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The liberation of minor elements from rocks during plutonic igneous cycles and their subsequent concentration to form workable ores, with particular reference to copper and tin

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Fifth Presidential Address to the Geological Society of Malaysia[2]

"Is there a science of the earth at all?" — J. Tuzo Wilson

Tuzo Wilson was prompted to this impious question in his Bancroft Award Lecture to the Royal Society of Canada in 1968 by a contemplation of the fragmentation of the earth sciences and the lack of any unifying general theory of the earth. He went on to conclude that the recent concepts of plate tectonics could provide such a theory, which would revolutionize earth science and change it from a descriptive to a predictive science. (24)

I am prompted in my turn to ask the further question: is there any hope of turning the study of ore deposits into a predictive science? This implies that at present it is not, and anyone who has had to explain to a board of directors why a given exploration programme has not found ore will I think agree with me that it is not. Others whose task it is to find oil, or to recommend to Government which ground has or has not got "mineral potential" may also agree with me.

Tonight I am going to assume a basic plate tectonic concept for the formation of igneous rocks, and then see if recent researches into the detail of ore deposits can be reconciled with a broad pattern of fundamental control. Protected by the now traditional immunity from questioning accorded the President on this occasion I am emboldened to follow my fancy a little way beyond the facts, and I hope you will all follow me a little way up the garden path with tolerance if not agreement. I have selected copper and tin for comment for two reasons, personal familiarity with their problems and the occurrence of significant deposits in Malaysia.

The overwhelming proportion of the world's current output of copper and tin is derived from deposits that are clearly associated with intrusive igneous rocks. The great porphyry copper deposits of the Western Americas and the tin deposits of Southeast Asia are alike in this, although secondary enrichment or placer developments may in many cases be responsible for the final enrichment to workable grade. The primary mineralization is clearly spatially related to igneous rocks of plutonic aspect, and a genetic connection is postulated by most geologists with substantial experience of these deposits. The precise nature of the link between magmatic activity and mineralization has however been the subject of much speculation and little agreement.

Little success has attended efforts to define "tin granites" or "copper porphyries" in petrological terms. Although a general association of tin with acid granites

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[2] Address delivered to the Society on February 4, 1972.

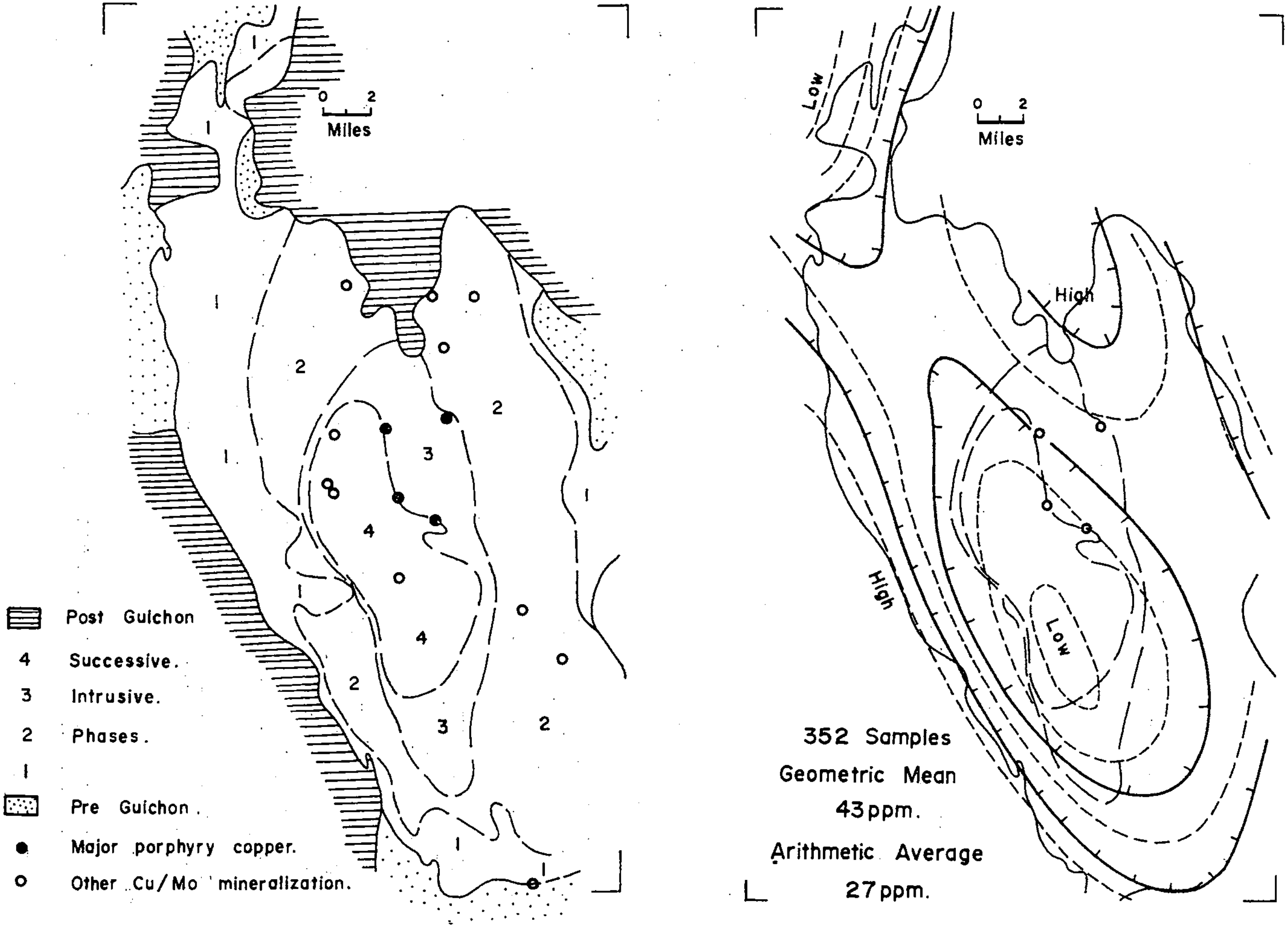


Fig. 1. Geology and Copper Content of the Guichon Greek Batholith After Brabec and White.

