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GEOCHRONOLOGY OF THE PANGUNA PORPHYRY COPPER DEPOSIT, BOUGAINVILLE ISLAND, NEW GUINEA.

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Abstract

K-Ar ages have been determined on the major intrusive and sub-volcanic bodies associated with the Panguna copper deposit on Bougainville. The earliest pre-mineralization intrusive has an age of 4 to 5 m.y., and the mineralized, strongly altered, intrusive bodies are 3.4 ± 0.3 m.y. old. The 3.4 m.y. age is interpreted as the age of mineralization of the Panguna rocks, and is not distinguishable from the age of the porphyries themselves. Thus a distinguishable time interval of about 0.5 to 1.5 m.y. is recognized between the initial magmatic emplacement at Panguna and subsequent mineralization associated with the porphyries. One of the intrusives that on field evidence is known to postdate mineralization has an age of 3.5 ± 0.3 m.y., and another such body was emplaced only 1.6 m.y. ago.

Introduction

Much attention has been focussed in the last five years on the intrusive rocks in the New Guinea and Solomon Islands region because some of these bodies have porphyritic phases and represent very favourable environments for porphyry copper mineralization. In this paper we report the results of isotopic dating studies on one of these deposits, the Panguna copper ore body on Bougainville Island.

Further geochronological studies from ineralized regions in mainland New Guinea are presented in Page and McDougall (1972). Dating of specific mineralized areas offers an opportunity to examine the age distribution of the deposits with respect to tectonic features and perhaps to establish definite metallogenic epochs in the region. The use of precise isotopic ages might also be useful in establishing genetic relations between ore and igneous rock. In dealing with a relatively young geological environment such as this, it was also hoped to investigate whether there was a distinguishable time interval between emplacement of the igneous rocks and their subsequent mineralization. The Panguna porphyry copper ore body on Bougainville Island was chosen for close study, because it is presently the only large proven ore body in the region, and the geological relationships are well known through surface and underground mapping and extensive diamond drilling.

Geology

Bougainville Island, politically part of Papua New Guinea, is structurally and tectonically part of the northwest trending Solomon Islands group. The geological features of the Solomon Islands have been described by Coleman (1966, 1970) and the geology of Bougainville by Blake and Miezitis (1967). Bougainville Island is about 200 km long and 60 km wide and like the rest of the Solomon chain is essentially an uplifted succession of Cainozoic volcanic rocks, sedimentary rocks derived from the volcanics, and subordinate organic limestones. It has mountainous interior ranges with several extinct, dormant and active volcanoes rising to an altitude of up to 2500 m. Bougainville is flanked to the northeast by the sea floor of the Ontong-Java Plateau and the Pacific Ocean, and to the southwest by a deep ocean trough, the extension of the New Britain Trench. Seismically, the region is very active (Denham, 1969).

The stratigraphy of Bougainville, as described by Blake and Miezitis (1967) is summarized in Table 1. In the vicinity of Panguna, in the central part of southern Bougainville, Blake and Miezitis (1967) and Macnamara (1968) have described the geological setting of the porphyry copper ore body (Figure 1). The deposit is associated with porphyritic quartz diorite and granodiorite bodies intrusive into the Panguna Andesite Member of the Kieta Volcanics Formation. North of Panguna, volcanic rocks correlated with the Kieta Volcanics are unconformably overlain by the Lower Miocene Keriaka Limestone, and hence the Panguna Andesite Member of the Kieta Volcanics has been considered to be pre-Miocene age. However, large extrapolations are required in such a correlation and the Panguna Andesite Member as mapped, may well include younger rocks. All of the supposed pre-Miocene volcanics exhibit a low grade greenschist facies regional alteration, and because of this are generally not suitable for dating purposes.

The rock types and mineralization at the Panguna mine have been mapped on the surface and through extensive tunnelling and diamond drilling by geologists of Conzinc Riotinto Exploration Pty. Ltd., and these results are reported by Macnamara (1968). The diorite and granodiorite intrusives crop out in an area of about 15 km^2 around Panguna, and Macnamara (1968) classifies them into four mineralized groups and a number of late stage barren types (Figure 1). Brief notes on some of these are given below.

(a) The Kaverong Quartz Diorite is restricted to the north of the map area and is the largest of the intrusive bodies. Because of its fresh unaltered appearance and its central relationship to the altered intrusives (see below), the Kaverong Quartz Diorite is considered to be the oldest of the Panguna intrusives. According to Macnamara (1968) it carries weak copper mineralization, and in places contains dark chloritic inclusions presumed to be xenoliths of the intruded country rock, Panguna Andesite.

TABLE 1: Stratigraphic succession on Bougainville Island.

