provincial relationship. A description of igneous rocks or of magmatic provinces that does not include the correlated ore deposits may be compared to an account of a volcanic eruption that omits to mention the exhalations and fumaroles.

The question why any special ore deposit appears in a particular region of magmatic activity and is absent in another, has its counterpart in the query why syenite, for instance, is only to be found in certain provinces. O r e d e p o s i t i o n i s a p a r t p r o b l e m o f m a g m a t i c d i f f e r e n t i a t i o n i n i t s w i d e s t s e n s e".

On the basis of this clear statement it is proposed to examine the wider problem in its general terms and to consider the nature of the fundamental relationship which connects these two contrasted types of magmatic phenomena. It is obvious, in this connection, that the first problem concerns the nature and origin of the magmatic melts themselves, as it is these which, in their later stages of evolution, give rise to the deposits of metallic ores.

II. Derivation of Magmas

The wider problem concerning the origin of magmas and the evolution and geotectonic relationships of the igneous rocks has been discussed by the writer in a previous publication (Lit. 2). For the purposes of the present paper it is proposed to follow the general conclusions outlined in that account, and to base the discussion on the conception of volcanic and plutonic associations. The main considerations which led the writer to establish these two great fundamental classes of igneous rocks can be summed up as follows:

1. Magmatic activity is expressed either in the subjacent intrusion of plutonic masses or by superficial volcanic action, and it is essential to understand the relationship which exists between the two types of phenomena.

2. The intrusive or extrusive nature of many igneous bodies is an accidental character which has been determined largely by chance and as a result of local conditions. It is important therefore to distinguish clearly between „accidental" intrusions which are related genetically to the volcanic class, and those in which the intrusive nature appears to be an inherent character.

3. As pointed out by Daly (Lit. 3):

„Among the visible intrusive rocks, the granites and granodiorites together have more than twenty times the total area of all the other intrusives combined.

Among the extrusives, basalt probably has at least five times the total volume of all the other extrusives combined: basalt and pyroxene-andesite together have at least fifty times the total volume of all the other extrusives combined.

The granite and granodiorite clans, although dominant among the intrusives, are among the subordinate clans represented by the extrusives.

The gabbro clan is likewise subordinate among the intrusives but predominates among the extrusives.

The igneous rocks of the globe belong chiefly to two types: granite and basalt... To declare the meaning of the fact that one of these dominant types is intrusive and the other extrusive is to go a long way towards outlining petrogenesis in general".

4. Plutonic masses are characterised by the abundance of inclusions both cognate and accidental which they contain, whereas associated effusive rocks are characteristically devoid of inclusions in any way resembling those of the plutonics.

5. There is a universal absence of lavas belonging to a period

contemporaneous with the rise of batholithic intrusions to their highest levels in the crust.

6. Fractional crystallisation goes far towards explaining the volcanic rock suites and their associated intrusions, but fails to explain the batholithic suites of the orogenic zones. On the other hand evidence of contamination is abundantly to be seen in the case of the batholitic rock suites, but fails to explain the genetical relationships among the volcanic rock clans.

On the basis of these observations and considerations it was concluded that no very direct relationship exists between subjacent plutonic intrusion on the one hand, and superficial volcanic action on the other. At the same time it was recognised that the conception of volcanic bodies requires to be extended to include also those intrusions which are directly and inseparably linked with superficial volcanic action. Such an assemblage constitutes a volcanic association, which, according to definition, includes „not only the superficial lava flows and vent intrusions but, in addition, all intrusive masses which are geneticaly related to a cycle of volcanic activity and originate in the same magmatic source". In general the intrusive igneous bodies from non-orogenic areas, even when composed of rather typical „plutonic" rock-types, actually belong to a volcanic association, and their connection with an effusive episode can be either demonstrated, or at least, postulated by analogy with similar masses of proved volcanic affinity.

Plutonic Associations, on the other hand, are restricted to orogenic regions and are unrelated to normal volcanic action. They include all subjacent masses (discordant and concordant, batholiths, stocks, sheet complexes and related bodies) intruded within an orogenic belt during or immediately after an active orogeny, together with their associated aplitic, pegmatitic and lamprophyric minor intrusions. The intrusive character appears to depend on some inherent quality of the magma and many of the rock types possess no effusive equivalents.

