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AGES OF MINERALIZATION OF GOLD AND PORPHYRY COPPER DEPOSITS IN THE NEW GUINEA HIGHLANDS

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Abstract

K-Ar and Rb-Sr ages are reported from five different areas of gold and porphyry copper mineralization in the Highlands of Papua New Guinea. The igneous rocks associated with these deposits are of calc-alkaline character, and range from porphyritic granodiorite to andesite. In some cases, the mineralized porphyries as well as related unmineralized rocks have been dated, thus providing a more detailed geological history for individual deposits, and allowing better comparisons to be made between the different areas.

Dating of the gold-bearing porphyries and related rocks in the Morobe Goldfield indicates a 3.1 to 3.8 m.y. age interval for at least some of the mineralization associated with porphyry intrusion. The data obtained also suggest a revised estimate of mid to late Pliocene age for occurrences of the well-known vertebrate fossil fauna in the nearby Otibanda Formation. Gold and copper mineralization in the Kainantu Goldfields is shown to be at least as young as mid to late Miocene. In the Yanderra copper prospect a time gap of about 5 m.y. is recognized between the main mid Miocene emplacement of the pluton and subsequent copper mineralization in the late Miocene. Preliminary dating of porphyries from the Frieda copper prospect indicates complex intrusion in the mid Miocene. The youngest porphyry copper deposit so far discovered in Papua New Guinea occurs in the west at Mount Fubilan, near the Ok Tedi River, where the mineralization event is shown to be Pleistocene, only 1.1 to 1.2 m.y. old. The deposits so far dated thus appear to be all mid Miocene or younger in age. This magmatic activity and mineralization may have been triggered by interaction and collision between the Pacific plate and the Australian plate in about mid Miocene times.

Introduction

The relatively youthful tectonic setting of the mineral deposits in the New Guinea region was emphasized by Thompson and Fisher (1967). The mineralization, mainly copper and gold, generally is closely associated with intrusive rocks which are an important feature of the geology of New Guinea, especially in the Highlands. In most areas stratigraphic control on the age of mineralization is poor. We report in this paper isotopic age results on rocks from five areas that are mineralized (Fig. 1); these data provide much firmer control on age than previously available, and enable meaningful comparisons to be made between areas. The results are also of some importance in terms of the overall geological evolution of New Guinea.

Some of the intrusives that have been prospected in the New Guinea region have features of "porphyry-type" copper mineralization. Assemblages such as quartz-sericite-K feldspar, K feldspar-biotite and epidote-calcite-albite-biotite are commonly present; pyrite, chalcopyrite, bornite and molybdenite and other sulfides are often found replacing the wall rocks and filling closely spaced cracks in the rock. The close genetic relationship between the ore minerals and alteration products, some of which can be dated by the K-Ar method, allows dating of the mineralization in certain cases.

The geology and geochronology of the five areas of concern are discussed in order from east to west in the New Guinea Highlands.

Analytical Procedures

The techniques of K-Ar dating used followed those described by McDougall (1966) and Cooper (1963), and the physical constants employed in the age calculations are: $\lambda\beta = 4.72 \times 10^{-10} yr^{-1}$; $\lambda\epsilon = 0.585 \times 10^{-10} yr^{-1}$; $K^{40}/K = 1.19 \times 10^{-2}$ atom percent. Errors quoted for each K-Ar age represent two standard deviations (see Page and McDougall, 1972).

Rb-Sr analyses were performed by isotope dilution mass spectrometry, principally along the lines described by Compston and others (1965). The present day Sr^{87}/Sr^{86} ratio was usually calculated from the spiked Sr run, and in some cases also determined by direct measurement on an unspiked Sr sample. Semi-quantitative X-ray fluorescence was used to determine approximate total Rb and Sr for three total rocks from the Yanderra prospect. Constants used in the Rb-Sr age calculations are: λ $Rb^{87} = 1.39 \times 10^{-11} yr^{-1}$; $Rb^{85}/Rb^{87} = 2.600$; $Sr^{88}/Sr^{86} = 8.3752$.

Geological Background and Geochronological Results

Morobe Goldfield

Gold and minor manganese mineralization in the Morobe Goldfield between Wau and Bulolo, southwest of Lae (Fig. 2), is associated with high level andesitic and dacitic porphyries which Fisher (1944, 1945) considered to be of late Tertiary age. The prophyries intrude schists and phyllites of the ?Cretaceous Kaindi Metamorphics, which may have suffered the latest metamorphism in early Miocene times (Page, in prep.). The porphyries are believed to postdate the mid Miocene Morobe Granodiorite (Fisher, 1944). In the Morobe Goldfield area, Fisher (1944, 1945) recognized two and possibly three generations of porphyry intrusion (Lower Edie Porphyry, Upper Edie

Porphyry and unclassified porphyries), based upon differences in degree of crystallization, silicification, mineralization, hydrothermal alteration and contact metamorphism. A much later minor porphyry (similar to those mineralized elsewhere) intruding breccia near Golden Ridges was also identified. Fisher (1945) suggested that the Lower Edie Porphyry predates the unclassified prophyries, which in turn predate the Upper Edie Porphyry. It is the last mentioned porphyry type with which the gold mineralization is mainly associated.

Explosive volcanic activity produced massive agglomerates and breccias that either followed or accompanied emplacement of the later porphyritic intrusions. The complexity of porphyry intrusion and mineralization is evidenced by the fact that the volcanic agglomerates in some areas postdate mineralization, whereas in other areas the agglomerates are cut by hydrothermal alteration and mineralization (Fisher, 1944).

Disconformably above the agglomerates and breccias rests the Otibanda Formation, a poorly consolidated, lacustrine sequence containing tuffaceous intercalations and fossil vertebrates (Plane, 1967). The Formation is mostly flat-lying or gently tilted, though locally much steeper dips occur. The age of the Otibanda Formation can thus provide a minimum estimate for the age of some of the porphyries and associated mineralization in the Morobe Goldfield. Three K-Ar ages (5.7, 6.1, and 7.6 m.y.) on plagioclase from the tuffs of the Otibanda Formation have been reported by Evernden and others (1964) and Plane (1967). They interpreted these ages as Pliocene, but on the presently accepted physical time scale the ages would be regarded as Upper Miocene (Berggren, 1969). One other K-Ar age of 3.9 m.y. on a plagioclase from a tuff has been recently reported by Plane (1972). A fuller discussion of these earlier results will be given after the data from the present study have been presented.

The latest stages of volcanism in the Wau area are represented by a relatively recent series of rhyolite flows and breccias near Golden Ridges. The volcanics overlie piedmont deposits, which in turn overlie the Otibanda Formation (Fisher, 1944; Plane, 1967). These rhyolites are deuterically altered and thus were considered unsuitable for K-Ar dating.

We have estimated the age of the gold bearing porphyries in the Morobe Goldfield in the Wau-Bulolo area by dating samples from (i) the oldest unmineralized porphyries, (ii) the agglomerates, and (iii) additional samples from tuffaceous beds in the overlying Otibanda Formation. Dates from the mineralized porphyries themselves were not obtained because of their highly altered and weathered nature. This restriction also thwarted any attempt to date the volcanic breccia.