Recent	Alluvium	
Pleistocene	Sohano Limestone	
Pliocene? to Recent	Bougainville Group	- volcanic rocks erupted from post-Miocene volcanics
Lower Miocene (e stage)	Keriaka Limestone	
Oligocene? to Pleistocene	Dioritic intrusions	
Oligocene? to Lower Miocene	Kieta Volcanics	- andesitic lavas, pyroclastics, and sedimentary rocks composed of volcanic material.

(b) The Biotite Diorite rock type occurs on the southern margin and is an altered variant of the Kaverong Quartz Diorite. The Biotite Diorite and Kaverong Quartz Diorite are texturally similar and the contact is believed to be a gradational one involving progressive replacement of hornblende by biotite aggregates. The Biotite Diorite is strongly fractured, veined and mineralized.

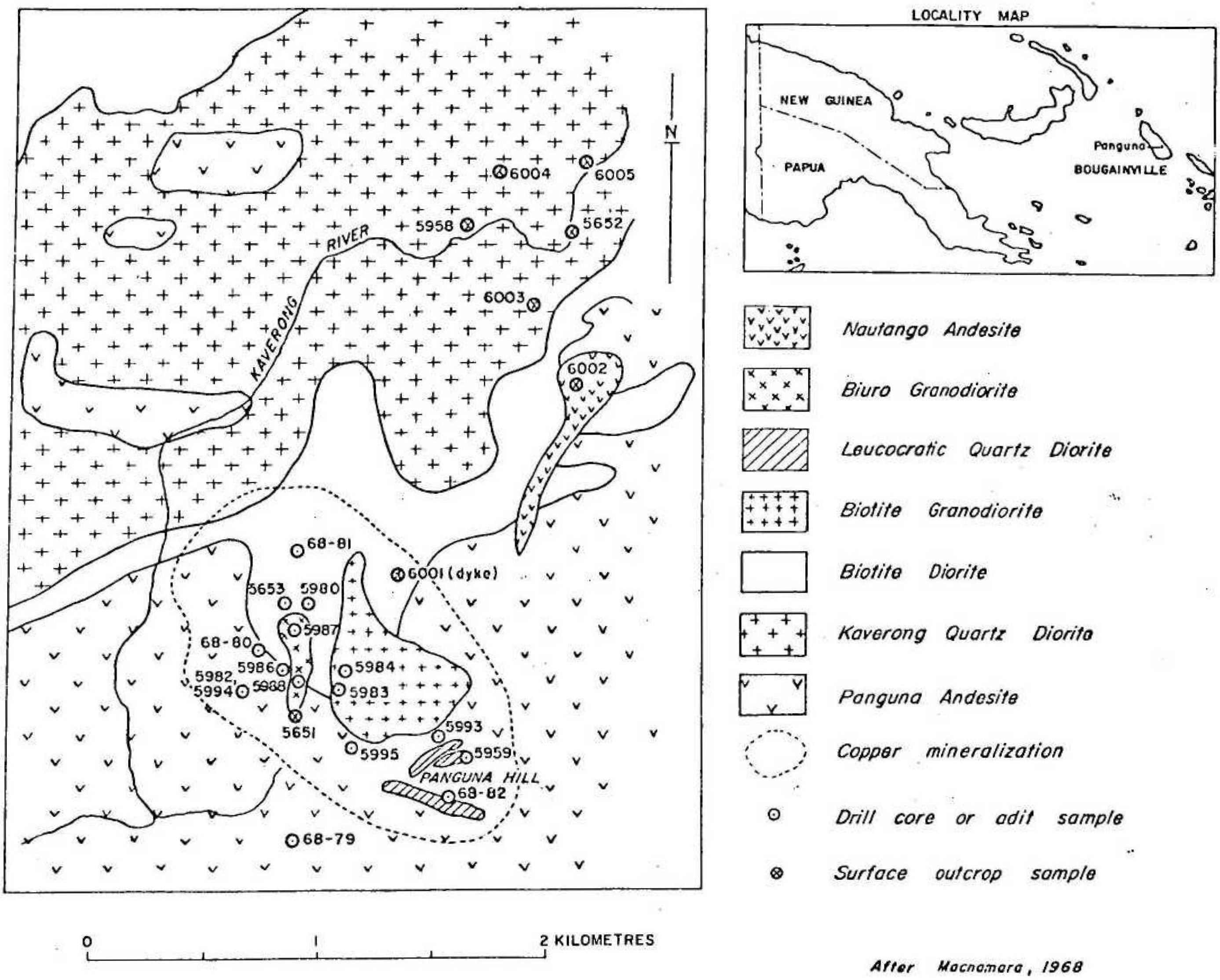

Figure 1. Generalized geological map of the Panguna area, Bougainville Island.

(c) The Biotite Granodiorite is a mineralized and fractured, steep-walled body that is kidney-shaped in plan, and is intrusive into the Biotite Diorite. The copper mineralization is roughly annular about the Biotite Granodiorite (Macnamara, 1968; Fountain, 1972). The dominant rock type is an altered quartz-plagioclase porphyry.

