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Intrusives associated with porphyry copper deposits

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Abstract: Porphyry copper deposits and their associated intrusives are widespread throughout the world and particularly abundant in the circum-Pacific region, although not all parts contain porphyry copper deposits. The available data indicate that some plutons related to porphyry copper deposits originated along subduction zones and some in continental crust so far removed from subduction zones that any relation is improbable. Of those deposits related to subduction zones, some, like those in the Caribbean and in places in the Philippines, formed at junctions between oceanic plates, and others, like those in the Andes of South Amerika, formed at the junctions between oceanic and continental plates. Plutons unrelated to subduction zones include those in the interior of the Soviet Union and most, if not all, of those in the western United States.

Potassium-argon ages of porphyry copper deposits indicate that they formed throughout the Phanerozoic Eon. However, because they form in tectonically active zones at depths of 3 km or less, erosion seems to have destroyed most of the older ones. The youngest porphyries are near active subduction zones. Here uplift and consequent erosion are the most active, exposing young deposits.

The composition of the plutons associated with Caribbean porphyry copper deposits shows that most are low in K-feldspar and quartz. With differentiation, the K-feldspar and quartz content increases. The array of compositions can be defined by a differentiation trend line that seems characteristic of igneous rocks derived from oceanic crust.

Pl-Qz-Or ternary diagrams for southern Arizona are similar for (1) all Laramide plutons, (2) Laramide plutons associated with porphyry copper deposits in space and time, and (3) all Laramide igneous rocks in the Ray district, which contains a large porphyry copper deposit. The differentiation trend line for all the southern Arizona igneous rocks is strikingly different in slope and direction from that for the Caribbean intrusive rocks. The ternary diagram for all igneous rocks in the Bingham district, which contains the most productive porphyry copper deposit in the United States, is distinct from that for southern Arizona. Other geographic provinces in the western United States in which no porphyry copper deposits occur contain suites of igneous rocks similar to other suites in the western United States associated with porphyry copper deposits, so that it appears that porphyry copper deposits are not related to any unique composition or suite of igneous rocks in continental crust.

A common feature of porphyry copper deposits from all environments is their spatial and temporal relation to an intrusive body that is among the most differentiated (quartz-and K-feldspar-rich) and among the youngest. This implies that differentiation plays a part in the origin of the porphyry copper deposits and in the characteristics of the igneous rocks with which they are associated.

The role of assimilation and contamination in igneous rocks associated with porphyry copper deposits is not clear. The initial strontium ratio of the El Salvedor deposit, South America, indicates no assimilation. In general, the few data obtained are contradictory on the contribution of wallrocks to ore deposits and magmas.

DISTRIBUTION AND GEOLOGIC SETTING

Porphyry copper deposits and spatially associated intrusions are widespread throughout the world, chiefly in Mesozoic and younger tectonically active zones. As generalized in figure 1, the world distribution of porphyry copper deposits shows a