The nature and relationships of these two great naturally occurring groups of igneous rocks can be summed up as follows (Lit. 2, pp. 31 and 32):

„a) Volcanic and Plutonic associations represent two distinct and apparently independent expressions of magmatic activity: they have their origins in different parent magmas and their subsequent evolution is controlled by different processes.

b) Volcanic associations are derived from a universal basaltic magma (or magmas) which originates by remelting of a basaltic earth shell, the intermediate layer.

c) Plutonic associations, despite their more deep-seated location, originate at a higher level and are derived from a primary, universal, granodioritic parent magma. The latter develops by remelting of the so-called „granitic layer". Such remelting would only be possible within the orogenic zones of the earth where tectonic thickening of the crust brings the base of the granite layer within the range of melting.

d) The actual mode of irruption differs in the two cases. The granite and granodiorite batholiths appear to penetrate slowly upwards, accompanied by a wave of granitisation and migmatitization of the country rocks, until arrested by some unknown form of hydrostatic control before they reach the surface. The ascent of basaltic magma is entirely different, no vast encrustal reservoirs are formed, and the basaltic melt appears to be irrupted directly towards the surface through a system of relatively narrow, dyke-like fissures. It is then either extruded in the form of lava flows or else gives rise to larger or smaller injected bodies, such as sills and laccolites, which may themselves represent volcanic reservoirs. Differentiation of the basic magma, moreover, takes place within the levels of crystallisation and, in consequence, the magmatic evolution is controlled largely by fractional crystallisation."

The general scheme, relating magmas to crustal layers on the one hand, and to igneous rock associations and petrographic provinces on the other, is shown below:

<table>
<tr><th colspan="2">Crustal Layer</th><th>Derivative Magma</th><th>Rock Association</th></tr>
<tr><td colspan="2">Granitic Layer</td><td>Granodiorite Parent Magma</td><td>Plutonic Association</td></tr>
<tr><td rowspan="2">Intermediate Layer</td><td>Tholeitic Layer</td><td>Tholeitic basalt Parent Magma of Calc-alkaline Provinces (basalt-andesite-rhyolite line of descent)</td><td rowspan="2">Volcanic Association</td></tr>
<tr><td>Olivine-basalt Layer</td><td>Olivine-basalt Parent Magma of Alkaline Provinces (basalt-trachyandesite-trachyte line of descent)</td></tr>
<tr><td colspan="2">Peridotite Layer</td><td></td><td></td></tr>
</table>

III. Distribution Factor of Metallic Ores within the Volcanic and Plutonic Associations

Having considered the evidence on which the conception of plutonic and volcanic associations was established, it now remains to review briefly the association of ore deposits with these two major categories of magmatic rocks. This problem has been adequately discussed by SPURR and by NIGGLI, and, in its general terms, is comparatively well understood. NIGGLI, indeed (Lit. 1, p. 29), on the basis of modes of occurrence, different rates of cooling, and the varying extent to which the volatile components can escape as a result of changes in load pressure, has recognised that, „The distinction between plutonic and volcanic types can therefore be extended to all deposits of magmatic origin". He has also, following SPURR, recognised that certain ore deposits are associated with specific types of magma, and, more particularly, that „the majority of magmatic ore deposits is... connected with magmatic activity in an orogenic area", that is, with calc-alkaline provinces. One can, however, go even further and recognise clearly that ore deposits are predominantly associated with rocks of the plutonic association. Certain of the heavy metallic elements only (platinum, nickel, cobalt) appear exclusively in the volcanic associations, and it is these elements which normally are found as direct magmatic segregations. There is no need to emphasise the predominant rôle played by the granites, granodiorites and related igneous rocks of the plutonic associations as ore-bearing magmas, nor is it necessary to stress the general absence of metallic ores in true alkaline volcanic provinces. We can recognise, therefore, in the granitic layer, and possibly in the immediately underlying tholeitic layer, the ultimate sources of the metallic ores. With this association in mind it still remains to explain, however, one of the most fundamental characteristics of ore deposits, e. g., their sporadic occurrence within the igneous rock provinces. SPURR has placed his finger upon the pulse of the matter, and in his illuminating book on the ore magmas has defined the problem as follows (Lit. 4, Vol. 1, p. 29):

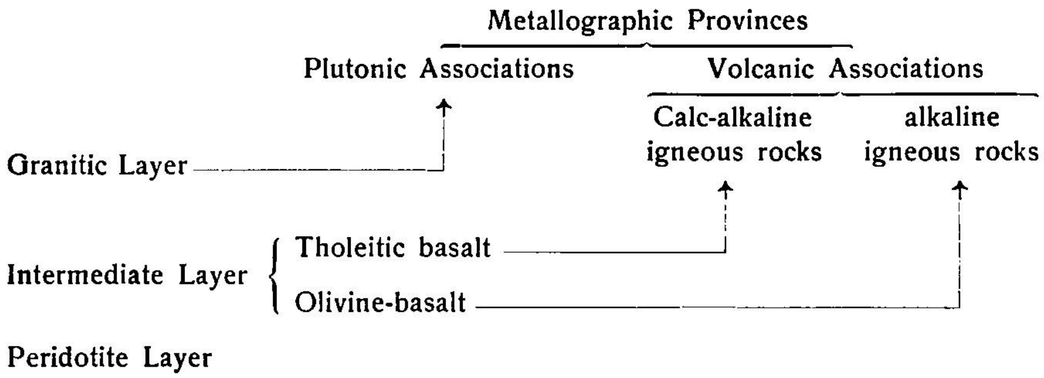
„Considering the earth as a whole, we find that the rarer metals are distributed very unequally, and occur mainly in certain provinces. Thus, tin occurs especially in Bolivia, in the Malay Peninsula, and in the Dutch East Indies. It is always closely associated with siliceous igneous rocks, especially granites; but there are vast areas of granite which are not associated with tin. Tungsten is a common associate of tin, but there are many tungsten-bearing provinces which carry no tin whatever. Tin ore is more closely restricted in its occurrence than is tungsten, yet tin is estimated to be a relatively more important component of the earth's crust in general. Silver is less abundant in the crust than tin, yet its commercial occurrences are very widespread. Again, the commercial concentrations of gold, one of the least abundant elements in the crust, are distributed very widely. Vanadium is an example of high concentration, occurring especially in Peru and in the Rocky Mountains.