(d) The Leucocratic Quartz Diorite is the third mineralized body and crops out as three sheeted pods intrusive into the Panguna Andesite. It is generally similar to the Biotite Granodiorite but is more strongly veined (with quartz-K feldspar). Macnamara (1968) regards all the above intrusives as comagmatic and considers the Leucocratic Quartz Diorite, as the youngest intrusive. From veining relationships, however, Fountain (1972) shows that the Biotite Granodiorite postdates the Leucocratic Quartz Diorite and that the Biotite Granodiorite is the closest intrusive time-equivalent to the mineralization event.

The intrusion of these quartz diorites and granodiorite porphyries has produced contact metamorphic effects (recrystallization, metasomatism) in the Panguna Andesite country rock. In all the mineralized intrusives and in the mineralized (hornfelsed) Panguna Andesite, chalcopyrite is the dominant copper mineral, with varying amounts of pyrite, bornite, molybdenite, silver, sphalerite, galena and gold (Macnamara, 1968). Mineralization of this kind is associated commonly with potash alteration in both the host (Panguna Andesite) and intrusive rocks. The alteration in the latter is in the form of myriads of irregular, thin quartz-chalcopyrite veinlets with pink orthoclase selvedges; in some cases the chalcopyrite is disseminated and associated with only biotite. Alteration/mineralization in the hornfelsed Panguna Andesite is similar to that in the intrusive rocks, but commonly an extremely fine-grained biotite-rich zone forms a selvedge to the quartz-rich veins. The approximate geographic limits of copper mineralization (Figure 1) correspond more or less to the zones of biotite alteration. There is little doubt that mineralization is related to one or more of the three dioritic intrusives, but no clear relationship has yet been established.

(e) The barren late stage intrusives are of two main types in the Panguna area. The Biuro Granodiorite intrudes both the Panguna Andesite and the Biotite Diorite in the centre of the map area and in places contains many xenoliths of both rocks. The Biuro Granodiorite is a porphyritic hornblende microdiorite with a fine-grained, quartzo-feldspathic mosaic groundmass.

The other late stage intrusive relevant to this study is the Nautango Andesite, the main outcrop of which is a plug-like knoll intruding Panguna Andesite and Biotite Diorite in the northeast of the map area. The rock is a fresh massive hornblende andesite with acicular hornblende crystals; similar rock types occur as dykes up to a few metres wide elsewhere in the Biotite Diorite.

Analytical Procedures

Mineral concentrates and whole rock samples have been dated by the K-Ar method. The isotope dilution method of argon analysis followed the techniques described by McDougall (1966), and analysis of potassium by flame photometry was done according to Cooper (1963). The physical constants used in the age calculations are: $\lambda_{\beta} = 4.72 \times 10^{-10}\ yr^{-1}$, $\lambda_{e} = 0.585 \times 10^{-10}\ yr^{-1}$, $K^{40}/K = 1.91 \times 10^{-2}$ atom percent.

Unless otherwise stated the errors quoted for each age represent two standard deviations, and are calculated from the statistical uncertainties derived directly from each analysis in the manner given by McDougall and others (1969). In some runs with high air argon contamination (greater than 90%), relatively large errors are found, but in most cases with moderate air argon contamination the standard deviation is about 2 to 3% of the calculated age.

K-Ar Dating Results

The ages of the intrusive rocks at Panguna, and indeed for the whole of Bougainville Island, are known only within the rather broad limits of Oligocene to Pleistocene (Blake and Miezitis, 1967). The present K-Ar study is restricted to the Panguna area, with the aim of determining as closely as possible the ages of emplacement and mineralization of the various rock types. These data are presented in three sections based on the known geological relationships. Respectively, these deal with -

(a) The pre-mineralization intrusive,
(b) the mineralized rocks themselves, and
(c) the post-mineralization intrusives.

(a) Pre-mineralization ages. As previously mentioned, the Kaverong Quartz Diorite is considered to be the earliest phase of the Panguna intrusive rocks. K-Ar measurements were made on hornblende and plagioclase separated from five diorite samples from the body and the results are given in Table 2. The dated samples were collected in the upper Kaverong River and northwest of Mount Nautango, between 1.5 and 2.0 km north of the Panguna mineralized zone (Figure 1). The hornblende ages show a spread from 3.9 to 4.7 m.y. The plagioclase (5652) was run in duplicate and although agreement is poor, a higher apparent age of about 7 m.y. is indicated. The total age spread of 4 to 7 m.y. for the Kaverong Quartz Diorite is well outside experimental error, indicating a complex intrusive history or perhaps partial updating of the ages due to heating effects from the later intrusives. Because all of the samples were collected within a radius of 0.5 km, a complex intrusive history seems unlikely. If updating due to later intrusions was the primary cause of the spread, one may have expected some correlation with distance from the intrusions. It is noted that the location of the hornblendes dated at 4 to 5 m.y. bears no relation to their distance from the later mineralized intrusives, and hence updating probably may be discounted. Another possibility is that the 7 m.y. age on the plagioclase is due to incorporation of extraneous argon during crystallization, but without analysing further samples this idea cannot be evaluated.