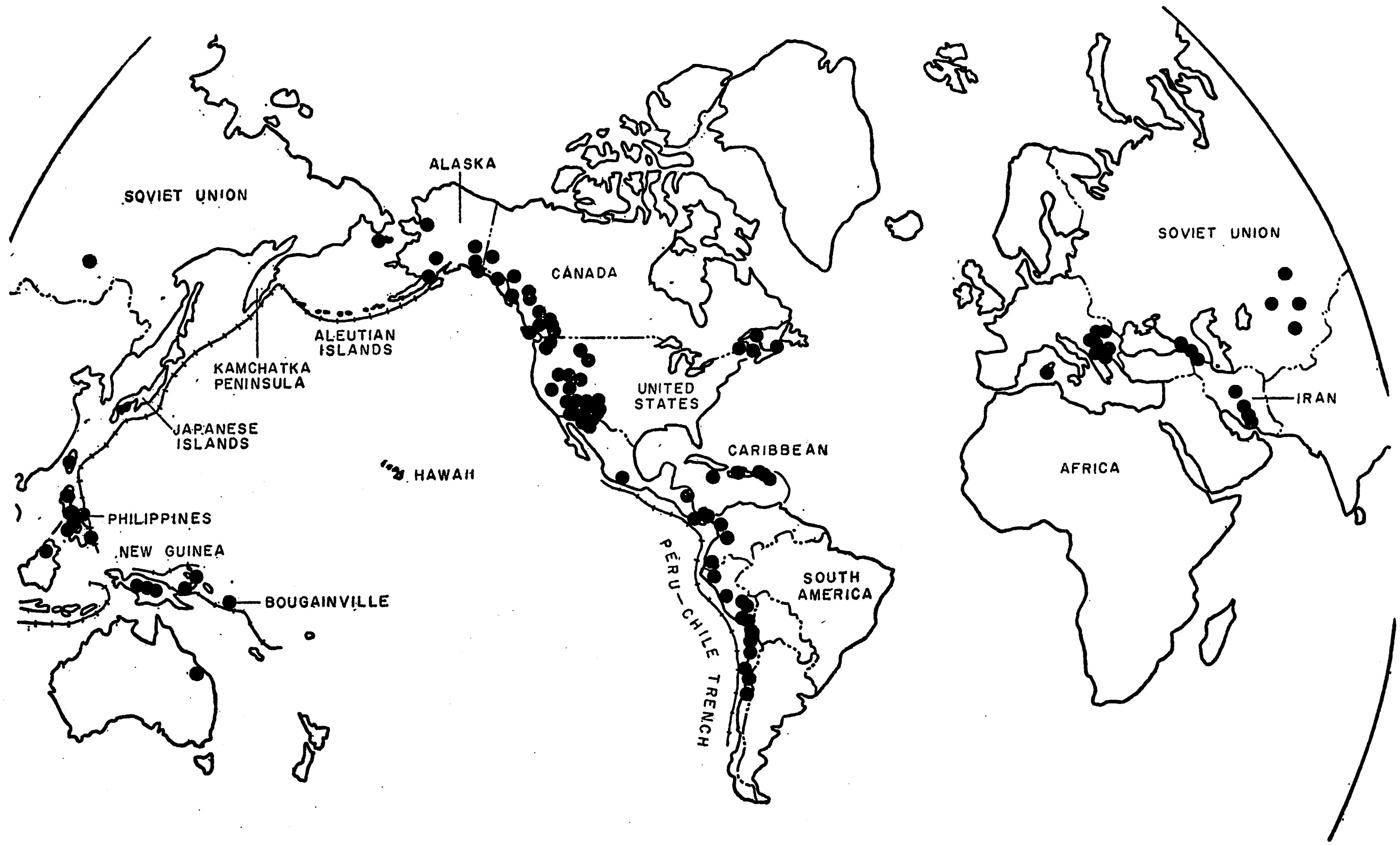

Fig. 1. Generalized world distribution of porphyry copper deposits. Not all deposits are shown, but one or more deposits are shown within geologic or geographic provinces where porphyry copper deposits are known. Trenches along subduction zones shown by hatched line.

striking concentration of porphyry copper deposits around the margins of the Pacific basin. The Pacific coastal area of South America, the western interior of the United States and British Columbia, Canada, abound in porphyry copper deposits, and discoveries during the past decade confirm the abundance of porphyry copper deposits in the Philippine and Malay archipelagos. The apparent paucity of deposits in Mexico, Central America, and perhaps Alaska probably reflects lack of intensive exploration and development. However, other areas of intense igneous activity, such as the Aleutian Islands, Kamchatka Peninsula, and the Japanese Islands, including Sakhalin Island, have been explored and are apparently barren of porphyry copper deposits.

The distribution of porphyry copper deposits shows that porphyry deposits and their associated igneous intrusives are both spatially associated with, and distant from coeval zones. The South American porphyries seem clearly related to the Peru-Chile trench, where oceanic crust is being subducted beneath the continental crust. This trench runs parallel to and about 300 km west of the volcanic crest of the central Andes (James, 1971). Only a small part of the Andean igneous rocks are spatially and temporally related to major porphyry copper deposits. Other porphyry copper deposits possibly related to oceanic-continental-plate junctions are in British Columbia, Canada, and New Guinea.

Some porphyry copper deposits are related to subduction zones entirely within ocean crust, at oceanic-oceanic-plate junctions, as exemplified by the porphyry copper deposits of the Caribbean, Bougainville, and perhaps part of the Philippines. Porphyry copper deposits also occur within continental crust far removed from any known subduction zones. Such occurrences are in the interior of the Soviet Union and probably include those in the interior of the western United States. The latter (fig. 2) are discussed at length in this report, partly because the author has studied these deposits for many years, and partly because opinion is divided on whether these Late Cretaceous-early Tertiary deposits are related to subduction along the east margin of the Pacific Ocean.

On the basis of our current knowledge of the dips of most oceanic-continental-plate junctions, most of the porphyry copper deposits in the western United States appear to be too far removed from the subduction zone for the associated intrusions to have originated by anatexis along the zone. Gilluly (1971), in studying the spatial relations between trenches and andesitic volcanic rocks associated with subduction zones, found that the volcanic rocks extended from about 200 to 600 km from the inferred position of the trench. With a dip of about 45°, which agrees with seismic data, the subduction zone would reach the low-velocity zone at a depth of about 100 km and would reach the bottom of the zone at about 400-500 km. This means that magma formed along such a subduction zone at depths of 100-500 km would appear inland from 100 to 500 km from the trench. Magmas would not be expected to develop very far beneath the low-velocity zone (500 km), and those that are generated would be kimberlite rather than the andesite and basalt associated with active subduction zones. Gillyly (1971, p. 2381) sums these data: "I think that to attribute magmatism more than 700 km from the outcrop of a subduction zone to activity along the zone is simply to assert that all magmatism of intermediate chemistry is related to plate tectonics and to prejudge the whole problem."

In contrast Lipman, Prostka, and Christiansen (1972) believe that the igneous activity in the western United States from the Pacific Ocean eastward for 1,5000 km during the period between about 75 m.y. ago and the inception of crustal extension

Fig. 2. Distribution of porphyry copper deposits in the Western United States.

in mid-Cenozoic time, which was marked by basin-and-range faulting, is due to two imbricate subduction zones. These subduction zones dip about 20°–25° and were uncoupled from the continental plate. The surface expression of the western zone was the trench along the east margin of the Pacific Ocean; the eastern zone never had an independent surface expression in the continental plate. Presumably it was somehow coupled to the western zone below the low-velocity layer, although the author's explanation is not clear on this point. The bases for the two shallow-dipping subduction zones are two geographic zones in which the potassium content of igneous rocks increases eastward. The depths to the subduction zones and their dips were calculated from the geographic locations and potassium contents of the igneous rocks. Although