<u>Porphyry ages</u>: The locations of the porphyritic rocks used in the age determinations are shown in Figure 2. No samples from the strongly mineralized parts of the Upper Edie Porphyry were suitable for dating. The porphyritic rocks are generally plagioclase-biotite-hornblende porphyries with a devitrified, originally glassy groundmass that shows varying degrees of alteration to epidote, calcite, chlorite and opaque minerals. Except for the presence of minor pyrite, the samples used in the dating are not mineralized. Most of the intrusives examined are andesitic in type, except 285 which is more dacitic, and 287 which is a microgranodiorite.

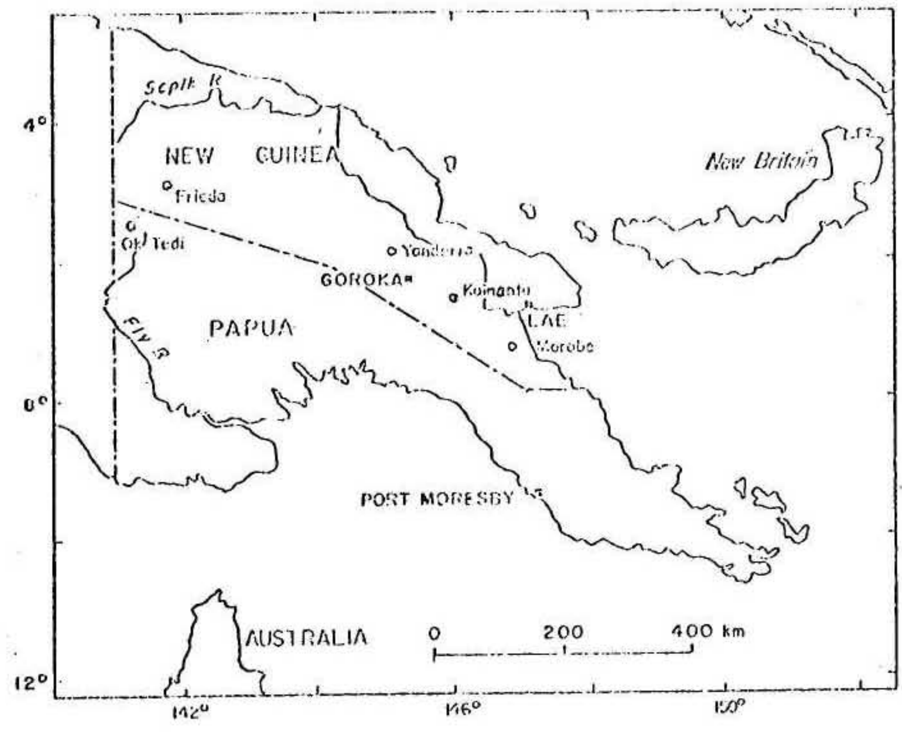
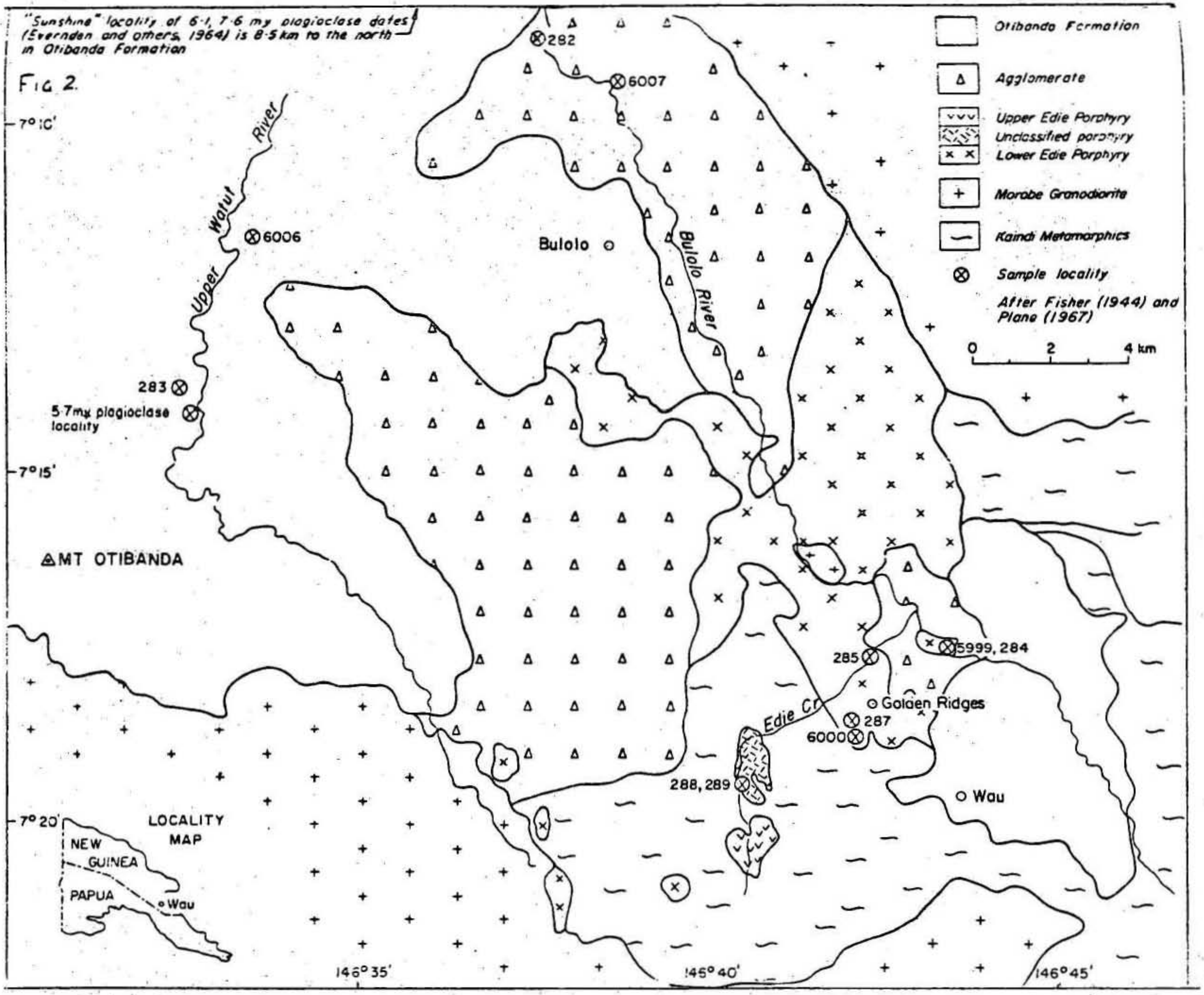

Sepik R
NEW GUINEA
Frieda
Ok Tedi
Yandera
GOROKA
Kainantu
LAE
Morobe
New Britain
PAPUA
Fly R
PORT MORESBY
AUSTRALIA
0
200
400 km
4°
8°
12°
142°
146°
150°

Fig 1


"Sunshine" locality of 6·1, 7·6 my plagioclase dates (Evernden and others, 1964) is 8·5 km to the north in Otibanda Formation
FIG. 2.
Otibanda Formation
Agglomerate
Upper Edie Porphyry
Unclassified porphyry
Lower Edie Porphyry
Morobe Granodiorite
Kaindi Metamorphics
Sample locality
After Fisher (1944) and Plane (1967)
0 2 4 km
282
6007
6006
Bulolo
Bulolo River
Upper Waiut River
283
5·7my plagioclase locality
MT OTIBANDA
285
5999, 284
Golden Ridges
Edie Cr
287
6000
288, 289
Wau
LOCALITY MAP
NEW GUINEA
PAPUA
Wau
7°10'
7°15'
7°20'
146°35'
146°40'
146°45'