Table 2. K-Ar ages from the Panguna Copper Deposit, Bougainville.

No.	Sample	K%	Rad. Ar^{40} $\times 10^{-7}$ cc NTP/g	$\frac{100 \text{ Rad. } Ar^{40}}{\text{Total } Ar^{40}}$	Calculated age (m.y.) ± 2 s.d.
Kaverong Quartz Diorite					
5652	Plagioclase	0.675) 0.678) 0.677	1.706 2.093	49.0 53.3	6.31 ± 0.17 7.74 ± 0.16
5958	Hornblende	0.436	0.815	11.0	4.68 ± 0.22
6003	Hornblende	0.422) 0.419) 0.420	0.715	11.4	4.24 ± 0.18
6004	Hornblende	0.359) 0.343) 0.351	0.539	10.5	3.91 ± 0.43
6005	Hornblende	0.481) 0.484) 0.483	0.763	17.1	3.96 ± 0.14
Biotite Diorite					
68-81	Biotite	5.471) 5.363) 5.417	2.481	43.5	1.15 ± 0.04
5653	Biotite	7.261) 7.207) 7.234	9.612	31.3	3.33 ± 0.10
5980	Biotite	6.851) 6.767) 6.809	7.868	45.3	2.89 ± 0.06
5982	Biotite	7.249) 7.276) 7.263	11.290	31.9	3.89 ± 0.08
Biotite Granodiorite					
5983	Plagioclase	1.154) 1.154) 1.154	1.546	21.5	3.36 ± 0.11
5984	Biotite	5.442) 5.471) 5.457	4.365	14.4	2.00 ± 0.07
Leucocratic Quartz Diorite					
68-82	Biotite	4.615) 4.660) 4.638	2.255	2.7	1.22 ± 0.31
5959	K feldspar	7.854) 7.872) 7.863	10.143	13.7	3.23 ± 0.11
Panguna Andesite Hornfelses					
68-79	Whole rock	0.371) 0.369) 0.370	0.537	12.0	3.63 ± 0.19
	Plagioclase	0.294) 0.291) 0.293	0.410	4.5	3.50 ± 0.49
5993	Whole rock	0.762) 0.761) 0.762	1.053	11.6	3.46 ± 0.13
5994	Whole rock	1.775) 1.774) 1.775	2.427	24.4	3.43 ± 0.07
5995	Whole rock	0.696) 0.691) 0.694	0.974	17.6	3.52 ± 0.10
Biuro Granodiorite					
68-80	Hornblende	0.448) 0.448) 0.448	0.530	3.3	3.00 ± 0.47
	Plagioclase	0.474) 0.476) 0.475	0.705	10.3	3.70 ± 0.76
5651	Hornblende	0.397) 0.396) 0.397	0.757 0.700	26.8 16.6	4.78 ± 0.15 4.42 ± 0.16
	Plagioclase	0.514) 0.506) 0.510	0.709	28.7	3.48 ± 0.11
5986	Plagioclase	0.504) 0.505) 0.505	0.743	15.0	3.68 ± 0.11
5987	Plagioclase	0.684) 0.681) 0.683	0.930	19.9	3.41 ± 0.08
5988	Hornblende	0.433) 0.431) 0.432	0.677	10.6	3.90 ± 0.17
	Plagioclase	0.696) 0.693) 0.695	0.901	26.7	3.25 ± 0.06
Nautango Andesite					
6001	Whole rock	1.306) 1.301) 1.304	0.648	40.1	1.25 ± 0.03
	Hornblende	0.542) 0.561) 0.552	0.340	10.3	1.54 ± 0.08
6002	Whole rock	1.178) 1.174) 1.176	0.586	24.3	1.25 ± 0.03
	Hornblende	0.506) 0.509) 0.508	0.340	11.2	1.68 ± 0.07

It is considered that the age of the Kaverong Quartz Diorite is best given by the four reasonably concordant hornblende results at 3.9 to 4.7 m.y. with a mean of 4.2 m.y. This is regarded as a minimum estimate of age, and taken at face value indicates that the body was emplaced in the early Pliocene.

(b) Mineralized source and host rock ages. Economic copper mineralization at Panguna is found within the three hyrothermally altered, porphyritic intrusive types as well as in the host rocks of the Panguna Andesite hornfelses. Thirteen K-Ar age measurements were made on mineral and whole rock hydrothermal alteration products from within these zones of intense copper mineralization. The results are listed in Table 2.