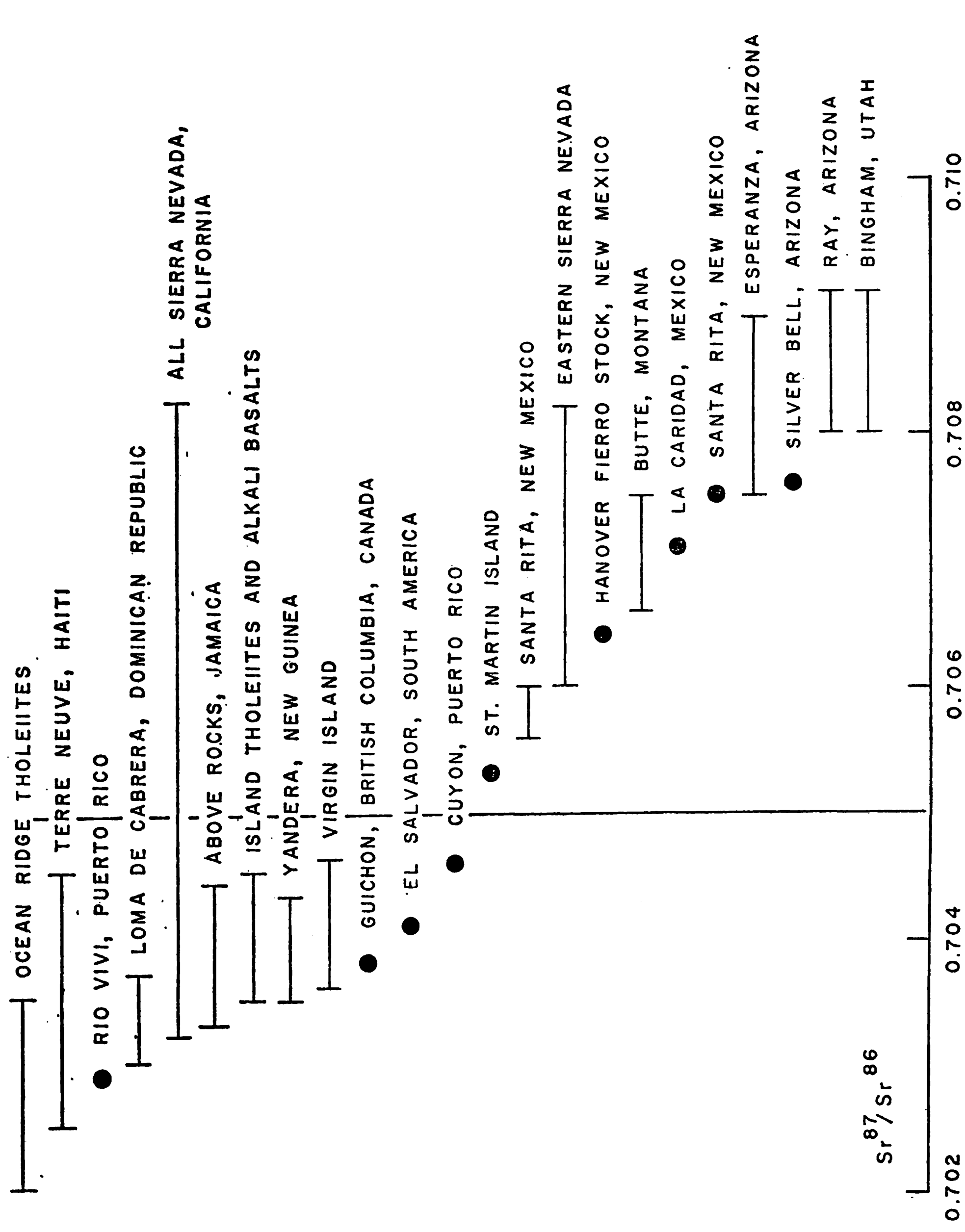

Fig. 3. Initial Sr^{87}/Sr^{86} ratios of intrusive rocks associated in space and time with porphyry copper deposits compared to ratios from Ocean Ridge tholeiites, island tholeiites and alkali basalts, and the Sierra Nevada batholith. Heavy line roughly separates oceanic from continental crust (modified from Kesler and others, 1975)

Lipman, Prostka, and Christiansen's model is intriguing, supporting data are so tenuous that the model is largely speculation.

Distribution of Late Cretaceous and early Tertiary sedimentary and volcanic rocks near the margin of the Pacific basin in California suggests that most of the porphyry copper deposits in the western United States (fig. 2) were formed more than 700 km from the outcrop of the subduction zone. In Arizona, deposits east of the latitude of Phoenix are more than 700 km from the trench, and in the states north of Arizona, those deposits east of the Nevada-Utah boundary are also beyond 700 km. Although the exact position of the subduction zone during the period from 40 to 80 m.y. ago, when most of the porphyry copper deposits in the western United States formed, is difficult to locate, in part because of lateral displacement along the San Andreas fault, the distribution of continental shelf and slope sediments of Upper Cretaceous age in the western margin of the Great Valley of California indicates the trench lay to the west. The Coast Ranges of California west of the Great Valley consists chiefly of oceanic basin sedimentary and volcanic rocks of Mesozoic age (Bailey and others, 1964). These two diverse groups of rocks are in contact along an east-dipping thrust fault that probably marks the approximate position of the trench (Hamilton, 1969). The western boundary of the Great Valley, therefore, can be used conservatively as the easternmost position of the trench from 80 to 40 m.y. ago. Such deposits as Santa Rita, New Mexico, formed more than 1,000 km from this trench. This is about twice the distance between the Peru-Chile trench and the easternmost igneous rocks in the Andean province.

The initial Sr^{87}/Sr^{86} ratios provide some of the most informative data on the source of the stocks (fig. 3). The ratios in stocks associated with porphyry copper in the western United States and northern Mexico (La Caridad deposit) are all greater than 0.705 in contrast to the island arc plutons. These high initial ratios, which are all characteristic of continental crust material, strongly indicate inclusion of continental crust in the origin of the stocks. This interpretation is supported by ratios of less than 0.705 in granitic plutons such as El Salvador (fig. 3) along the margins of continents near subduction zones at oceanic-continental-crust junctions. These ratios show that plutons of oceanic-crust derivation but emplaced in continental crust retain initial Sr^{87}/Sr^{86} ratios indicative of the oceanic crust. The high strontium ratios of stocks in the western United States therefore suggest that the stocks were formed by some process other than subduction of oceanic crust without assimilation of substantial amounts of continental crust.

AGE

Porphyry copper deposits range in age from about 3 to almost 500 m.y. (fig.4). The bulk of the dated deposits are younger than 80 m.y. In a general way, the age distribution probably reflects their frequency distribution. This relation probably is largely a function of depth of erosion. Data on depth of formation of porphyry copper deposits suggest that most formed at depths of 3 km or less in tectonically active zones. Many shallow-seated porphyry copper deposits therefore must have been destroyed through erosion. The British Columbia deposits that cluster around 200 m.y. occur in an area that subsided in Mesozioc time; they have been covered most of the time since they formed.