Biotite and plagioclase were separated from the porphyries, and the K-Ar dates on these minerals (Table 1) show a total spread from 2.4 to 6.4 m.y. Sample 285 is the only dacitic rock in the suite and gives the youngest ages on both biotite and plagioclase, in excellent agreement at 2.4 m.y. This much younger age may well be real, as the sample is from a small flow-banded outcrop in the middle of the Lower Edie Porphyry body. This is thought to be of volcanic origin and much later than the porphyry intrusion (N.H. Fisher, pers. comm.). The other four biotites from the porphyries give ages lying between 3.5 and 4.2 m.y.; these values are generally considerably lower than the corresponding plagioclase dates which range from 3.6 to 6.4 m.y. It could be argued that the oldest plagioclase date (6.4 m.y.) represents a minimum value for the age of porphyry intrusion, and that the younger plagioclases and biotites have been updated by the later Upper Edie Porphyry and its associated mineralization, and by later volcanism in the Golden Ridges area. The calculated plagioclase ages show large discordancies even between samples collected very close to one another. We consider that the large temperature gradients necessary to explain the discordant results are unlikely to have existed over such short distances, and therefore some explanation other than updating could be sought to explain the data. An alternative interpretation is that the higher and non-uniform plagioclase ages (3.6 to 6.4 m.y.) result from incorporation of varying amounts of extraneous radiogenic argon in this mineral (Damon, 1968).

To test the hypothesis that extraneous argon occurs in the minerals, an argon isochron diagram (McDougall and others, 1969; Hayatsu and Carmichael, 1970) was used and a regression analysis made of the separate and combined biotite and plagioclase data. In favorable cases, plotting of K-Ar data on an isochron diagram allows a more direct test of two of the assumptions of the K-Ar method. These assumptions are that at the time of crystallization the samples lose all pre-existing radiogenic argon, and that argon other than that produced by <u>in situ</u> radioactive decay of K^{40} has the composition of atmospheric argon (i.e. $Ar^{40}/Ar^{36} = 295.5$). In the isochron diagram Ar^{40}/Ar^{36} is plotted against K^{40}/Ar^{36}. A suite of cogenetic samples which have had no atmospheric argon contamination added to them subsequent to crystallization, when plotted on such a diagram, will lie on a straight line whose slope is proportional to the age since closure of the system. The Ar^{40}/Ar^{36} in the samples at the time of closure is given by the intercept; if the value is greater than 295.5 this indicates the presence of what is commonly called excess or extraneous argon.

The results of regression analysis for the Wau porphyries using the method of McIntyre and others (1966), are given in Figure 3, with the errors quoted at the 95 percent level of confidence. The mean square of weighted deviates (M.S.W.D.) gives a measure of the goodness of fit of the samples to the straight line, and when greater than unity is an indication of geological effects other than those that can be attributed to experimental error. Sample 285 is not included in the regression because it is distinctly younger than the remainder of the population. For the plagioclase samples, whose conventionally calculated ages range from 3.6 to 6.4 m.y., the isochron age is 3.39 ± 0.22 m.y. The plot demonstrates that the individual plagioclase samples can be of the same age provided that the initial Ar^{40}/Ar^{36} value is 326 ± 7, that is significantly greater than the value normally assumed of 295.5 in calculating K-Ar ages. These results provide strong evidence that the plagioclase incorporated extraneous argon in their lattices at the time of crystallization. The biotite data alone are too few to be significant in the isochron plot, but an age of 4.1 ± 0.4 m.y. and initial Ar^{40}/Ar^{36} of 276 ± 30 are indicated. When the biotite results are pooled with the plagioclase data, an age of 3.51 ± 0.11 m.y. and an initial Ar^{40}/Ar^{36} ratio of 320 ± 5 are obtained. These values are not distinguishable from the plagioclase data treated alone, and although they indicate that extraneous argon may also be present in the biotites, such argon is probably masked by the very much greater amounts of true radiogenic argon.

Within the experimental uncertainties, the plagioclase isochron age of 3.39 ± 0.22 m.y. is virtually indistinguishable from the conventional biotite ages which have a mean of 3.79 ± 0.32 m.y. (2 s.d.). On the presently accepted Tertiary time scale, these limits indicate an age of mid-Pliocene for the Lower Edie and unclassified porphyries. This age is consistent with the geological relationships of the porphyries which are considered to be later than the mid Miocene Morobe Granodiorite. The mid Pliocene age of the porphyries dated here, also provides a maximum estimate for the main mineralization associated with the Upper Edie Porphyry.

Agglomerate ages: The mid Pliocene porphyry ages (above) are clearly at variance with the 6 to 7 m.y. plagioclase ages reported for the overlying Otibanda Formation tuffs by Evernden and others (1964) and Plane (1967). Samples of the agglomerate (believed to be virtually contemporaneous with intrusion of the later porphyries (Fisher, 1944; Plane, 1967; Dow and others, in prep.) were dated to further investigate the geological history and to test the consistency of our results.

The agglomerate forms massive cliff outcrops in the area around Bulolo. These masses blocked the drainage system and caused damming in the Bulolo Valley allowing subsequent deposition of the fresh water Otibanda Formation whose associated thin tuff beds represent the waning stages of the explosive igneous activity. The agglomerates and tuffs are mineralogically similar to each other, but are texturally distinct because of the different size ranges of their crystal and fragmental content. In both tuffs and agglomerates occur crystals (phenocrysts) of quartz, plagioclase, biotite, hornblende, sphene and pyroxene in various states of preservation in a feldspathic-chloritic groundmass. Lithic fragments of phyllite, quartzite, porphyry and granite, derived from the underlying Kaindi Metamorphics, Edie porphyries and Morobe Granodiorite are widespread in the agglomerate phase and are also common in the Otibanda Formation tuffs. Clearly, any K-Ar age determination on either the agglomerate or tuffaceous material should be regarded as a maximum value of the time of formation of the deposits because of the distinct possibility of inherited argon from older rock fragments.

K-Ar data on biotite, hornblende and plagioclase from two agglomerate samples north of Bulolo are given in Table 1. The ages show a spread from 3.2 to 3.7 m.y., so it is suggested that a maximum age of around 3.5 m.y. may be assigned to the agglomerate in the area. This value would also be a maximum figure for the age of the overlying Otibanda Formation and its associated tuffs. The good agreement of the agglomerate ages with those obtained on the porphyries demonstrates either that the two units do have a close time relationship or that the agglomerate is composed essentially of the same porphyry fragments.