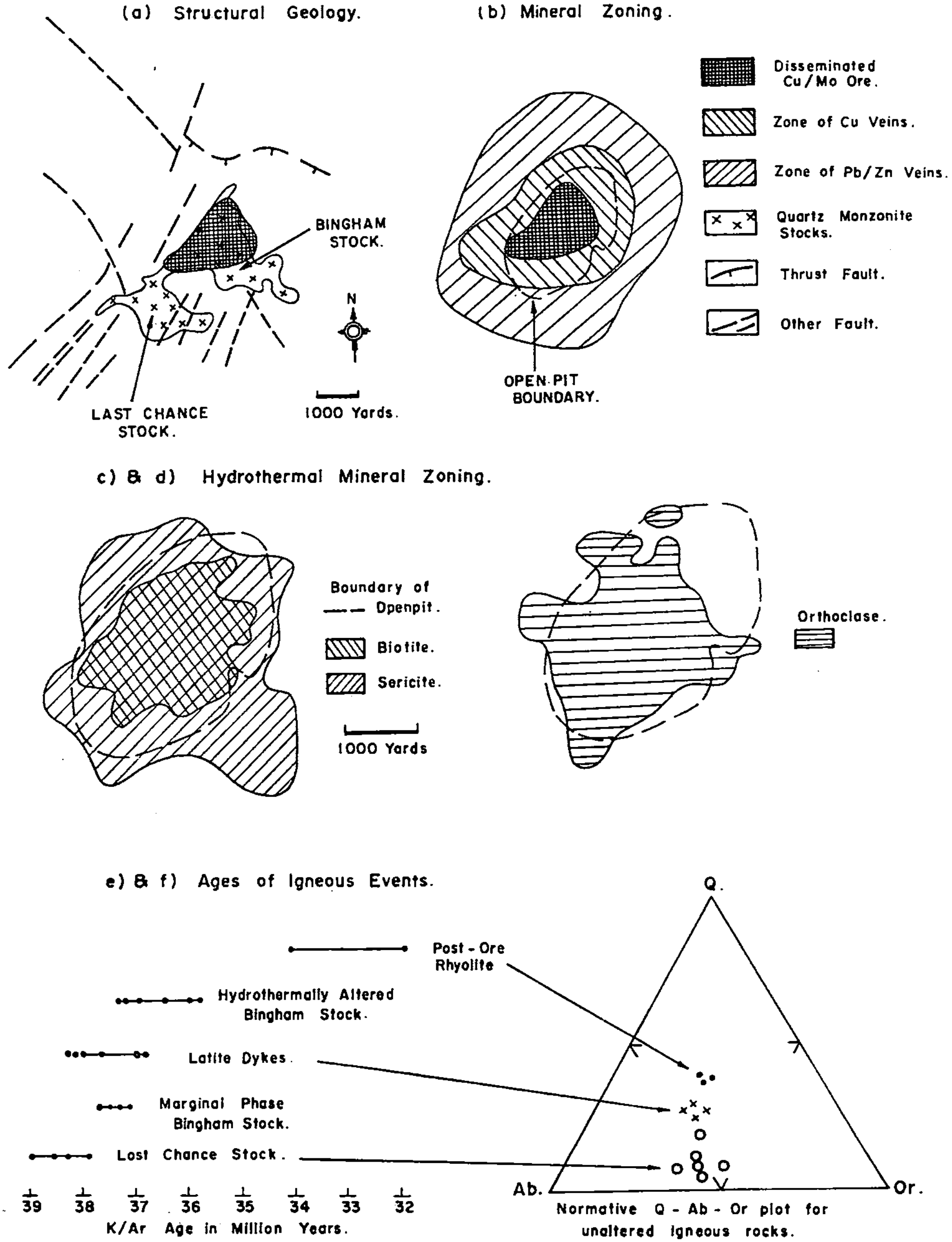


Fig. 2. Bingham Canyon, Utah.
after Peters *et. al.* (4) and Moore *et. al.* (8)

and copper with rocks of granodioritic composition has been established, it is no very precise or useful in practice in guiding exploration (20). The prime difficulty is that though, when one finds tin one can feel fairly sure there is a granite somewhere near, the reverse is not the case. Rather more success has attended efforts to discriminate barren from mineralized intrusions by trace chemical analysis of whole rock samples, but as the results from the Guichon Batholith (Fig. 1) show metal levels are frequently much lower than one would expect and quite frequently the evident source rock is very low in the metal (1).

Basically this is because the metal in these deposits is epigenetic and is concentrated in discrete ore minerals of high metal content (Chalcopyrite or cassiterite) which are not normal rock forming minerals. Pervasive rock alteration of distinctive type (23), frequently in the case of porphyry coppers affecting the entire intrusive stock, (fig. 2) normally accompanies the ore mineralization, and the altered rock normally contains a little of the ore mineral itself. In rare cases, such as the Bethlehem Copper Mine in British Columbia, the major part of the metal may be disseminated finely through the body of the altered rock but normally the valuable metal is concentrated in fractures with quartz or other sulphides to form veins or veinlets. In porphyry copper deposits the pervasive alteration is thought to pre-date the copper sulphides, and indeed may occur without them, but it definitely post-dates the consolidation of the host rock. While less work has been done on primary tin stockworks in granite, the consensus of opinion is that a similar sequence is found, with cassiterite deposition occurring as a late phase.

What then is the genetic connection between a rock already crystalline and the epigenetic orebody occurring within and around it and why is it not possible to clearly distinguish petrologically between metal bearing and barren intrusives? As a guide to exploration for new districts, classical geology is a dim and uncertain light and exploration has usually relied upon direct detection, either to find the outcrop or its geophysical or geochemical expression. Where a body is large, obvious, well exposed, and yielding a strong anomaly this is satisfactory enough but the saturation prospecting needed to find bodies, even large ones, with less than optimum expression is slow and expensive. What is needed is a better genetic theory to tell us why the ore is where it is and what were the fundamental controls on its occurrence.