Porphyry copper deposits older than 250 m.y. are few and are scattered through northeastern United States and eastern Canada. They contain only a very small part

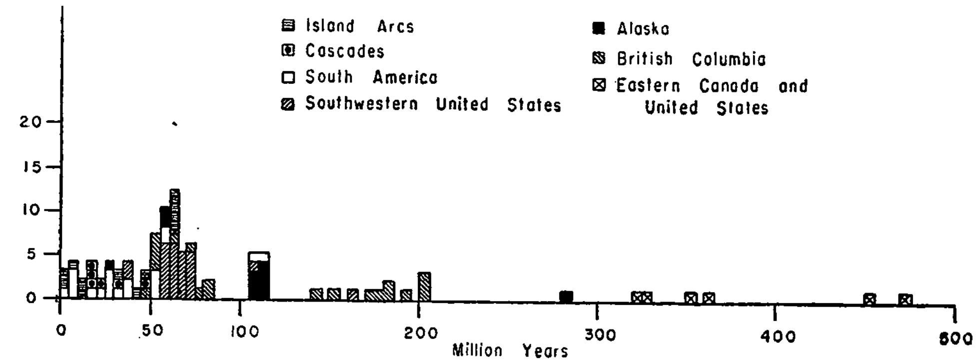

Fig. 4. Potassium-argon isotopic ages of some porphyry copper deposits, North America, South America, and Indonesian Island Arc.

of the porphyry copper resources, but they do demonstrate that the processes responsible for porphyry copper deposits operated throughout the Phanerozoic Eon.

Two other age-related features are of interest. The island arc and South American porphyry coppers are young. They are in areas of active subduction zones where tectonism and erosion are most active. This rapid erosion probably accounts for their exposure a relatively short time after they formed. The other feature is the large number of dated deposits in the southwestern United States. In part, at least, this reflects the large number and widespread distribution of porphyry copper deposits in the western United States, particularly in southern Arizona.

COMPOSITION OF INTRUSIVES

Comprehensive studies of the composition, either modal or chemical, of intrusives related to porphyry copper deposits from different geographic or geologic environments have not been made. Some information, however, shows that porphyry copper deposits are not related to a particular composition or suite of igneous rocks. But in any mineralized area characterized by igneous activity extending over a considerable period, the pluton most closely related to the porphyry copper deposit is among the youngest and most differentiated.

The most comprehensive data on porphyry-copper-related plutons not hydrothermally altered and from an island arc environment that involves only oceanic crust are for the Caribbean (fig. 5). The bulk of the plutonic rocks there are exceedingly low in potassium, as is shown on figure 5 by the low K-feldspar content. This reflects the oceanic crust source rocks, chiefly tholeiitic basalt. The scattering of compositional points from the Qz-Pl join toward the Kf or A corner is interpreted to indicate concentration of alkali in the magma through differentiation, and the straight line curve that summarizes the array of rock compositions is herein called the differentiation trend line. It is used to compare the island arc plutons with others.

Analyses from other similar island arc environments are practically non-existent, largely because most of the plutons of interest are too altered for chemical analyses to be meaningful. However, from our knowledge of the composition of oceanic crust, plutons associated with porphyry copper in other island-arc environments involving

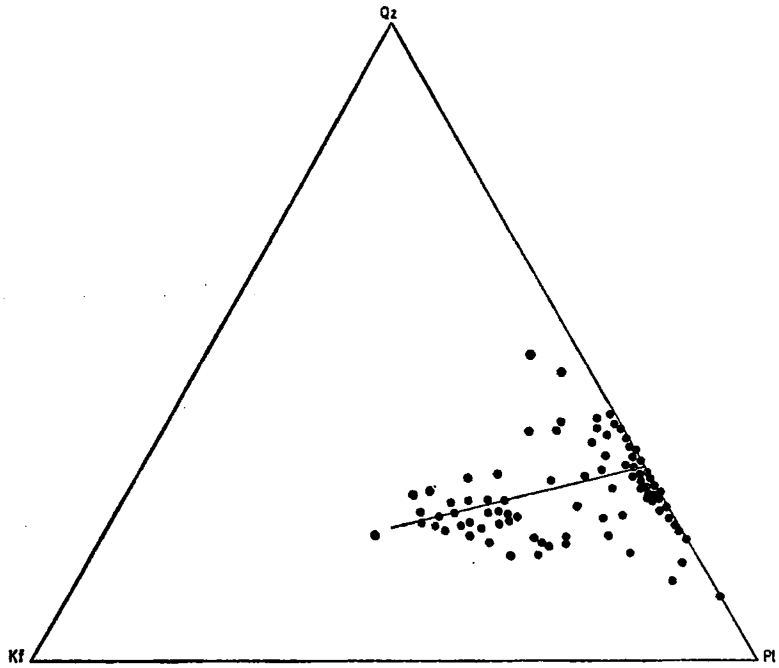

Fig. 5. Pl-Qz-Or ternary diagram of the modal composition of intrusives of northern Caribbean (Kesler and others, 1975).

only oceanic crust would be expected to show about the same distribution on a Pl-Qz-Or diagram as in figure 5.

The porphyry copper deposits in the Caribbean are spatially and temporally associated with the K-feldspar-rich plutons (fig. 5). The differentiation process that resulted in the K-feldspar-rich plutons is thought also to have had something to do with the origin of the porphyry copper deposits.

The normative Pl-Qz-Or composition of Laramide intrusives in southern Arizona, shown on figure 6, include stocks related to and others not related to porphyry copper deposits. Collectively, they form a coherent suite of rocks whose differentiation trend line extends from the Pl corner to the temperature minimum where quartz, albite, and K-feldspar crystallize simultaneously. This is exactly as would be expected if these rocks represent different stages in differentiation of magmas of about the same initial composition. The plots for the dated Laramide stocks in southern Arizona spatially and temporally related to porphyry copper deposits (fig. 7) show a differentiation trend line with the same location and length as on figure 6.