The four Biotite Diorite samples are from different vertical and inclined drill holes in the central and southern parts of the body (Figure 1). The analysed biotite is associated with chalcopyrite in veins and in very fine-grained decussate aggregates; quartz and plagioclase in the rocks show signs of recrystallization. The apparent biotite ages range from 1.2 to 3.9 m.y., a spread which is much larger than the experimental uncertainties. There seems to be a correlation (Figure 2) between apparent age and K content of the biotites, as the two partly chloritized samples with lower K (5980, 68-81) give distinctly lower ages. The two fresh biotites (5653, 5982) give somewhat discordant results at 3.33 ± 0.10 m.y. and 3.89 ± 0.08 m.y., and these are interpreted as minimum ages for the hydrothermal alteration (recrystallization) of the Biotite Diorite.

The two dated samples of Biotite Granodiorite are from drill cores in the western part of the mass. The plagioclase (5983) with rather high K is dated at 3.36 ± 0.11 m.y. Again the low biotite age can be identified with the partly chloritized nature (5.4% K) of the sample (cf. Figure 2). The measured ages of the Biotite Granodiorite will again be related to the recrystallization of the rocks, and although no independent age estimate is possible from these two results, it is noted that the plagioclase age (5983) of 3.4 m.y. is in good agreement with the minimum ages obtained for the Biotite Diorite alteration.

The two samples dated from the Leucocratic Quartz Diorite were collected in the adit beneath Panguna Hill. The chloritized biotite sample (68-82, with 4.6%K) again gives a rather low age of 1.2 ± 0.31 m.y.; the large uncertainty is due to the unfavourable analysis, there being only 2.7% radiogenic argon component in the run. The K feldspar age of 3.23 ± 0.11 m.y. is related to a mineralized, partly sericitized, K feldspar-rich vein (about 2 cm wide) in the Leucocratic Quartz Diorite, and can be regarded as a minimum age estimate for the hydrothermal veining and alteration in the body.

The mineralized host rocks of the Panguna Andesite are typified by close jointing and pervasive biotite alteration with which the copper is associated, within the contact aureole of the diorite and porphyry intrusives. The aureole is at least 500 m wide, as evidenced by sample 68-79 which is a thoroughly recrystallized basic hornfels. Three other drill core samples of Panguna Andesite (5993, 5994, 5995) closer to the intrusive complex are also fine-grained hornfelses, and consist of the assemblage amphibole-plagioclase-quartz-biotite, as well as chalcopyrite. Because the plagioclase is of oligoclase-andesine composition, it is suggested the rocks belong to the hornblende-hornfels facies, and may therefore have been metamorphosed at