THE PROBLEM OF THE ORIGIN AND LOCATION OF PORPHYRY COPPER DEPOSITS

A great deal of work has been done on the geology of the Porphyry Coppers, largely in North America (2), and a consensus of opinion on origin is beginning to emerge. This may be briefly summarized as follows:—

A. Basic characteristics of Porphyry Coppers

1. Large size. Porphyry coppers can be very large and within the top 1,000–1,500 feet normally explored can contain up to 3,000,000,000 tons of ore. There is of course no lower limit of size.

2. Even Grade. In a porphyry copper deposit of several hundred million tons of 0.50% ore it is difficult to find more than a few million tons with a grade of more than 1% Cu. Similarly except where bounded by post ore structures, there is rarely a sharp cut-off of values but rather a slow decline outward from the focus of mineralization.

3. Fine Shattering. Almost always the mineralized rock is finely shattered with the density of fracture being closely related to the grade of the ore on both regional and local scales (e.g. Boss Mt. B.C. and Silver Bell Arizona ((3) figs. 3 & 4).

4. Hydrothermal Alteration. Pervasive alteration affecting both stock and wall rock and extending well beyond the ore zone is invariably found. Usually an inner orthoclase-biotite alteration zone is surrounded by a sericite-chlorite-epidote zone (4) but sometimes only massive silicification is found (e.g. in Sabah).

5. Gradation into "Pyrometasomatic" or "Hydrothermal Vein" Types. Many porphyries are ringed by lead-zinc veins of hydrothermal type or, where intrusive-limestone contacts are found by tactites and skarns with much copper ore. There is in fact a transition from true "Porphyry Coppers" to ore deposits of the Butte Montana type where individual veins are large enough to be worked (fig. 5).

6. Isotope data indicating deep seated source. Studies of isotopes of S, O, H, Rb/Sr, and Pb in porphyry copper and related hydrothermal vein deposits suggest a mantle source for the rocks and the sulphur (5) and a magmatic source for the water in the biotite-orthoclase alteration zone but a meteoric source for the waters in the sericite and kaolinite alteration zones (9).

7. Narrow composition range of associated plutonic igneous rocks. The intrusive rocks associated with porphyry copper deposits range only from quartz diorite through granodiorite to Quartz Monzonite in composition, equivalent to the andesite-dacite volcanic suite of island arcs (2) (23).

8. Absolute ages of host-rock, ore and associated volcanism are very close. At Bingham K/Ar dates show a duration of igneous activity of 7 million years (39–32 MY) with Barren intrusive quartz monzonite earliest and

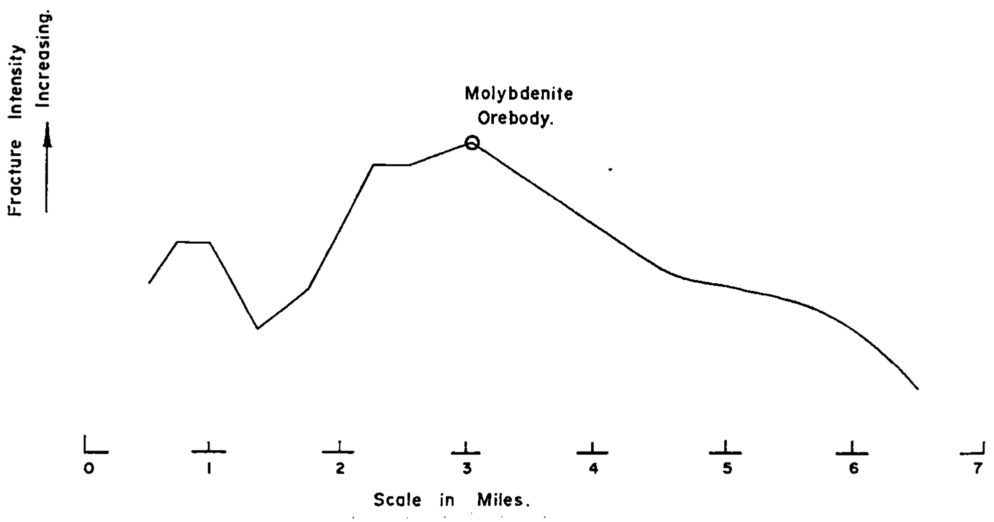


Fig. 3. Random Fracture Intensity Profile of Boss Mountain.