The plots for the mineralized plutons (fig. 7) fall about in the central third of the total spread for all Laramide intrusives (fig. 6). This suggests that the mineralized stocks might be intermediate in composition among the plutons in a given district in which they occur. This, however, is not the case. Each of the mineralized plutons is among the most differentiated in the district; only late dikes are commonly more differentiated. Comparison of the two figures does point out, however, that many highly differentiated plutons are barren.

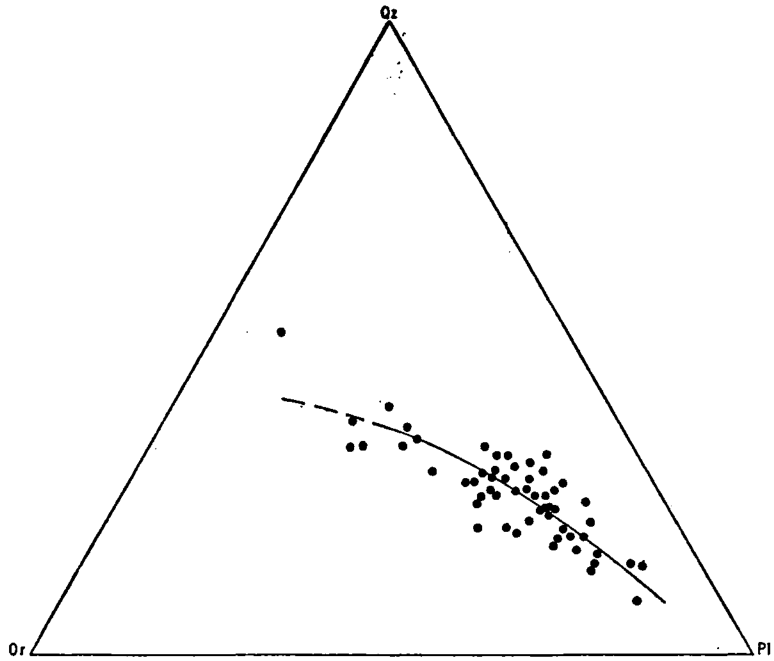

Fig. 6. Pl-Qz-Or ternary diagram of the normative composition of Laramide intrusive rocks of southern Arizona, U.S.A.

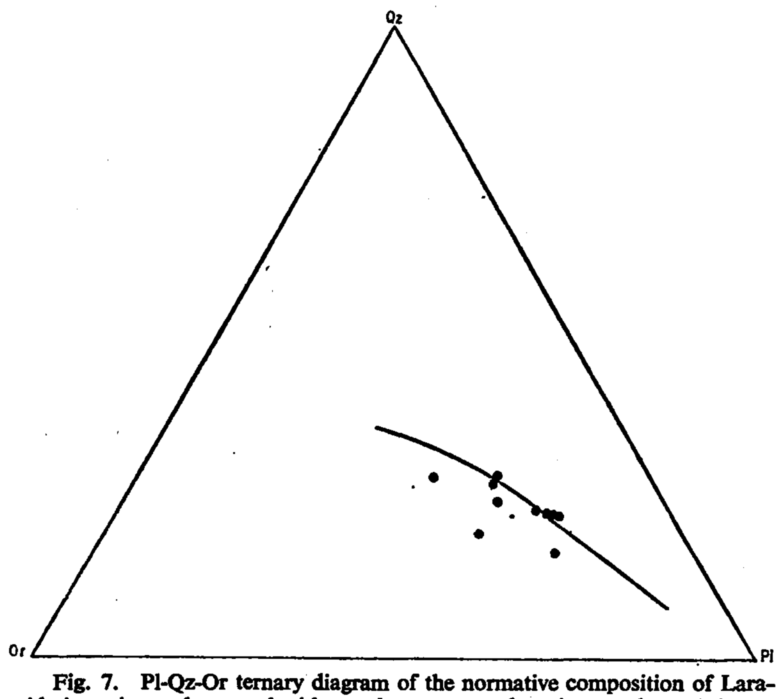

Fig. 7. Pl-Qz-Or ternary diagram of the normative composition of Laramide intrusive rocks coeval with porphyry copper deposits, southern Arizona, U.S.A.

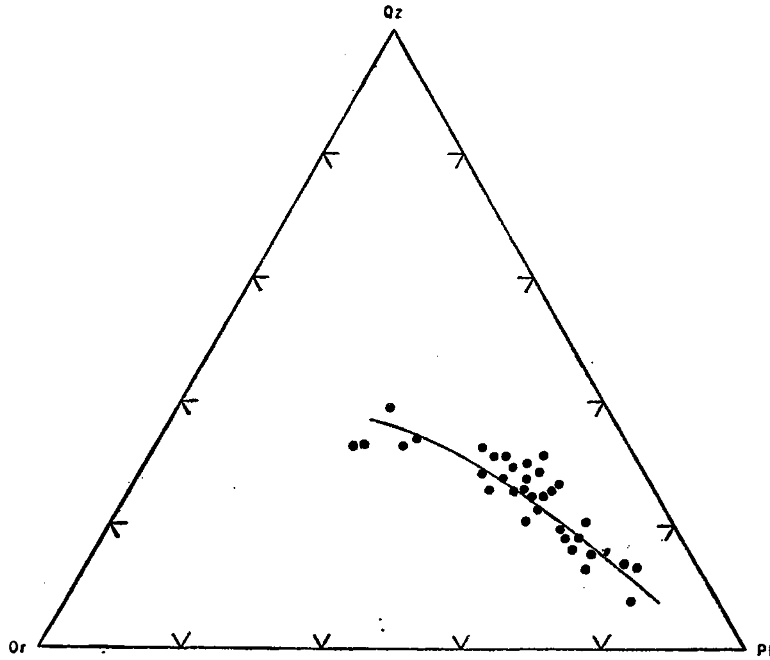

Fig. 8. Pl-Qz-Or ternary diagram of the normative composition of Laramide igneous rocks, Ray area, southern Arizona, U.S.A. Star indicates composition of stock most closely associated in space and time with the Ray deposit (Banks and others, 1972)

Figure 8 shows the plots of all the Laramide igneous rocks, including numerous dikes in the Ray area of southern Arizona, which encompasses about 650 km². The plot shown by a star is considered to be the closest in time and space to the porphyry at the large Ray porphyry copper deposit; most of the plots showing a higher proportion of Qz and Or are dikes. The differentiation trend line is the same as shown in figures 6 and 7. The spread along the differentiation trend line for the Ray area is as large as for the entire south half of Arizona. This suggests that during the Laramide event, differentiation in the magmas was as complete locally as regionally.