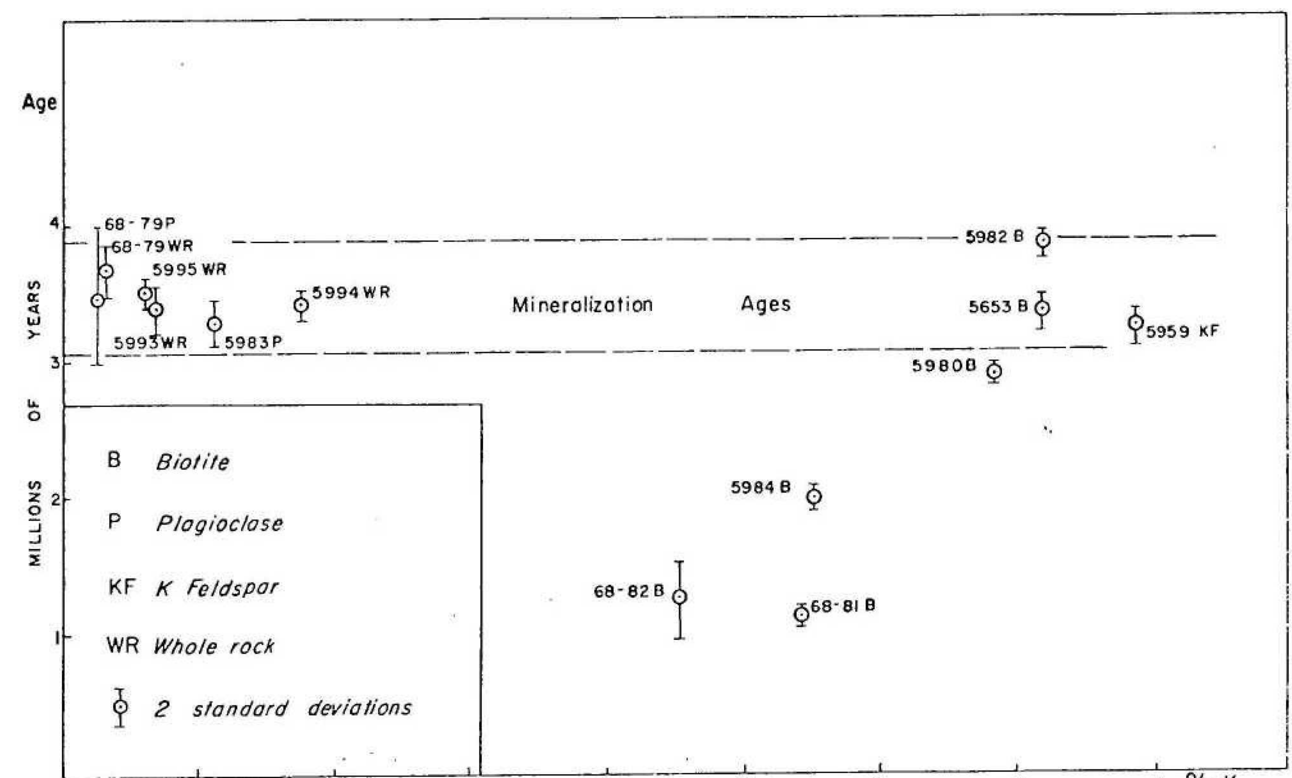

Figure 2. Plot of K-Ar age versus K content of the hydrothermally altered samples.

temperatures of the order of 500^{o} to $700^{o}C$ (Turner and Verhoogen, 1960). The four whole rock hornfelses give consistent results close to 3.5 m.y., and the plagioclase age of 68-79 is also concordant (Table 2). The good agreement of all the hornfelses suggests that the apparent age of around 3.5 m.y. is geologically significant, particularly as the K contents of the samples differ by a factor of more than 6. It can be inferred from these data that any pre-existing radiogenic argon was completely outgassed from the Panguna Andesite hornfelses, and the age of 3.5 m.y. is reflecting the time of contact metamorphism and hydrothermal alteration of the rocks.

The dates from all bodies in the mineralized zone are summarized in Figure 2. There is a very clear grouping of the ages of both the intrusive diorites and the Panguna Andesite hornfelses between 3.1 and 3.9 m.y. The partly chloritized biotites well outside of this band give much younger apparent ages of 1 to 2 m.y., probably indicating variable loss of radiogenic argon. Neglecting these three chloritized biotites, a mean age of 3.42 ± 0.25 m.y. (standard deviation) is obtained from a consideration of the remaining ten ages in the Panguna mineralized zone. The data do not show any age difference between the three mineralized and altered intrusive types.

In summary, the ages determined on the hydrothermal products in both the dioritic intrusives and the host Panguna Andesite strongly suggest that the alteration/mineralization event, which was probably synchronous with the Biotite Granodiorite and/or Leucocratic Quartz Diorite emplacement, occurred in mid-Pliocene time, 3.42 ± 0.25 m.y. ago.

(c) Post mineralization intrusive ages. The cross-cutting nature of the Biuro Granodiorite and Nautango Andesite with respect to the other rock types, as well as veining relationships within the Biuro Granodiorite, are good evidence that these two bodies are the youngest intrusions in the Panguna area. They are unaltered and generally barren of mineralization except where contaminated by pre-existing mineralized rock. Their ages should provide a firm younger limit for the age of the Panguna mineralization.

The K-Ar ages on hornblende and plagioclase from five samples of Biuro Granodiorite are given in Table 2, and their locations are shown on the map (Figure 1). Three of the dated rocks were obtained from vertical and inclined drill cores, one from the underground Western Adit. and one from surface outcrop. Except for 5651 hornblende, seven of the eight minerals dated from the Biuro Granodiorite yield ages between 3.00 and 3.90 m.y. The mean indicated age for the group is 3.49 ± 0.29 m.y. (standard deviation). The general consistency of the dates is convincing evidence that this is the age of intrusion of the body. The anomalously high hornblende age (5651) of about 4.6 m.y. requires explanation. It is quite rare to find extraneous argon in hornblende (Dalrymple and Lanphere, 1969) and as this sample has a moderate K content, incorporation of extraneous argon is unlikely to account for the large age discrepancy. It is possible that the older age of 5651 hornblende represents incomplete degassing of an older hornblende-bearing inclusion ; that is, it may be a "relict" age due to inherited Ar^{40}. This is a distinct possibility because sample 5651 comes from the southernmost apophysis where the Biuro Granodiorite intrudes and incorporates many xenoliths of Panguna Andesite.

The mean age of the Panguna mineralized rocks is thus not distinguishable from the age of the Biuro Granodiorite. As the geological relationships unequivocally indicate that the Biuro Granodiorite was intruded subsequent to the mineralization event, a firm younger limit for the age of the Panguna mineralization can be given as 3.4 to 3.5 m.y. It could be argued that the Biuro Granodiorite heated the surrounding rocks at 3.5 m.y., causing loss of argon and updating of the mineralized rocks. This is not considered likely, however, in view of the limited areal extent of the Biuro Granodiorite, and in view of the consistent ages obtained on whole rocks and minerals from both the intrusive and host mineralized bodies, at varying distances from the Biuro Granodiorite.