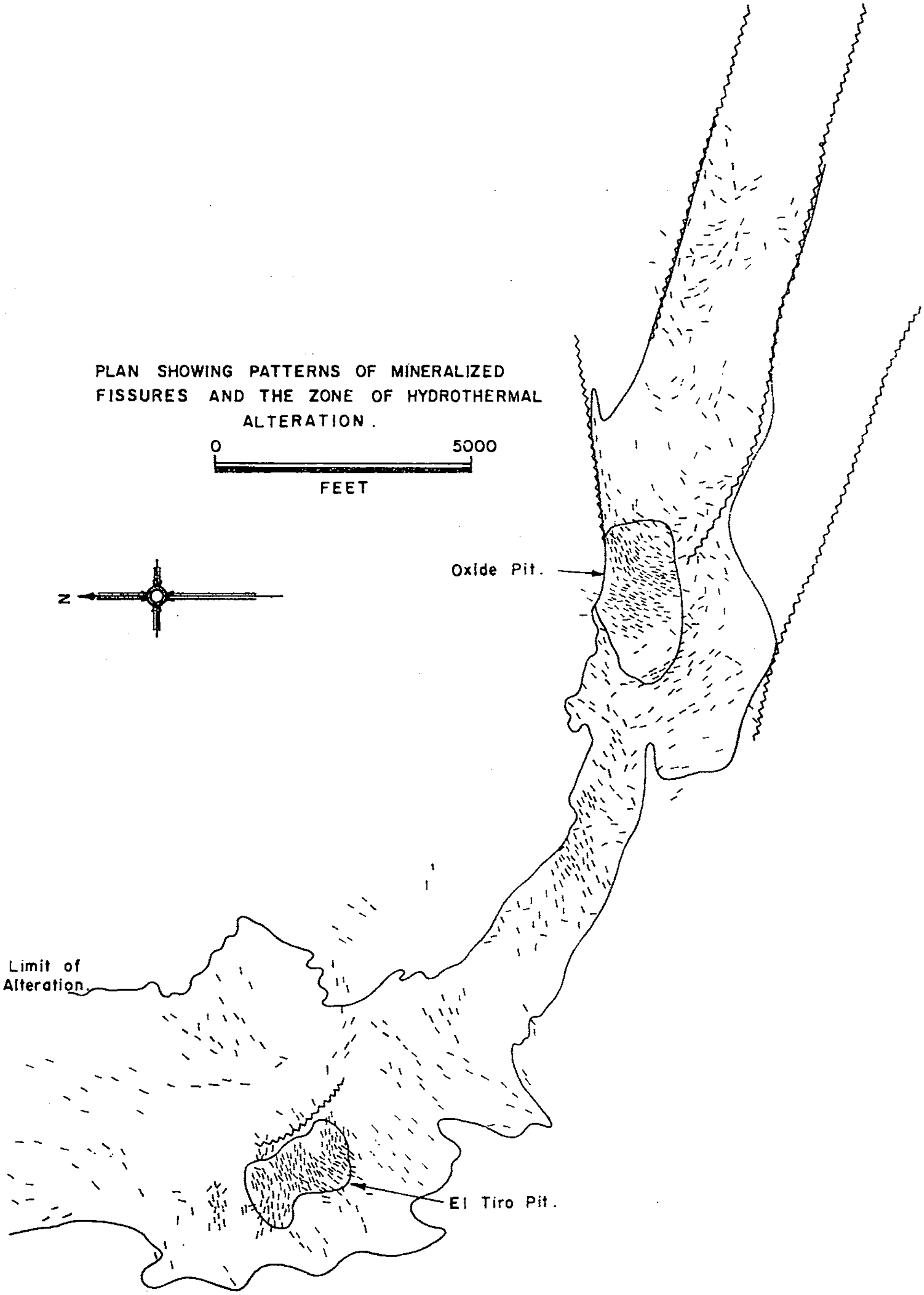


Fig. 4. Silver Bell District Arizona after Richard and Courtright (3)

Barren volcanic rhyolites latest (8). Dates on the margins of the Bingham stock, cross cutting dykes in the Bingham Stock and hydrothermal biotites accompanying the mineralization, overlap and all dates lie within the limits of analytical accuracy. In Bougainville the igneous intrusive phase and the mineralization cut submarine andesites and are overlain by subaerial andesites and belong to an igneous cycle at least 7 million years long.

9. Zoning of Metals. A marked zoning of the ore metals about the intrusive stock is normal with a Cu-Mo core surrounded by a Pb-Zn shell with Au and Ag on the outer fringe. Attention has recently been drawn to the fact that island arc porphyries (i.e. Bougainville) have a Cu-Au Association with little Mo, while continental porphyries (e.g. Bingham) have little Au, but more Mo (10), and in fact grade into a group of Mo porphyries with subordinate tungsten and trace tin but little Cu (e.g. Climax).

10. Mineralizing fluids are very saline brines. Recent fluid inclusion studies at Bingham, Butte and Climax has shown that the core mineralization with Cu and Mo are accompanied by exceedingly saline fluids with 35%–60% of dissolved solids, mainly NaCl and KCl, while fringe deposits are much less saline (7). Evidence of boiling and steam generation has been found. Parallel studies of vapour-dominated hydrothermal systems (geyser systems) have predicted the occurrence of dense brines in depth (6).

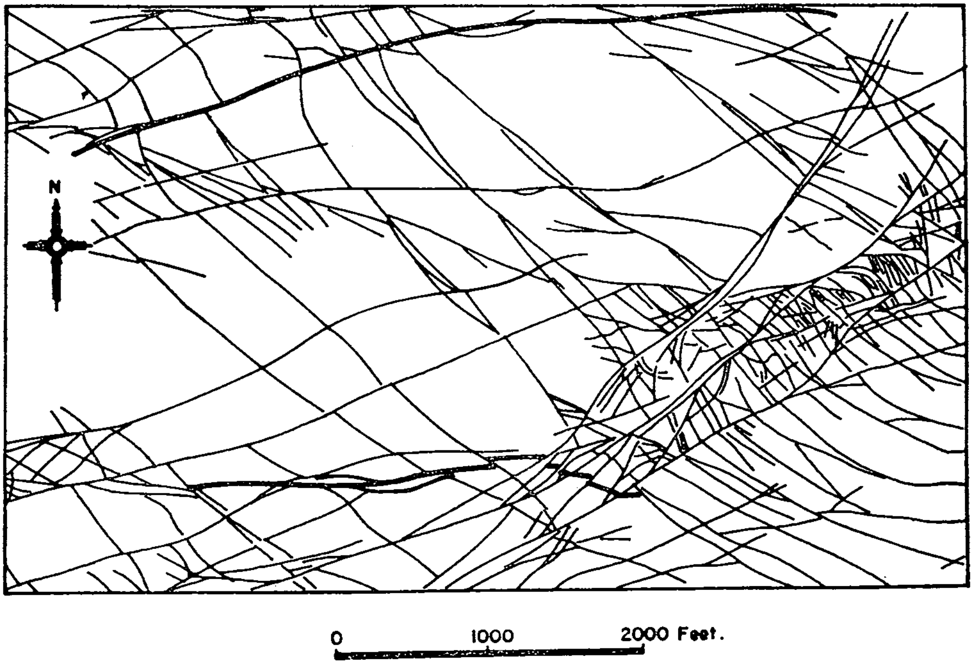


Fig. 5. Horizontal Section of a part of the 1500 Foot Level, Butte, Montana. (after Reno Sales) Showing Complexity and Density of Veining. N.B. Host rock is Quartz Monzonite.