The Bingham porphyry copper deposit in Utah, the most productive copper deposit in the United States, contains a suite of igneous rocks significantly different from those in southern Arizona (fig. 9). Both intrusive and coeval extrusive rocks were plotted for the Bingham district, and all the rocks whose compositions lie near the temperature minimum are late premineral dikes and flows rich in quartz and K-feldspar. The bulk of the rocks, however, are monzonites* quartz. All of the rocks plotted on figure 9 were emplaced within a few million years of one another, and the metallization in the deposit is about 1 m.y. younger than the youngest rock (Moore and Lanphere, 1971).

* Named according to the rock classification of the American Geological Institute. However, according to the classification of the IUGS Subcommission on the Systematics of Igneous Rocks, the rocks are chiefly quartz monzonites.

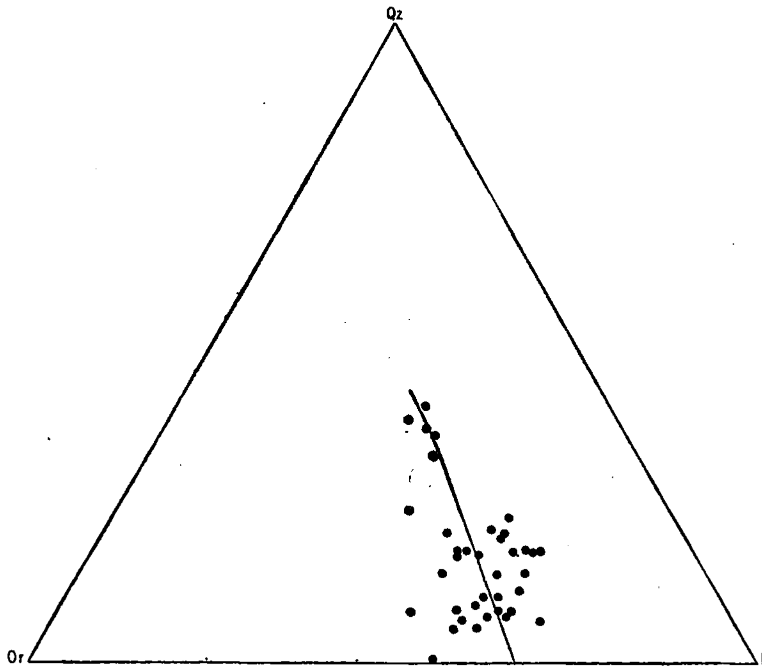

Fig. 9. Pl-Qz-Or ternary diagram of the normative composition of igneous rocks in the Bingham mining district, Utah, U.S.A. (Moore, 1973).

The differentiation trend line for the Bingham igneous rocks (fig. 9) differs significantly from that for the Arizona intrusive rocks; however, both suites of rocks are believed to have been derived from continental crust with no apparent contribution from oceanic crust. A plot of SiO_2 against K_2O (fig. 10) clearly shows the distinction between the southern Arizona stocks, the igneous rocks from the Bingham district, and the Caribbean intrusive rocks. An obvious possible explanation for the difference between the Bingham igneous rocks and the southern Arizona stocks is inhomogeneities in the continental crust.

The composition of the rocks in the Snake Range in eastern Nevada (fig. 11) is similar to rocks in southern Arizona associated with porphyry deposits, yet the Snake Range contains no known copper deposits. The range is geographically much closer to the Bingham district than to any Arizona porphyry copper deposit, but the compositions of the rocks differ markedly from those at Bingham. The relations on figure 11 show that differentiation alone does not assure commercial copper deposits, although in all the copper districts examined, the rocks were differentiated and the copper deposits were most closely related to intrusives that were among the most differentiated and youngest.

Figure 12 compares the differentiation trend lines from the Caribbean, southern Arizona, and Bingham with those from southern California, Idaho, Boulder, and Sierra Nevada batholiths and from Laramide stocks from Colorado and New Mexico. The differentiation trend line from Caribbean rocks differs in slope and direction from all the others, which are somewhat alike. The Caribbean trend line is the only