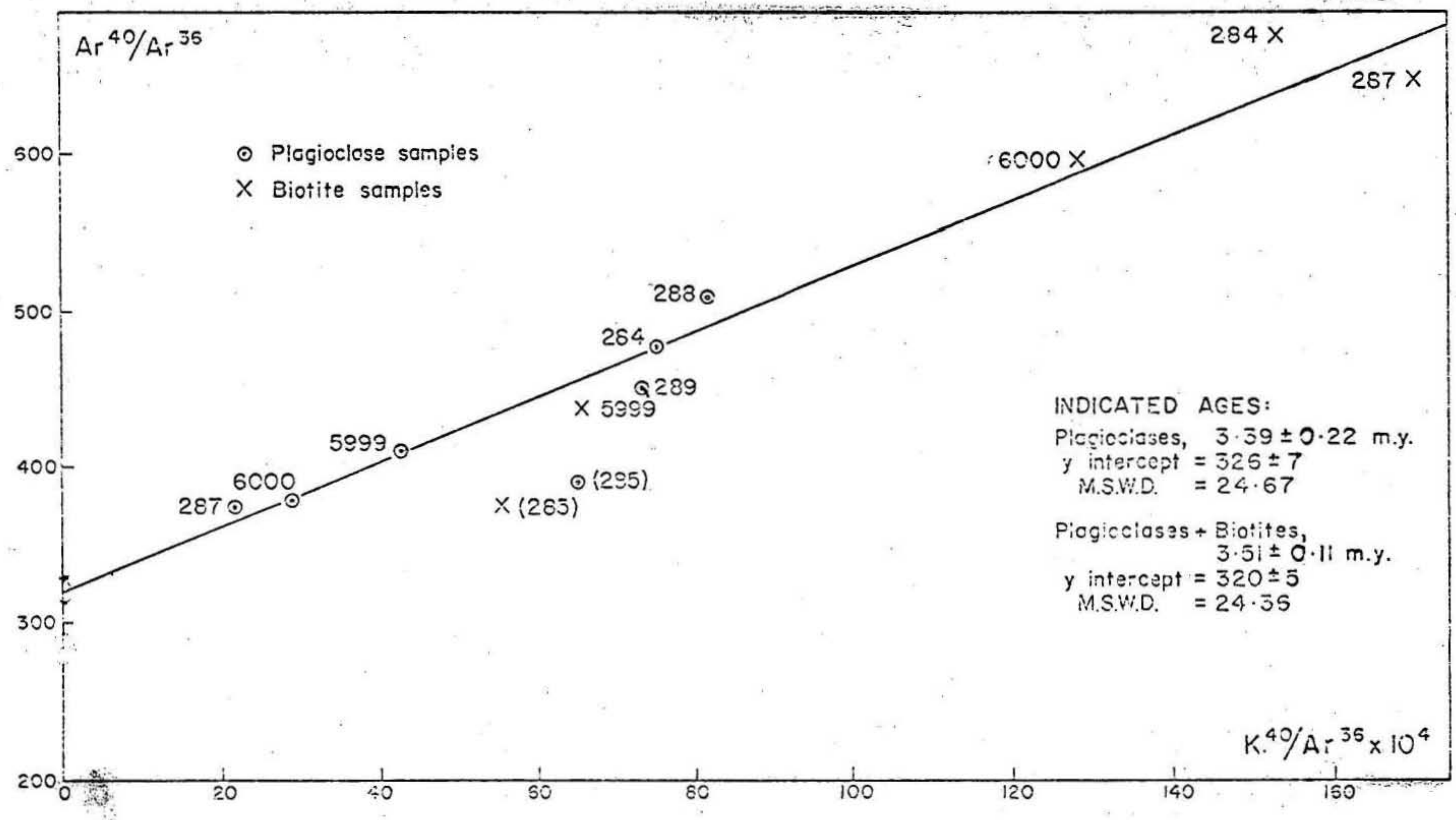
Otibanda Formation tuff ages: Because of their partly relict character the tuffs (like the agglomerates) are not particularly suitable for K-Ar dating, and the analyses were performed mainly to resolve the apparent discrepancies between our data on the Wau porphyries and Evernden and others' (1964) age data on the overlying tuffs.

Out of several tuff samples collected and examined, only two were found suitable for dating (Table 1). Plagioclase ages of 5.9 and 6.6 m.y. are in the range of ages determined by Evernden and others (1964) on the same

Table 1 K-Ar ages from the Morobe Goldfield

No.	Sample	K%		Rad. Ar^{40} $\times 10^{-7}$ cc NTP/g	100 Rad. Ar^{40} / Total Ar^{40}	Calculated age (m.y.) $\pm$ 2 s.d.
(i) Porphyritic Rocks						
5999	Biotite	6.752, 6.719	6.736	9.640	31.9	3.6 ± 0.1
	Plagioclase	0.277, 0.276	0.277	0.511	27.9	4.6 ± 0.2
6000	Biotite	6.842, 6.814	6.828	10.732	50.0	3.9 ± 0.1
	Plagioclase	0.250, 0.245	0.248	0.496	22.0	5.0 ± 0.2
284	Biotite	6.770, 6.794	6.782	11.257	55.9	4.2 ± 0.1
	Plagioclase	0.276, 0.264	0.270	0.439	37.6	4.1 ± 0.2
285	Biotite	6.987, 7.039	7.013	6.797	20.9	2.4 ± 0.1
	Plagioclase	0.296, 0.293	0.295	0.284	23.7	2.4 ± 0.2
287	Biotite	6.866, 6.889	6.878	9.582	54.0	3.5 ± 0.1
	Plagioclase	0.311, 0.313	0.312	0.801	21.2	6.4 ± 0.2
288	Plagioclase	0.265, 0.266	0.266	0.472	41.7	4.5 ± 0.1
289	Plagioclase	0.274, 0.275	0.275	0.397	34.3	3.6 ± 0.1
(ii) Agglomerates						
6007	Hornblende	0.400, 0.400	0.400	0.504	22.5	3.2 ± 0.2
	Plagioclase	0.246, 0.246	0.246	0.365	10.4	3.7 ± 0.3
282	Biotite	6.736, 6.731	6.734	9.118	9.8	3.4 ± 0.3
	Hornblende	0.438, 0.437	0.438	0.574	21.4	3.3 ± 0.3
(iii) Otibanda Fm. Tuffs						
6006	Biotite	7.026, 7.058	7.042	8.382	12.3	3.0 ± 0.1
				9.242	13.1	3.3 ± 0.2
	Plagioclase	0.252, 0.254	0.254	0.597	35.4	5.9 ± 0.3
283	Biotite	7.052, 7.068	7.060	12.034	37.5	4.3 ± 0.1
				12.494	49.9	4.4 ± 0.1
	Plagioclase	0.254, 0.254	0.254	0.671	29.1	6.6 ± 0.3

FIG 3


Ar 40/Ar 36
Plagioclase samples
X Biotite samples
284 X
287 X
6000 X
288
264
289
X 5999
5999
6000
287
(295)
X (285)
INDICATED AGES:
Plagioclases, 3·39 ± 0·22 m.y.
y intercept = 326 ± 7
M.S.W.D. = 24·67
Plagioclases + Biotites,
3·51 ± 0·11 m.y.
y intercept = 320 ± 5
M.S.W.D. = 24·36
K.40/Ar 36 x 10 4
600
500
400
300
200
0
20
40
60
80
100
120
140
160

mineral, though the samples are not from the same localities. The respective biotite ages from the same tuff samples, are much younger at 3.1 and 4.3 m.y. In the light of the field evidence and the K-Ar ages determined on the underlying agglomerate and porphyries, it would appear that all the plagioclase ages are excessively old and the biotite ages marginally so, because of incorporation of extraneous radiogenic argon in the crystal and rock fragments prior to eruption and deposition. It can only be stated definitely (from the consistent results obtained from the agglomerates) that the age of the Otibanda Formation is less than 3.5 m.y. The youngest date from the Otibanda Formation tuffs of 3.1 m.y. may be a closer estimate of the maximum age.