B. Possible Mode of Origin

A six-fold cycle of activity can be postulated, leading to the development of a primary porphyry copper deposit.

1. Partial melting of basic rocks below the continental crust to yield an andesitic magma, which may later yield more acid rocks by differentiation.
2. Extrusion by volcanism at the surface with the development of cylindrical subvolcanic magma chambers in the crust.
3. The build up of sub-aerial volcanoes of andesitic type.
4. Explosive caldera phase, with intermittent boiling of fluids in the stock below the volcano and shattering of vertical zones below the explosions.
5. Pause or termination of magmatic activity, solfatara and geyser activity at surface with boiling of fluids in depth and mingling of ground and magmatic waters. Pervasive alteration of rocks.
6. Main phase of mineralization.

The occurrence of porphyry copper deposits of major size in an oceanic island arc structure like Bougainville and the age of the mineralization (3–6 million years) demonstrates that continental crustal rocks need play no part in the development of a major orebody. Apart from elevated coral reefs all the rocks on Bougainville belong to the andesite clan and the island has been built up by the products of selective melting of ocean floor rocks in a major active subduction zone. It is logical therefore to search for the source of the copper in the same place.

Using the concept that the basic rocks which floor the ocean basins are generated along mid-ocean ridges by partial melting of ultra-basic rocks (the low melting fraction of a peridotite constitutes 40% by weight and has the composition of basalt (18)) and that andesites are generated by the partial melting of sea-floor basalts as these descend into the mantle along subduction zones under either island arcs or continental margins, then we may compute the cycle of the ore metals through these two processes. The average abundances of trace elements in different rocks are taken from Vinogradov (in 16) and the following assumptions are made:—

1. 40% of the ultramafic mantle melts to give basalt.
2. 40% of the sea floor basalt melts to give andesite.
3. The unmelted portion of the sea floor basalt has a similar holding capacity for trace elements as the original mantle rock.

The copper cycle may then be calculated as follows, using a base amount of one million metric tons, and the following average element abundances, ultramafic rock: 80 ppm, mafic rock: 140 ppm, andesite: 35 ppm.

1,000,000 metric tons ultramafic rock @ 80 ppm Cu contains 80 metric tons of Cu.

Mid Ocean Ridge: Partial fusion yields
400,000 metric tons basalt @ 140 ppm Cu containing 56 metric tons of Cu.

Subduction Zone: Partial fusion yields
160,000 metric tons andesite @ 35 ppm Cu containing 5.6 metric tons of Cu
and
240,000 metric tons of ultramafic rock @ 80 ppm Cu containing 19.2 tons of Cu
and
31.2 tons of Cu surplus

This suggests that very substantial amounts of Cu can be liberated with the volcanic rocks overlying a subduction zone—almost 2 tons of Cu for every 10,000 tons of andesite or diorite rock. The copper is liberated fundamentally by the incongruent

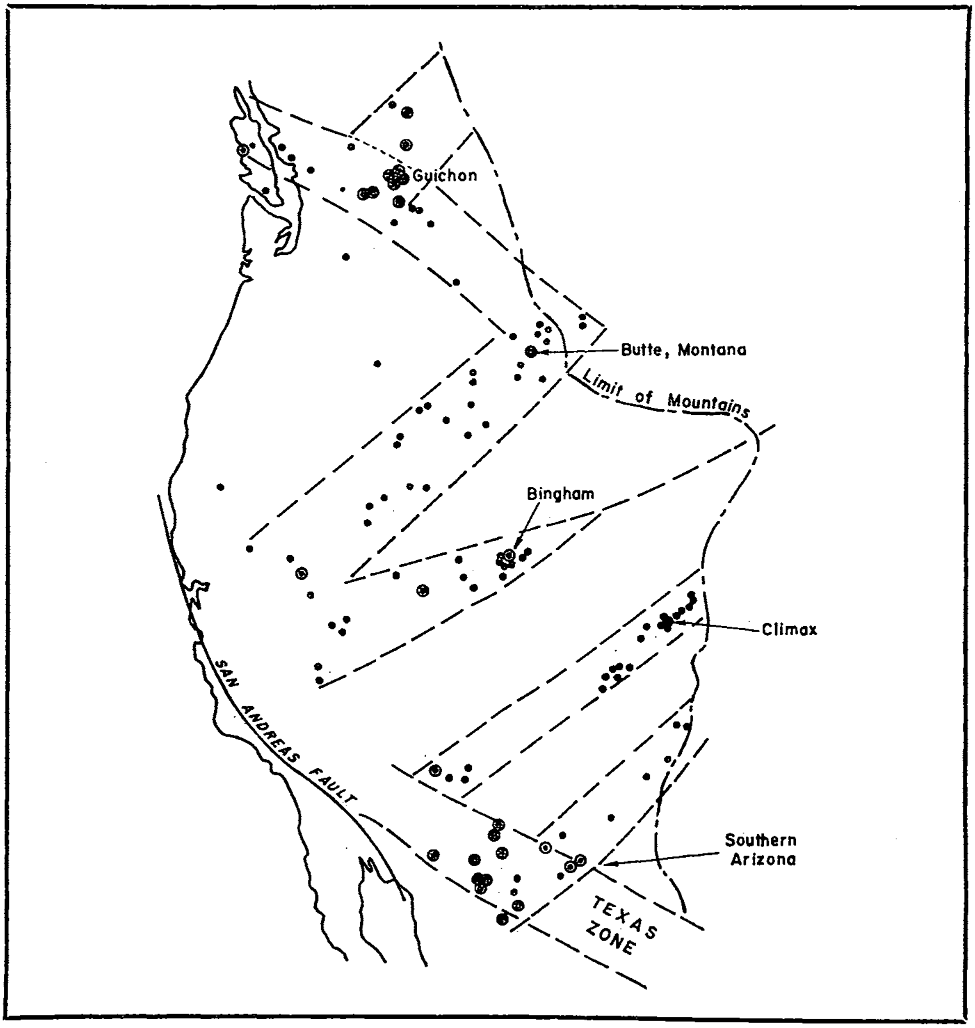


Fig. 6, Western North America Showing Location of major porphyry and other hydrothermal ore deposits. Mainly after Landwehr (11 and 12).