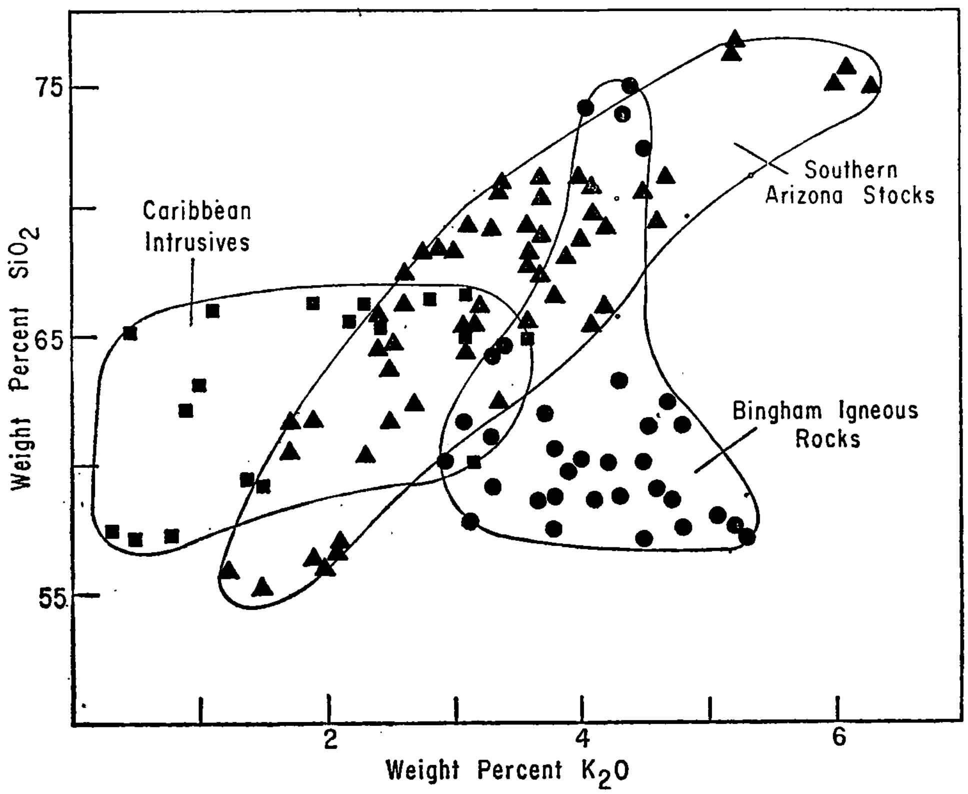

Fig. 10. SiO_2–K_2O fields for Caribbean intrusive rocks, southern Arizona stocks, and igneous rocks in the Bingham district.

one of the group that represents rocks entirely from an oceanic-crust environment. All the others represent magmas emplaced within continental crust, although some may have formed at oceanic-continental-crust junctions. The similarity in slope and location between the differentiation trend line for southern Arizona and the Sierra Nevada and between thosefor the Bingham district and Laramide stocks of Colorado and New Mexico is striking and points out the similarity of rocks associated with porphyry copper deposits and rocks that have no known association with large copper deposits. In the major chemical elements and in silicate mineralogy, the rocks associated in space and time with the porphyry copper deposits are not distinctive.

The extent to which assimilation of wallrocks contributes to the composition of a pluton is unresolved. Some data indicate a substantial contribution, whereas other equally convincing data indicate none. The Sr^{87}/Sr^{86} ratio of the pluton associated with the El Salvador porphyry copper deposit (fig. 3) is of interest because the pluton lies in the high Andes of South America within continental crust that is underthrust by oceanic crust along the Peru-Chile trench. The pluton associated with El Salvador most likely formed from subducted oceanic crust and sediments, and the initial strontium ratios accurately reflect this origin. However, to reach its place of crystallization high in the crust, the magma must have intruded many kilometers of continental crust.

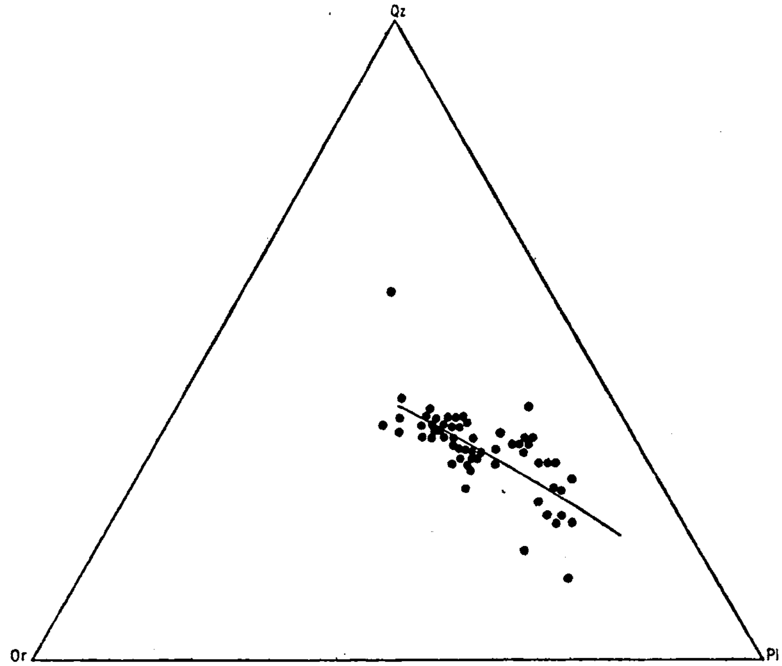

Fig. 11. Pl-Qz-Or ternary diagram of the normative composition of igneous rocks in the Snake Range, Nevada, U.S.A. (Lee and Van Loenen, 1971).

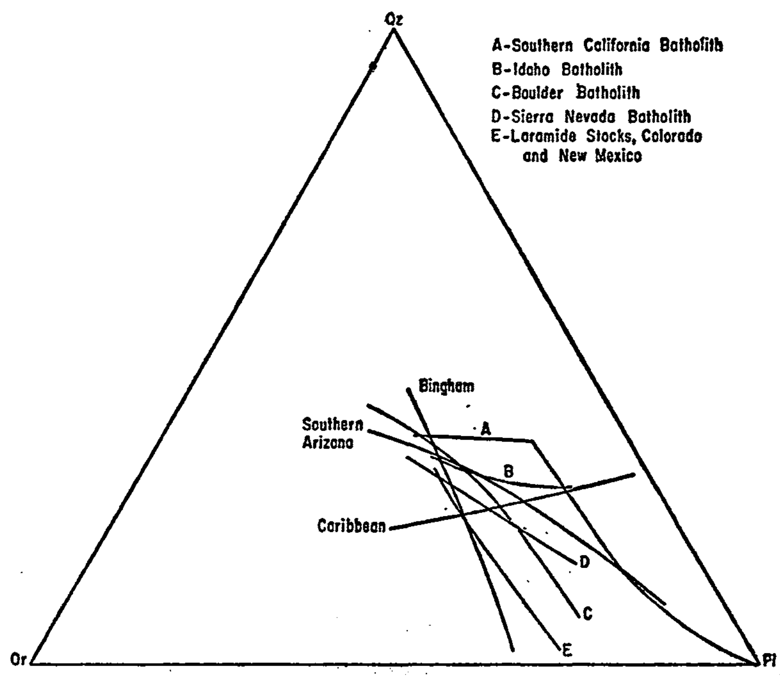

Fig. 12. Comparison of differentiating trend lines from porphyry copper deposits and other plutonic rocks in the Western United States (modified from Bateman and others, 1963).