Previous age estimates for the marsupial fauna in the Otibanda Formation described by Plane (1967) and Stirton and others (1967) were based on Evernden and others' (1964) 6 to 7 m.y. plagioclase dates. These were interpreted by Plane (1967) and Stirton and others (1967) as mid Pliocene, although they would now be reagrded as late Miocene. As inferred from our plagioclase analyses, extraneous radiogenic argon may be the explanation for the apparently higher plagioclase ages. This may also apply to Plane's (1972) recently published plagioclase date of 3.9 m.y. on another tuff from the Otibanda Formation. It is noted that the potassium contents of the plagioclase from the Otibanda Formation tuffs are quite similar to the potassium contents of plagioclase from the porphyries, and are also close to the plagioclase potassium values given with Evernden and others' (1964) K-Ar analyses. Using the present K-Ar ages and Berggren's (1969) Tertiary time scale, the Otibanda Formation can be regarded as mid to late Pliocene or younger in age.

Age of the Morobe Goldfield mineralization: As earlier mentioned, Fisher (1944) has shown that at least two phases of porphyry intrusion and mineralization have occurred in the Wau area; the experimental errors associated with the age measurements presented here are no doubt masking our recognition of any such discrete episodes. The K-Ar age data, taken together with the known geological relationships do, however, enable limits to be placed on the main mineralization episode. An older limit on the age of the main mineralization is provided by the dates on the oldest porphyries (Lower Edie Porphyry), and two possible interpretations, of these dates are suggested. One is that the oldest plagioclase dates of around 6 m.y. represent true ages, and that the younger biotite dates result from updating effects due to later magmatic activity. This would mean that the Lower Edie Porphyry and its associated minor mineralization could be as old as late Miocene in age. Arguments have been advanced earlier for a second alternative that the porphyry samples are 3.4 to 3.8 m.y. old (based on the biotite ages and the plagioclase isochron age), and that the older conventionally calculated plagioclase dates are due to incorporation of extraneous argon. This mid Pliocene age is supported by the results obtained from samples of the agglomerate, which are believed to be composed, in part, of the same porphyries. There appears to be no definitive case for either of the above interpretations, but the younger 3.4 - 3.8 m.y. age interval is regarded by the authors as the more likely older limit for the age of the mineralization.

A younger limit for the main mineralization is more difficult to derive, but is regarded by Fisher (1944) as earlier than the deposition of the Otibanda Formation, the age of which we have shown to be not older than 3.1-3.5 m.y. Because these age limits are maximum values, however, no unequivocal younger limit on the age of mineralization can be assigned. Field evidence (N.H. Fisher, pers. comm.) indicates that gold mineralization later than that attributed to the Upper Edie Porphyry, continued in the Wau - Edie Creek area until a comparatively recent age, and it may not be possible to put an upper limit to it.

Kainantu Goldfields area

The source of alluvial and lode deposits of gold and copper in the Kainantu Goldfields in the Eastern Highlands of New Guinea is related to the emplacement of several hypabyssal stocks known as the Aifunka Volcanics and Elendora Porphyry (Dow and Plane, 1965). These occur as small isolated bodies and although they are mineralized only locally, in such areas the rocks are quite propylitized and kaolinized, rendering them unsuitable for K-Ar dating. Dow and Plane (1965) considered these intrusives to be Pliocene in age. The only isotopic data relevant to the age of the Aifunka Volcanics and Elendora Porphyry are reported by Page (1971, and in prep.). From six hornblende K-Ar ages, it is shown that the Elendora Porphyry bodies were emplaced between 7.5 and 10 m.y. ago, that is, in the late Miocene. Two whole rock dates from the Aifunka Volcanics are mid Miocene, between 14 and 16 m.y. Mineralization accompanied or postdated emplacement of these bodies, and thus took place either in the mid Miocene and the late Miocene, or later than late Miocene.

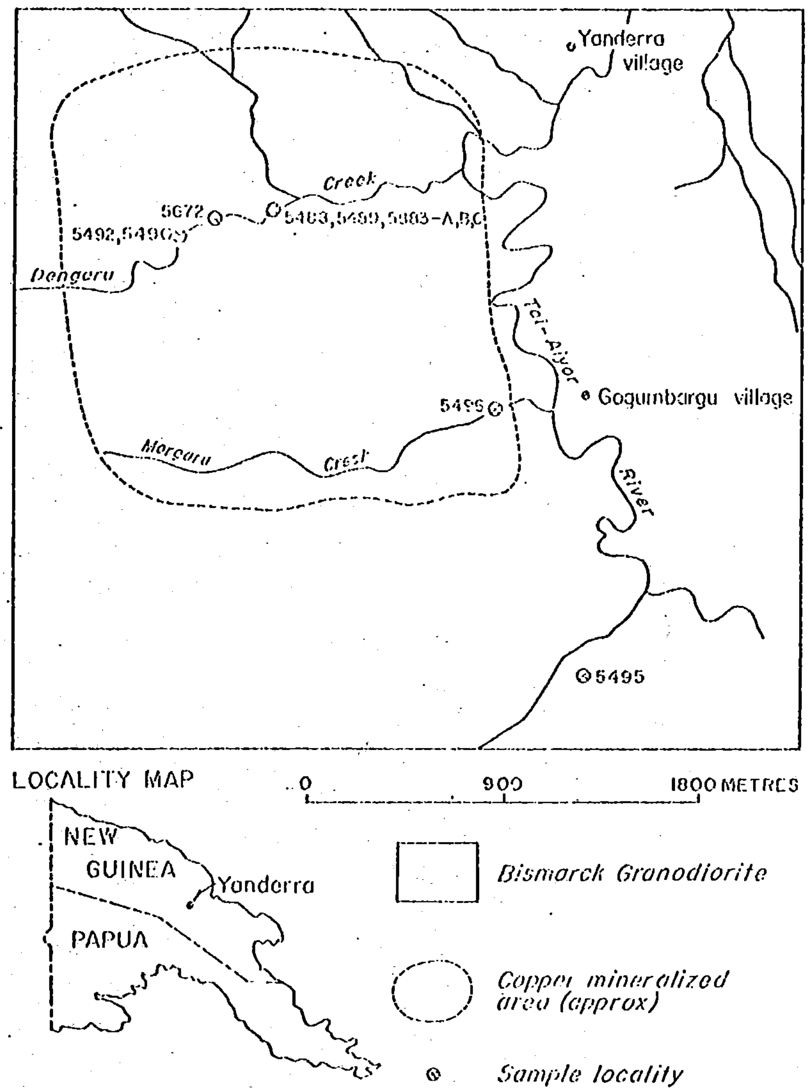
Yanderra copper prospect

The Yanderra copper prospect lies in the northeastern part of the Bismarck Granodiorite massif, 55 km northwest of Goroka (Dow and Dekker, 1964). Page (1971, and in prep.) reports a number of K-Ar and Rb-Sr analyses on the Bismarck Granodiorite, including some from the area north of Yanderra village. The copper prospect itself is an area of about 9 square km, located 2 to 3 km southwest of Yanderra village (Fig. 4). Plane (1965) showed that the dacitic to andesitic porphyry dikes which intrude the Bismarck Granodiorite have introduced the disseminated copper and minor gold mineralization. Following Dow and Dekker's (1964) estimate based on the regional geology, Plane (1965) suggested that the porphyries were probably of Pliocene age.