melting of pyroxene to give olivine + liquid. The resultant liquid, together with the melted Na-K feldspar subsequently crystallizes as andesite or diorite with far fewer crystal lattice positions for the copper to occupy, and hence a low copper content. The surplus Cu is then free to enter a minor phase of high Cu content. What other elements are likely to accompany it?

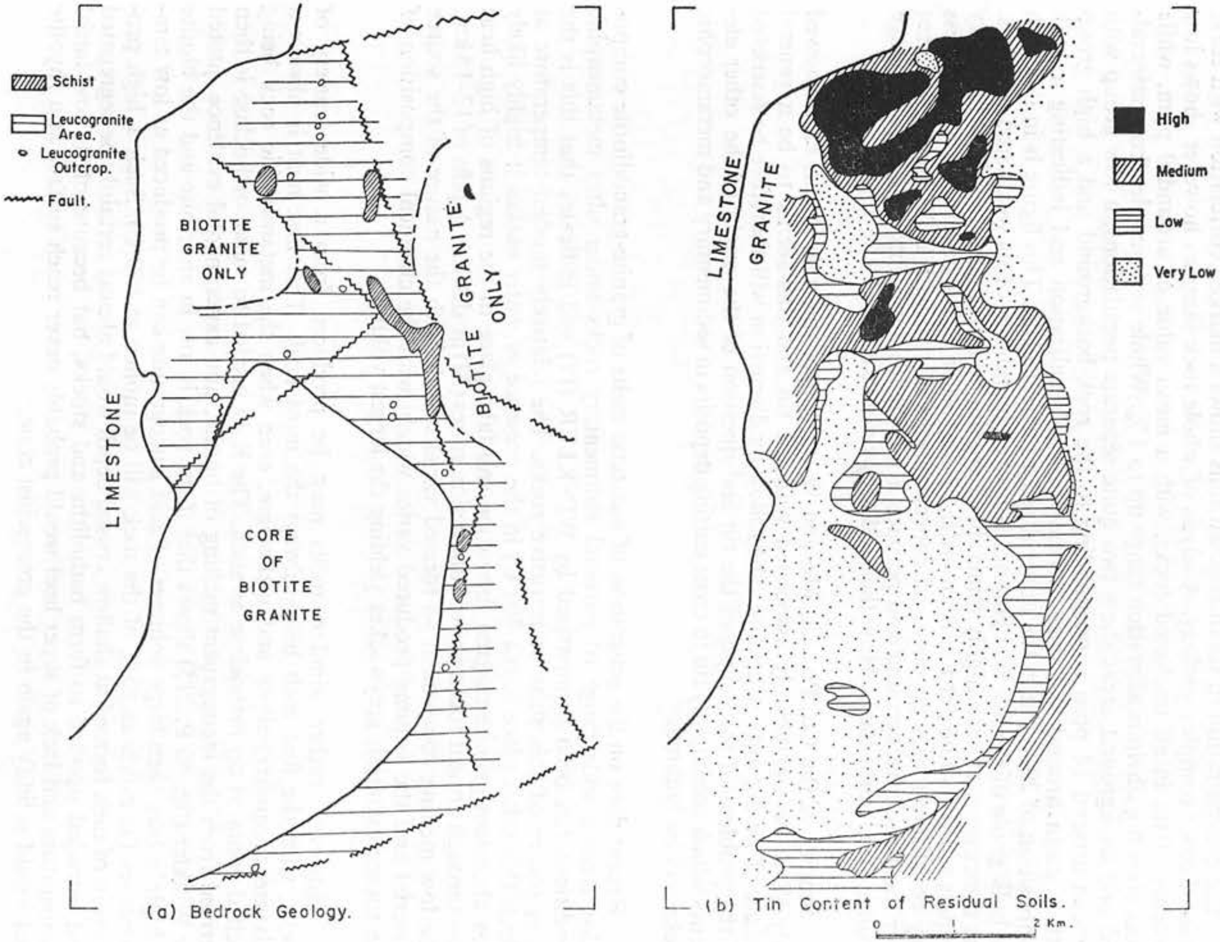
A series of elements was followed through the cycle of two partial melts given above for copper. Iron, sulphur, manganese, copper and zinc are markedly in surplus at the andesite stage while molybdenum, silver and antimony show a significant fractionation into the surplus phase but at low absolute levels. Magnesium, nickel, cobalt and chromium are markedly in deficit. No reliable figures are available for lead, tin or tungsten; all three may concentrate in the surplus, but tin and tungsten at very low levels, reflecting their low concentration in peridotite.

I would suggest that the evidence indicates that the porphyry coppers have been formed by partial fusion in subduction zones in that part of the zone where the ocean floor basalts melt to yield andesitic magma. They form in the roots of andesite sub-aerial volcanoes and are therefore controlled by the same factors as control the location of such volcanoes. As the origin is at the base of the crust they tend to lie at the intersection of very deep seated fractures or "lineaments" as they are often called (11, 12, 15). Such lineaments frequently cut the major tectonic trends visible in the surface geology at a high angle, with particularly intense mineralization occurring at the intersection of two major lineaments, as in Arizona and southern British Columbia (fig. 6). The same elements occur in the ore deposits associated with submarine andesitic vulcanism such as the bedded pyrite-chalcopyrite and kuroko ores of Japan—the primary metal release mechanism is the same, but the final concentration is different. Instead of caldera formation and geyser activity building up metal rich brines within the sub-volcanic rocks the metal is discharged more evenly, into the sea or into the water soaked volcanic sediments of the sea floor and there precipitated by rapid cooling and dilution of the hydrothermal phase with sea water (13).