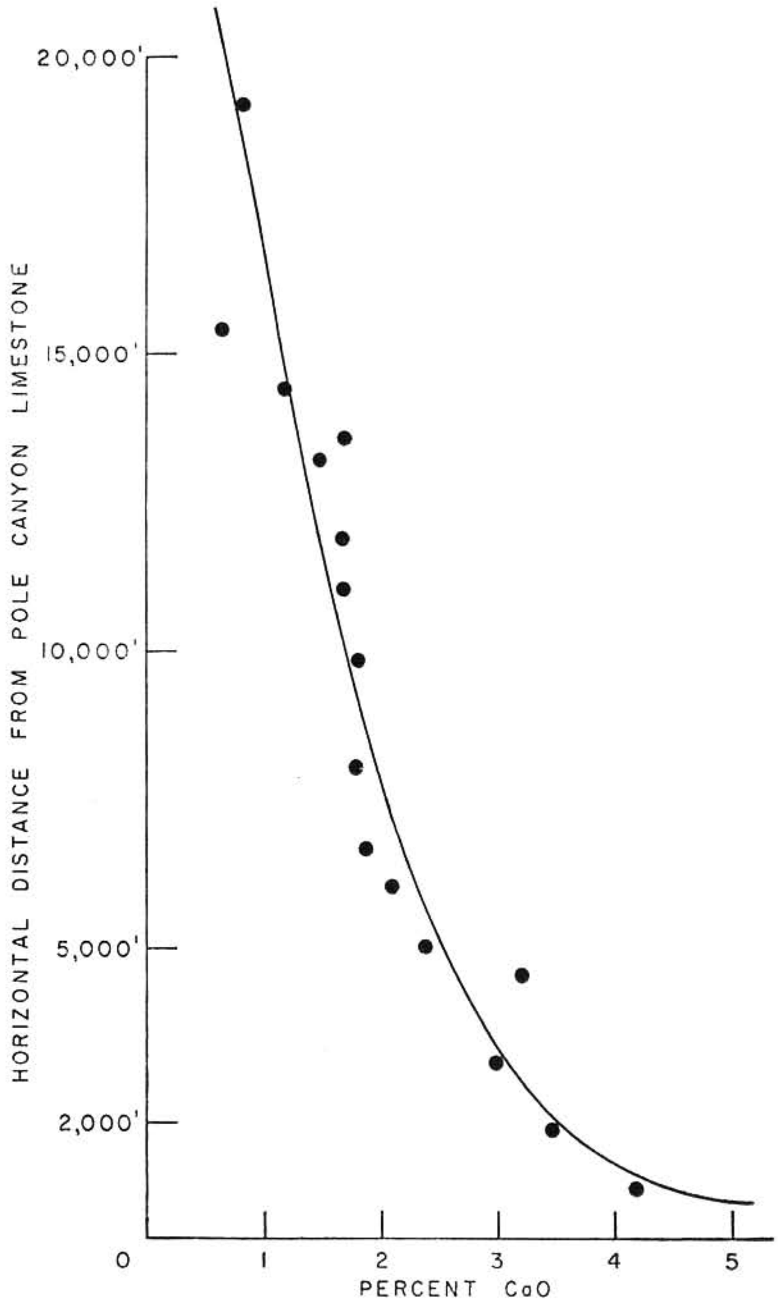

Fig. 13. Variation of CaO in a granitoid intrusive rock as a function of distance from a limestone body. From Lee and Van Loenen (1971).

Any significant assimilation of continental crust would be reflected in the initial strontium ratio. In their discussion of the ratio, Gustafson and Hunt (1975) say: "This [the ratio] indicates that the porphyry melts did not assimilate a significant amount of this crust during their passage through it, although incorporation of overlying Tertiary volcanics cannot be excluded."

Unequivocal examples of transfer of major elements or metals from wallrocks to ore deposits or magmas are rare. One of the most convincing was Zartman's (1974) study of lead in ore deposits of the western Cordillera of the United States. He determined that the isotopic composition of the lead in the ore deposits was the same as in the contiguous country rock, and the isotopic composition of the lead in the deposits changed from one geologic province to another to correspond with changes in the country rock. The agreement between the isotopic composition of lead in ore deposits and contiguous rock is about as clear as anything ever is in geology, and the simple explanation is equilibration of lead between country rock and ore deposit.

Lee and Van Loenen (1971) measured the CaO content of a granitoid intrusive rock as a function of the distance from the intrusive contact with the Pole Canyon Limestone (fig. 13). Their data show a systematic decrease in CaO with distance from the limestone-intrusive contact. Their interpretation is assimilation of limestone by the intrusion, an explanation that is compatible with the data presented; however, their description of the pluton does not preclude a pluton zoned by differentiation, the periphery being rich in calcium, magnesium, and iron and the core rich in alkalis and silicon.

Despite the uneven distribution of data from around the world on the composition and relations in time and space of intrusives associated with porphyry copper deposits, a consistent pattern seems to exist. Porphyry copper deposits are not associated with a unique type or suite of rocks. They are found as often with rocks derived from oceanic crust as with rocks derived from continental crust. Within any single mining district that contains a complex igneous event, including plutons, dikes, and extrusive rocks, the porphyry copper deposits are related to the youngest and most differentiated intrusives rich in quartz and K-feldspar.

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