The age of the main mass of the Bismarck Granodiorite as determined on a variety of mineral and rock types, is shown by Page (1971, and in prep.) to be approximately 12.5 m.y. (i.e. mid Miocene). The mineralized porphyries and granodiorites within the Yanderra copper prospect have now been dated by both the K-Ar and Rb-Sr methods to see if there is any significant difference between the age of emplacement of the Bismarck Granodiorite and the age of the subsequent mineralization.

The results of the K-Ar and Rb-Sr study are given in Tables 2 and 3. Only one hornblende-feldspar porphyry (5488) has been dated as these rocks were generally very strongly altered. Hornblende and plagioclase ages of 11.8 $\pm$ 0.5 and 9.8 $\pm$ 0.8 m.y. were determined on the sample, but in the absence of further determinations on the porphyries and as 5488, itself, is not mineralized, it is difficult to give much significance to the result.

Fig 4



Yanderra village
Creek
5672
Dengeru
Tai-Aiyor River
Goguinbargu village
Morearu Creek
5495
LOCALITY MAP
0
900
1800 METRES
NEW GUINEA
Yanderra
PAPUA
Bismarck Granodiorite
Copper mineralized area (approx)
Sample locality

The mineralized granodiorites that have been dated from the Yanderra prospect were sampled in the area between Dengaru Creek and Gogumbargu village (Fig. 4). Although the granodiorites contain pyrite and chalcopyrite mineralization, there is no apparent gross alteration of the rocks. Of the five samples, four yielded fresh biotite, and the K-Ar ages on this mineral are grouped between 6.5 and 8.0 m.y.; the plagioclase from 5490 is also in this range at 7.0 ± 0.6 m.y., whereas the hornblende from 5492 is older at 10.0 ± 0.3 m.y. The four biotites and several total rocks were also analysed by the Rb-Sr method (Table 3). All the total rocks have fairly low present day Sr^{87}/Sr^{86} ratios, indicating deep crustal or upper mantle affinities. Two of the biotite Rb-Sr ages are in the same range as the younger K-Ar ages at 7.6 and 9.7 m.y., and the other two biotites give apparently concordant and higher Rb-Sr ages at about 13.6 m.y. The reason for the rather large spread in the Rb-Sr biotite ages is not at first apparent.

In view of the fact that the biotite and plagioclase K-Ar ages are between 1 and 7 m.y. younger than the respective Rb-Sr biotite ages, and about 5 to 6 m.y. younger than the age of the general emplacement of the Bismarck Granodiorite, it can be concluded that argon loss has occurred from biotite and plagioclase. The consistency of the K-Ar biotite and plagioclase ages at around 7 to 8 m.y. is considered to be geologically meaningful, so that the observed Rb-Sr age spread probably represents differential response of the individual biotites to the process that influenced the K-Ar clock. It is not unexpected that the K-Ar hornblende age of 5492 (10.0 m.y.) is somewhat higher than the 7 to 8 m.y. biotite and plagioclase ages, because hornblende has consistently higher activation energies for argon diffusion (cf. Mussett, 1969). As the young biotite ages are considered to be meaningful, it is necessary to postulate an event approximately 7 m.y. ago, during which the temperatures were locally raised to allow for relatively uniform argon loss from the biotites, but rather non-uniform diffusion of radiogenic strontium. The most probable explanation is that the 7 m.y. K-Ar ages are reflecting the intrusion of the feldspar porphyries with the associated introduction of copper mineralization into the granodiorites of the Yanderra prospect. An alternative suggestion that the young K-Ar biotite dates represent uplift ages is not regarded as likely in view of the pattern of ages established elsewhere in the Bismarck Granodiorite (Page, in prep.). This apparent greater sensitivity of argon diffusion than strontium diffusion in biotite is somewhat contradictory to the results of Hurley and others (1962). These authors made a series of measurements on biotites from the Alpine Fault Zone of New Zealand, and concluded that the diffusion coefficients for argon and strontium in biotite are similar at low temperatures. Armstrong and others (1966) also reached this conclusion working on biotites from the southern and central European Alps. It is surmised that the diffusion characteristics of argon and strontium are markedly dependent on environmental conditions and on whether the geological events are of long or short duration.

In summary, the K-Ar and Rb-Sr data on minerals from the Yanderra copper prospect indicate that the granodiorites in the area were emplaced at about the same mid Miocene time as the remainder of the Bismarck Granodiorite, but mineralization associated with intrusion of porphyritic dikes did not take place until the late Miocene, about 7 to 8 m.y. ago.

Frieda River Copper Prospect

The Frieda River porphyry copper prospect is situated in the remote foothills south of the Sepik Plains (Fig. 5). The geology of the area has been outlined by Dow and others (1972) and Hall and Hartley (1970). The group of high level andesitic intrusives, tuffs and agglomerates in the region are known collectively as the Frieda Porphyry, and they crop out north and south of the easterly trending Frieda Fault. On opposite sides of the Fault the rocks intrude the Ambunti Metamorphics and Cretaceous to Eocene metasediments of the Salumei Formation. North of the Fault the porphyries are unconformably overlain by the Tertiary f_{1-2} stage Wogamush Beds, whereas south of the Fault there is tentative evidence that one group of the porphyritic rocks intrudes Tertiary f_{1-2} stage sediments. On the basis of this stratigraphi evidence, Dow and others (1972) have suggested that the Frieda Porphyry complex may consist of intrusives of two or more ages.

The Frieda River copper prospect is situated in the porphyry body south of the Frieda Fault. These mineralized rocks are intensely fractured, propylitized, alunitized and kaolinized. As a result, only two of a number of samples collected from the mineralized region were suitable for K-Ar dating. The porphyry bodies north of the Frieda Fault are fresher hornblende andesites and microdiorites and are only slightly mineralized.

The K-Ar dating results of six rocks from different areas in the Frieda Prophyry are given in Table 4, and the localities of the dated samples are plotted on the generalized geological map (Fig. 5). The four hornblende ages from the relatively unmineralized area of the Frieda Porphyry north of the Frieda Fault range between 13.5 and 16.6 m.y. For the southern mineralized region, a hornblende age of 14.7 + 0.6 m.y. (5878 - fresh andesite), and a sericitized plagioclase age of 16.3 $\pm$ 0.7 m.y. (5891 - heavily mineralized andesite) were obtained. There are too few samples to enable a thorough interpretation; but these limited data suggest a complex intrusive history for the Frieda Porphyry between 13 and 16 m.y. ago in the mid Miocene. The apparent 3.m.y. spread in the ages of the Frieda Porphyry is consistent with the known stratigraphic control, as it appears that igneous porphyries in the Frieda River area were intruded both before and after the Tertiary f_{1-2} stage sedimentation (Page and McDougall, 1970). The Frieda ages are also in accord with the late Oligocene to early Miocene ages determined on the Ambunti Metamorphics (Page, in prep.) which are intruded by the Frieda Porphyry. Since the 16.3 m.y. age for the one sericitized plagioclase is not distinguishable from the hornblende ages for the unaltered porphyries, it may be tentatively concluded that intrusion and mineralization were virtually concurrent, or at least occurred within a few million years of each other.