THE PROBLEM OF THE ORIGIN AND LOCATION OF PRIMARY TIN MINERALIZATION

While the geological literature of the last 10 years abounds with data and hypotheses on porphyry coppers, the literature on primary tin deposits is sparse. It is however very clear that tin is not associated in even by-product quantities with porphyry copper deposits, nor does it occur in island-arc terrains. It seems therefore that the oceanic and primary volcanic island arc cycles are insufficient to concentrate tin to any marked extent. Data on the content of tin in rocks is sadly lacking and much of the data in the literature is of suspect quality. However it does seem that most rocks, even so-called "tin granites" carry less than 10 ppm of tin (14). In these circumstances the two stage partial melting process outlined above could not result in the build up of sufficient tin to yield large scale disseminations. A further stage of concentration is required.

It is pertinent here to consider the level to which tin will build up within a granite mass, and the Malayan West Coast Tin Belt provides a wealth of examples of obvious high tin granites which have fed rich placers but which contain only small and inconsistent vein systems which have not in general repaid working (25). Published data is scant but the results of a recent geochemical survey provides an indication of the answer (fig. 7). In the area sampled the predominant rock is biotite granite, usually medium to coarse grained with feldspar phenocrysts, and this occurs



(a) Bedrock Geology.

(b) Tin Content of Residual Soils.

Fig. 7. Relationship of Tin Content to Bedrock Geology, Margin of the Main Range Granite, Kinta.

throughout. Leucogranite and schist occur only in the north and along the western and southern margins, where faulting also seems to be concentrated.

The concentration of tin in residual soils shows a marked correlation with these areas of more complex geology. Analysis of whole rock samples however shows low contents of tin in all unaltered rocks, with a mean value of around 9 ppm, while rocks showing obvious alteration range up to 1%. Whole soil samples from mineralized and background areas show two quite separate populations, a low group with a mean around 18 ppm corresponding to the rock background and a high group with a mean around 400 ppm derived from mineralization and indicating a bulk composition of 200 ppm in the mineralized granites (fig. 8). This figure is in line with the bulk grade of the Sg. Besi granite, as proven by mining of its weathered portions. The dimensions of such highly mineralized granite bodies is comparable to porphyry coppers but the value per ton is an order of magnitude below payability. Nonetheless they constitute major geochemical concentrations of tin, with a 20 fold enrichment over local rock background and perhaps a hundredfold enrichment against average granite on a world basis. How then did they originate?

Studies of the Cu, Pb, Zn, Mo and W content of the soils in this area showed only W to be significantly associated with the tin and this seems to be a general feature of tin deposits in granite. The following discussion will therefore be restricted to the problem of the origin of the tin and question of the origin of the other elements which accompany tin in cross cutting deposits in sedimentary and metamorphic rocks will be ignored.

Recent data on the generation of anatectic melts of granite-granodiorite composition from a wide range of parental sedimentary rocks under ultra metamorphic conditions has been summarized by WINKLER (17) and indicates that this is the main source of this suite of intrusive rocks. The relatively modest temperature at which this takes place (circa 700°C) in the presence of water makes it highly likely that abundant granite magma formation can take place in the regions of high heat flow through crustal rocks above subduction zones (22) at shallow depths of 12–15 km. The low melting component so formed varies a little with the nature of the source material and the volume produced varies widely with the chemical composition of the source material; greywackes yielding the largest volume.

However rather similar melts may be produced from a wide variety of rocks, with the first melt being always the most acid. This first melt is always a mixture of quartz, albite and orthoclase, even when the metamorphic rock being melted contains no orthoclase as such. The K_2O needed to make orthoclase is then derived from the incongruent melting of biotite, and experimental evidence quoted by Winkler (fig. 40 P. 215) shows that if the rock is low in anorthite and the biotite is high in iron then large volumes of acid leucogranite can be produced at low temperatures (as much as 55% of the rock will be molten at 690°C). Such a high proportion of melt formed at shallow crustal depth would almost certainly be segregated and intruded upward to form batholiths and stocks, but because of its low initial temperature and lack of super heat would probably never reach surface as a rhyolite and would solidify again in the greenschist zone.

Tin is known to occur in amounts of up to 100 ppm in biotites (19) and it has been claimed that it shows a positive correlation with the iron content. It is further known that the tin content in biotites is readily extracted for chemical analysis by