It is necessary to postulate that the Biuro Granodiorite was emplaced in the waning stages of the mineralization activity while the whole area was still at elevated temperatures. That the mineralization process and the emplacement of the Biuro Granodiorite occurred over a short period of time is consistent with the shallow depths at which the magmas probably crystallized; geological evidence suggests a maximum of only 2 to 3 km (Macnamara, 1968).

The Nautango Andesite plug and similar smaller dykes intrude the eastern margin of the mineralized Biotite Diorite and Panguna Andesite, and therefore provide a further upper limit to the age of mineralization. The Nautango Andesite sample (6002) and the dyke sample (6001) are fresh hornblende andesites and show no sign of copper mineralization. Whole rock and hornblende K-Ar ages were determined for both samples and the results are given in Table 2. The ages fall in the range 1.3 to 1.7 m.y. Both whole rock ages are marginally younger than the respective hornblendes, perhaps due to some leakage of radiogenic argon from the feldspars in the rock. The best estimate for the age of the rock is given by the hornblende results at about 1.6.m.y. This age is consistent with the geological evidence that the Nautango Andesite and related dyke rocks postdate the Panguna mineralization.

Summary and Discussion

K-Ar dating of the early intrusive phases, the hydrothermally altered rocks, and the late-stage intrusives associated with the Panguna porphyry copper body, confirms the general field relationships and enables a more precise geological history to be given for this rather youthful (Pliocene) deposit. The K-Ar age histograms (Figure 3) provide a useful summary of the data.

The Kaverong Quartz Diorite, the earliest intrusive in the Panguna area, has a minimum age of 4 to 5 m.y. The only other intrusive body on Bougainville which has been previously dated is a granodiorite from the southern part of the island, 15 km southwest of Panguna (A.W. Webb, in Blake and Miezitis, 1967); the duplicated biotite age of 5.5.m.y. represents approximately the same late Miocene-early Pliocene time of emplacement as indicated for the unaltered Kaverong Quartz Diorite at Panguna.

The age of hydrothermal alteration and mineralization of the Panguna copper ore body is approximately 3.4 m.y., some 0.5 to 1.5 m.y. after the emplacement of the Kaverong Quartz Diorite. Fountain (1972) has shown from