Ok Tedi Copper Prospect

In the headwaters of the Fly River is northwest Papua (Fig. 6), a number of high level porphyritic bodies intrude the Mesozoic to Upper Tertiary marine strata. Smit (1968) with geologists from Kennecott Explorations (Aust.) Pty Ltd, mapped the area on a reconnaissance basis, and three palaeontological papers by Belford (1965), Terpstra (1968) and Binnekamp (1970) report on the stratigraphic ages and distribution of the Tertiary foraminiferal limestones in this general region.

At least six separate intrusives are known to exist in the area. The five bodies in the Ok Tedi River area (one of which is the Ok Tedi or Mount Fubilan prospect) are andesitic porphyries, diorites, and porphyritic granodiorites, and they intrude limestones and siltstones from which Binnekamp (1970) has recorded Tertiary upper e to lower f stage (Lower to Middle Miocene) larger foraminifera. Skarns and developed near some intrusive/limestone contacts.

Fig 5

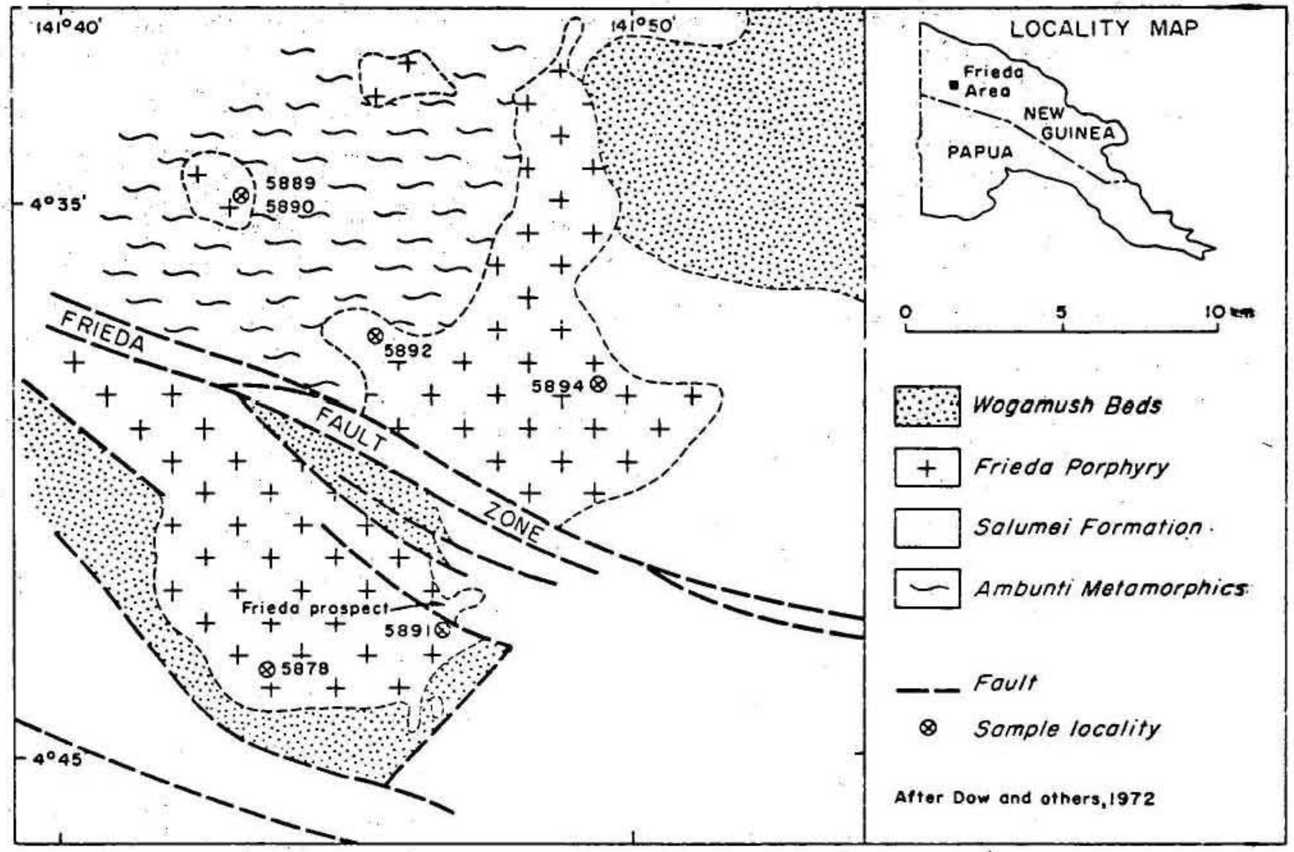

141°40'
141°50'
4°35'
4°45'
5889
5890
5892
5894
5891
5878
Frieda prospect
FRIEDA FAULT ZONE
LOCALITY MAP
Frieda Area
NEW GUINEA
PAPUA
0
5
10 km
Wogamush Beds
Frieda Porphyry
Salumei Formation
Ambunti Metamorphics
Fault
Sample locality
After Dow and others, 1972

Table 2. K-Ar ages from the Yanderra Copper Prospect

No.	Sample	K %		Rad. Ar^{40} $\times 10^{-6}$ ccNTP/g	$\frac{100 \text{ Rad. } Ar^{40}}{\text{Total } Ar^{40}}$	Calculated age (m.y.) ± 2 s.d.
5488	Hornblende	0.413) 0.413)	0.413	0.195	26.9	11.8 ± 0.5
	Plagioclase	0.275) 0.275)	0.275	0.108	8.4	9.8 ± 0.8
5489	Biotite	6.922) 6.891)	6.907	1.860	53.9	6.7 ± 0.2
5490	Plagioclase	0.266) 0.265)	0.266	0.074	7.9	7.0 ± 0.6
5492	Biotite	7.630) 7.622)	7.626	1.979	60.3	6.5 ± 0.2
	Hornblende	0.618) 0.615)	0.617	0.247	26.1	10.0 ± 0.3
5495	Biotite	7.596) 7.592)	7.594	2.433	72.3	8.0 ± 0.2
5496	Biotite	7.390) 7.376)	7.383	1.970	50.4	6.7 ± 0.2

Table 3 Rb-Sr data from the Yanderra Copper Prospect

No.	Sample	Rb (ppm)	Sr (ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	Sr^{87}/Sr^{86}_{**}	Rb-Sr age (m.y.)
5489	Biotite	448.3	23.0	56.347	0.7114		9.7
	Total Rock	71.8*	551.5*			0.7039	
5492	Biotite	529.5	9.3	164.835	0.7209		7.6
	Total Rock	61.0	585.1	0.301	0.7027	0.7035	
5495	Biotite	304.6	13.0	67.652	0.7168		13.7
	Total Rock	37.7*	851.6*			0.7039	
5496	Biotite	391.0	12.4	91.233	0.7214		13.6
	Total Rock	55.4*	566.0*			0.7043	
5672	Total Rock	71.2	374.1	0.549	0.7042	0.7042	
5883A	Total Rock	57.7	562.2			0.7039	
5883B	Total Rock	69.0	402.4			0.7039	
5883C	Total Rock	17.8	629.8			0.7038	