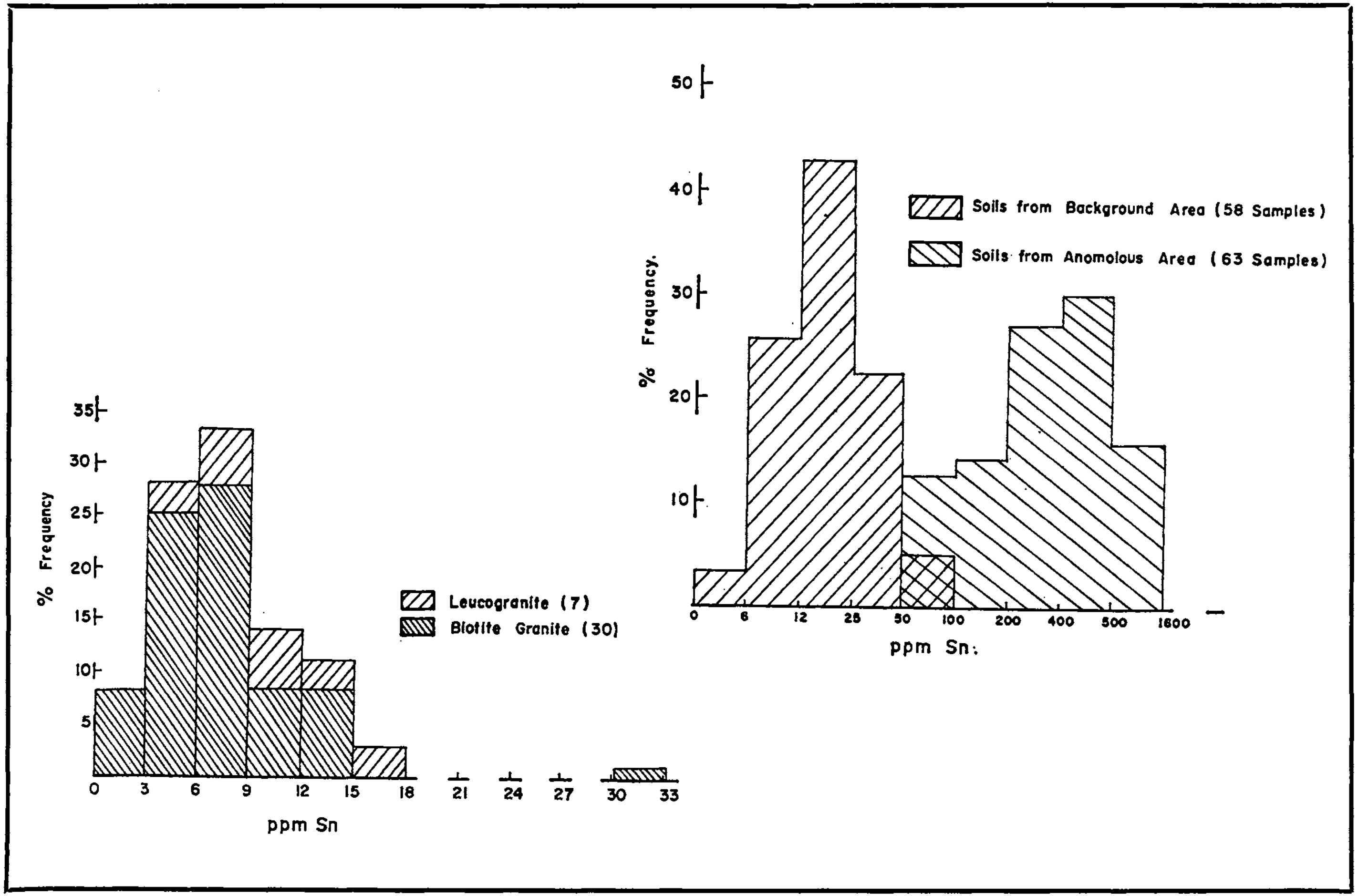


Fig. 8. Tin Content of Rocks and Soils Margin of Main Range Granite, Kinta.

mild attacks (21). This suggests that the first low melting fraction extracted from a biotite rich rock could have the composition of an acid granite high in tin. There is no need for the original rock to be very high in tin, so long as a substantial part of the tin is segregated into an early melt and that melt is separated. For example a biotite schist containing 10 ppm tin and losing half to an initial low melting fraction of 5% by volume could yield a melt containing 100 ppm Sn. Continued melting could then yield large volumes of granite-granodiorite with 5–7 ppm Sn, and possibly several phases.

In this way it is possible to visualize a complex batholith arising with a small tin rich fraction at its apex. High viscosity hinders mixing during the intrusive phase and, during final crystallization a tin rich high volatile residuum accumulates in fractures and joints. Lack of suitable lattice positions in acid silicate minerals results in the crystalization of the tin as cassiterite either within the granite, if the fluids are impounded, or in the country rock if fractures are available.

Such a model would explain most of the features of the Kinta–Kuala Lumpur granite areas, but is almost wholely speculative and is not backed by the kind of experimental evidence that backs the porphyry copper story. Nonetheless some such "special incongruent melting" theory is probably the best explanation for the rarity of tin granites and their restriction to certain elongate zones of crust, widely spaced around the world.

CONCLUSIONS

We are now perhaps in a position to answer a few of the questions I posed at the outset. The ore metals are the surplus elements which remain without a silicate mineral to hold them when an original host rock is partially melted. They migrate with the magmatic fraction until the latter crystallizes when, if structural or hydraulic factors prevent their escape, they will alter and mineralize the still hot magmatic rock. Rocks of identical bulk chemical composition may be generated in varying amounts from the wide variety of geological materials, and in particular rocks of the granodiorite-granite clan are of many origins. The final mineralogy is rather simple and the silicates will carry few heavy metals in lattice position. Therefore petrology and whole rock element analyses will tell us little about their favourability for mineralization. More subtle features, such as age relations to host rocks, ratios of isotopes or trace elements content in specific minerals may be revealing and their spatial relations to fundamental crustal fractures or fracture intersections even more so.

Because of their relation to extremely large scale and deep seated magmatic events, major Mesozoic and Tertiary ore districts are far from accidental in their occurrence, they are highly systematic. The science of geology is only now beginning to understand the nature of the structures to which they are related, raising the hope that in the future concealed ore districts can be predicted and located, rather in the way that deep and totally concealed oil bearing structures have been located. The problems are more complex perhaps, but the world's growing need for metals and fuels requires their solution, which can only come from a truly integrated science of the earth.

The "New Global Tectonics" is as yet imperfectly understood: even for the Tertiary there are major areas of uncertainty, the Mesozoic is only dimly understood while earlier eras, totalling 9/10ths of the history of the earth, are not understood at all. The world's major sources of iron and nickel and a large part of the lead, zinc, gold and copper reserves are in these rocks. Any hope of turning the study of these ore deposits into a predictive science is vain until the basic geological history of the earth is understood. The best that can be said at present is that there is hope of unravelling the tangled skein of the earth's history. In this task the study of those concentrations of rare elements we call orebodies will cast much light and give clues to some of the deep seated structures and processes acting in the earth. There is no conflict between 'pure' and 'applied' geology, they are complementary and the one is incomplete without the other.

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