This selection by each metal of certain spots on the earth's crust for its concentration is difficult to explain; but it must mean that there exists in that portion of the earth which is below the crust exposed to our view by erosion, a highly individualized distribution of the metals. For this there is no better illustration than the remarkable Arizona copper-bearing metallographic province. The igneous rocks which accompany the ore deposits in Arizona are not restricted to Arizona alone; the late Tertiary lavas, for example, have an immense distribution all around the Pacific, yet only locally are they copper-bearing, as in Arizona. We must conclude that in the Arizona metallographic province the magma wave must have acquired some additional peculiarity not originally inherent in itself, but inherent in this particular spot of the earth's crust: in other words, that on reaching this spot it has experienced an addition of copper. This suggests an heterogeneous under-earth, which has remained stably heterogeneous during the whole of our geologic historical record; and this argues a prehistoric epoch of high earth fluidity and opportunities for chemical segregation".

SPURR clearly recognises the association of metallic ores with specific types of magma on the one hand, and specific sectors of the earth's crust on the other, and would attribute the distribution to factors operating during an early stage of the earth's history and prior to the generation of the magma which carried the metals into their present position in the upper part of the earth's crust. He envisages the metallic ores as material added to or picked up by the magma from a localised pre-existing concentration.

NIGGLI, on the other hand, would appear to identify ore deposits with *processes* of igneous differentiation, rather than with specific magma types, and would consequently regard the metallic ores as original constituents of any magma at the time of its generation.

It is clear that igneous rocks of the same composition, and presumably evolved by identical processes may, or may not, carry metallic ores according to the particular sector of the earth's crust in which they are located. The metallic elements appear, therefore, to be concentrated locally within the crust and more specifically within the *granitic layer* of the crust. Local concentrations within the granitic layer would alone serve to explain the sporadic geographical distribution of ore deposits and their predominant occurrence within the plutonic association. Remelting of the granitic layer is considered by the writer to give rise to the granodioritic parent magma of the plutonic associations, and it is to this process, and to the subsequent uprise of the magma, that incorporation of the locally concentrated metallic elements is to be ascribed. There remains a further possibility, however, namely, that as the *tholeitic basalt layer* appears to have been formed partly at least by interaction between the barren olivine-basalt layer on one hand and the granitic layer on the other, the derivatives of the tholeitic magma type (calc-alkaline volcanic rocks) might also, to some extent, carry ores derived from the incorporated granitic layer material. This appears to be in accordance with the observed facts. The general scheme is as follows:



The rôle of igneous rocks in ore genesis appears, therefore, to be a secondary one involving transport and reconcentration of metallic ores previously concentrated by other processes and localised within specific sectors within the granitic layer of the earth's crust.

It still remains to consider, however, how the original concentrations within the granitic crust were effected. This must be largely a matter of speculation but the following factors are presented for consideration:

1. Igneous activity, in view of its failure to accomplish any degree of ore concentration within non-metalliferous regions, would appear to be ineffective in this connection.

2. The granitic crust, as all students of the pre-Cambrian, and of deeply eroded mountain chains in general, realise, consists partly of igneous rocks, and partly of incorporated sediments, represented by paragneisses and injection gneisses. It is suggested, therefore, that the original ore concentrations may be related to the sedimentary portions of the granitic layer, and that processes of sedimentary and metamorphic differentiation may have played a predominant rôle in the original segregation.

As NIGGLI has stated, „The problems encountered in the study of ore deposits are parts of the wider problems arising in connection with the study of igneous rocks". The writer, however, would extend this statement to include the detailed study of sedimentary and metamorphic processes.

Literature

1. NIGGLI, P., „Ore Deposits of Magmatic Origin", London 1929.
2. KENNEDY, W. Q., and ANDERSON, E. M., „Crustal Layers and the Origin of Magmas", Part I: „Petrological Aspects of the Problem" by W. Q. KENNEDY, Bulletin Volcanologique, Série II, T. III (1938), 23—41.
3. DALY, R. A., „Igneous Rocks and their Origin", 1914.
4. SPURR, J. E., „The Ore Magmas", 2 vols., New York 1923.

Received: December 1947.