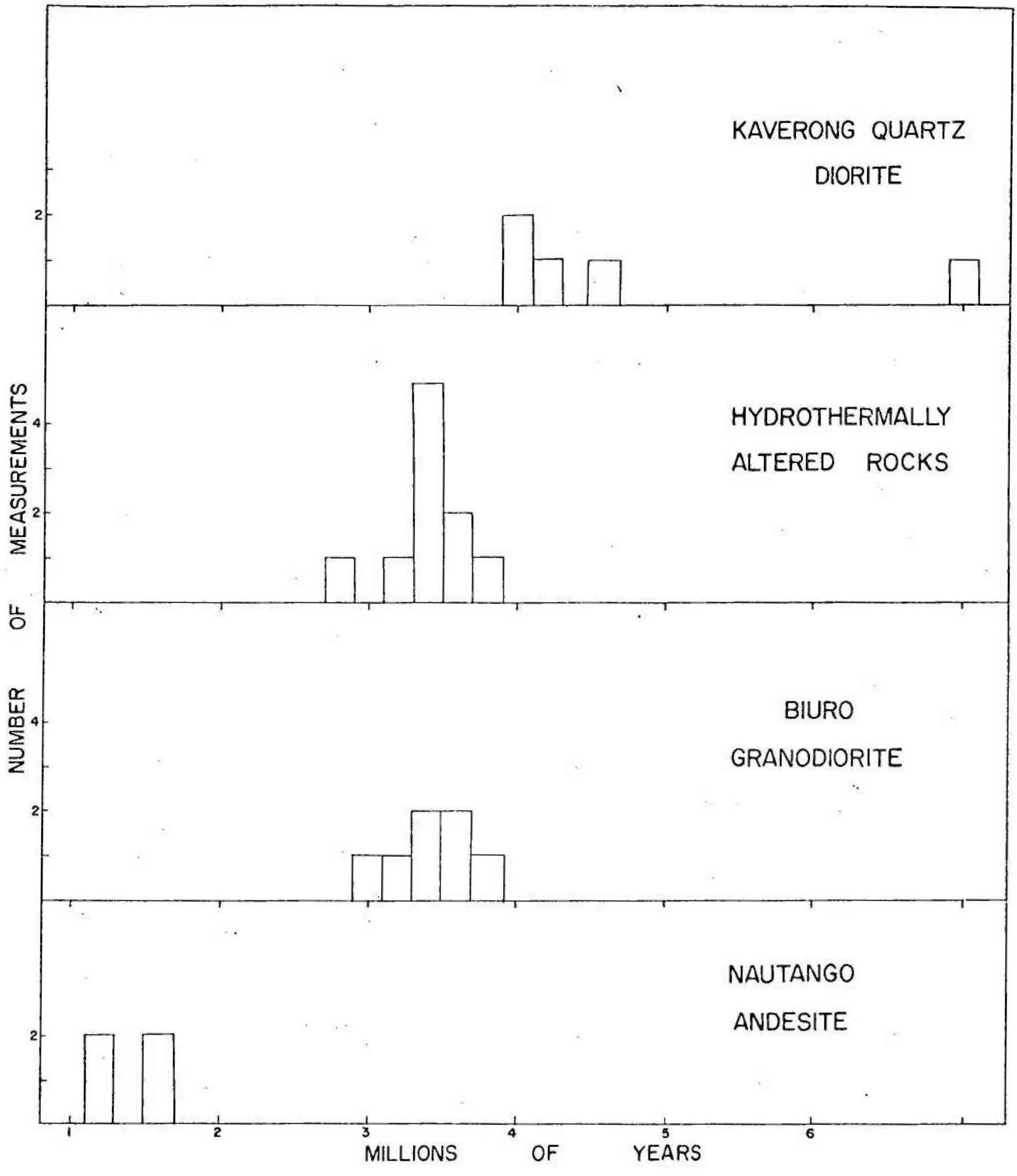

Figure 3. Histograms of K-Ar dates on the four units associated with the Panguna copper deposit.

veining relationships that the Biotite Granodiorite porphyry is the intrusive most closely associated (in space and time) with the copper mineralization. However, the K-Ar ages of the three mineralized igneous bodies (Biotite Diorite, Biotite Granodiorite and Leucocratic Quartz Diorite) are not distinguishable from the age of alteration/mineralization or from each other, within the experimental uncertainties, and hence the isotopic age data do not provide any evidence as to which of the intrusives introduced the copper mineralization. Outlined below are two further lines of evidence which may be considered in relation to the source of the Panguna mineralization.

The short time interval between emplacement of the mineralized dioritic intrusives and the relatively barren Biuro Granodiorite, and the general compositional similarity between the two (except for K metasomatism in the former) would suggest that all these rocks were comagmatic. Because the Biuro Granodiorite is virtually barren of copper mineralization, the proposed comagmatic character of the Biuro Granodiorite and mineralized intrusives would imply that the original source of the copper ore lies outside of normal magmatic or differentiation processes.

Another general restriction on the ultimate source of the copper-bearing fluids at Panguna can be inferred from trace element results on several of the younger andesitic volcanic rocks on Bougainville Island. Taylor and others (1969) found that Cu abundances are generally less than 50 ppm, this being merely an average abundance for this element in any igenous rocks of intermediate composition (Turekian and Wedepohl, 1961). Assuming that the mineralized Panguna diorites were derived by similar processes from the same region as the younger andesitic rocks of Bougainville Island (viz., upper mantle; Taylor and others, 1969), then in view of the low to moderate Cu content in the andesite it is unlikely that the copper ore-forming fluids of the mineralized diorites were also generated at this source. This again argues against derivation of the copper through a direct cognate relation with the diorites.

The evidence outlined above thus suggests that the Panguna copper ores, although physically associated with the dioritic intrusives, are neither from the same source region nor derived from them by differentiation processes. Of the several models that have been proposed in the past to explain the general features common to many porphyry copper deposits, those of White (1968) or Burnham (1967) appear to be most consistent with the present restrictions. White (1968) argues that the source of the mineralizing fluids is mainly external to the magmatic system; he suggests that leaching by connate and meteoric waters set in motion by proximity to an igneous body (heat source) has occurred. In this manner metal constituents may be dissolved and concentrated (in a highly saline environment) from widely disseminated traces in ordinary country rocks. In this model copper mineralization may be introduced under the influence of thermal gradients established by the intruding magma, but no appeal has to be made to a single magma enriched in copper at its source. Burnham's (1967) model for porphyry copper formation invokes initial generation of an aqueous phase within the magma and its subsequent sudden release at a high level in the crust by a "boiling process". The volatiles migrate outward through the fractured intrusive and country rocks, and with meteoric or connate water may perform a leaching role analogous to that described in White's (1968) model.

The geochronological data presented here point to the very juvenile character (early to mid Pliocene) of the magmatic and mineralization events associated with the Panguna copper deposit on Bougainville. Given the large-scale magmatic processes thought to be operating in such active island arc/ orogenic environments (e.g., Dickinson, 1970), it would appear that other young high-level intrusives in the region may be of considerable economic interest.

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