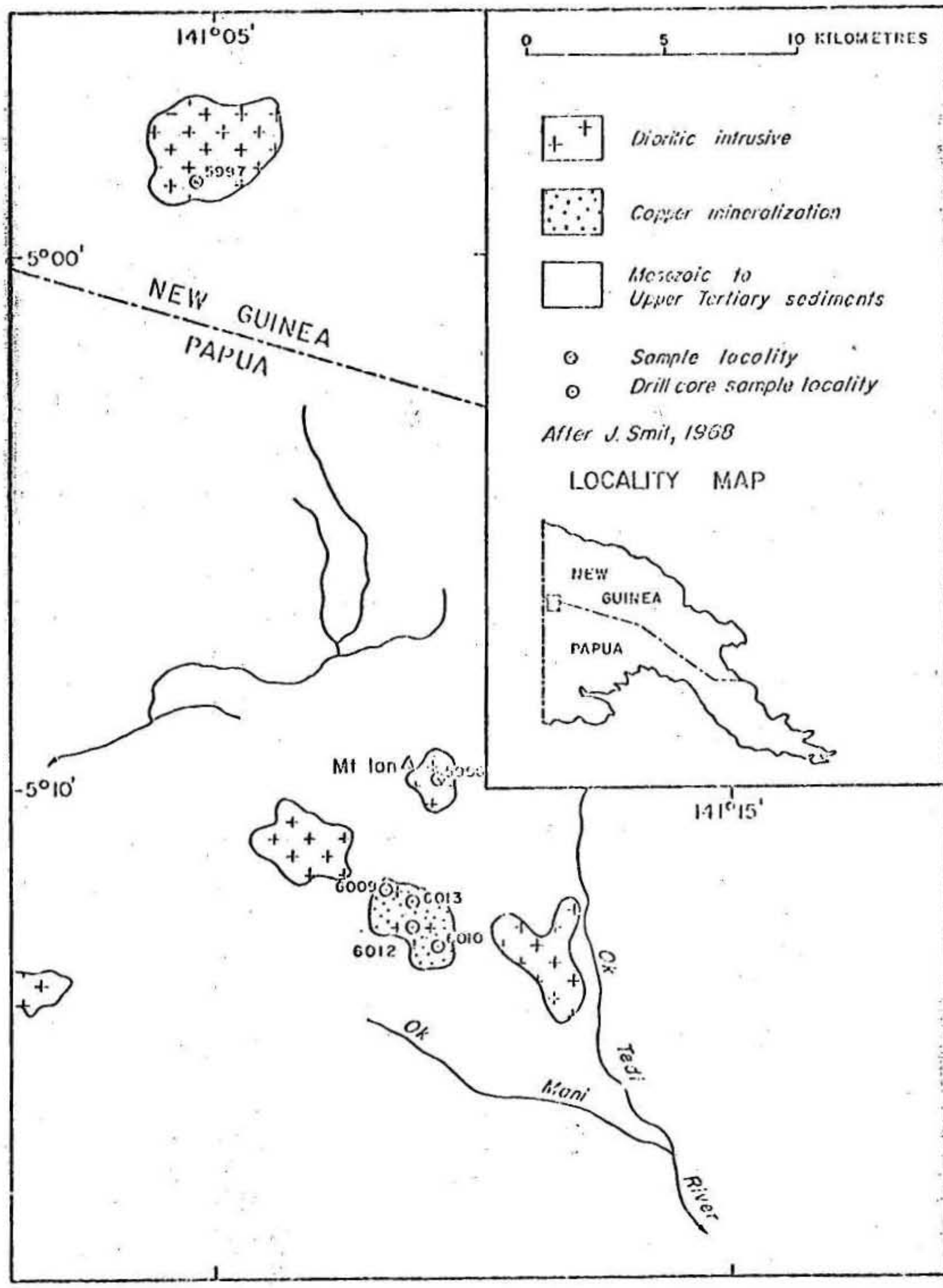
*Approximate XRF measurement

**Measured value, unspiked run

Table 4 K-Ar ages from the Frieda Porphyry

No.	Sample		K %	Rad. Ar^{40} $x10^{-6}$ cc NTP/g	100 Rad. Ar^{40} / Total Ar^{40}	Calculated age (m.y.) ±2 s.d.
5878	Hornblende	0.638) 0.631)	0.635	0.373	62.4	14.7 ± 0.6
5891	Plagioclase	1.666) 1.662)	1.664	1.086	68.8	16.3 ± 0.7
5889	Hornblende	0.710) 0.705)	0.708	0.383	34.5	13.5 ± 0.6
5890	Hornblende	0.711) 0.704)	0.708	0.429	61.5	15.1 ± 0.6
5892	Hornblende	0.542) 0.536)	0.539	0.359	59.0	16.6 ± 0.7
5894	Hornblende	0.509) 0.504)	0.507	0.311	48.4	15.3 ± 0.6

Fig 6


141°05'
141°15'
5°00'
5°10'
0
5
10 KILOMETRES
Dioritic intrusive
Copper mineralization
Mesozoic to
Upper Tertiary sediments
Sample locality
Drill core sample locality
After J. Smit, 1968
LOCALITY MAP
NEW
GUINEA
PAPUA
NEW GUINEA
PAPUA
5997
Mt Ian
6009
6013
6012
6010
Ok
Mani
River
Tedi
Ck

Eleven mineral and whole rock K-Ar ages were measured on six samples from the area and the results are given in Table 5. Two fresh diorites (5996, 5997) come from the small intrusive stocks well removed from the area of the Ok Tedi mineralization. Only one hornblende age of 4.88 ± 0.11 m.y. has been measured on the northernmost mass, and the single date can be regarded as a tentative minimum estimate for the age of intrusion. The other relatively unaltered diorite near Mt Ian (5996) yielded fresh primary biotite which has been dated in duplicate at 1.85 ± 0.03 and 2.07 ± 0.05 m.y. This age is again interpreted as a minimum intrusive age, although the relationship with the 4.88 m.y. hornblende age is not known. Taken at face value, the two ages indicate periods of diorite intrusion in the early and late Pliocene.

The Ok Tedi (Mount Fubilan) copper prospect itself is a complex porphyritic andesite and granodiorite stock, part of which is intensely fractured, hyrothermally altered and mineralized with copper sulfides. The samples dated are the type locally known as "Hong Kong intrusive", and are from drill core supplied by Kennecott Explorations (Aust.) Pty Ltd. These rocks all show strong potash alteration (note very high K values up to 8.7%) and in some instances minor chlorite, calcite and sphene are developed. On a macro- and microscopic scale the alteration is associated with copper mineralization, and it could be reasonably inferred that the two processes were concurrent. The rocks dated can be described as recrystallized andesites and monzonites: there are large crystals (up to 8 mm across) of plagioclase, biotite (? Mg-rich), and of partly to completely pseudomorphed amphibole grains in a fine-grained, recrystallized groundmass of quartz, perthitic K feldspar, plagioclase, biotite, minor apatite and sphene; the groundmass is peppered with opaque granules, and chalcopyrite and pyrite are identifiable in larger aggregates. K feldspar and biotite are the main secondary minerals after plagioclase and hornblende respectively; in some sections, perfect rhomb-shaped (amphibole) sites are now a decussate mass of fine-grained biotite. Veinlets rich in chalcopyrite, alkali feldspar and biotite in places cut pre-existing primary igneous structures. With the exception of 6013 from which biotite was obtained, mineral separation was not generally practicable for the mineralized rocks because of the limited quantity of specimen available and the fine-grained nature of the potassic phases. Because the minerals are all fresh, even in the intensely potash metasomatized rocks, whole rock dating was undertaken to determine the age of the Ok Tedi mineralization.

The K-Ar ages on the mineralized rocks are listed in Table 5, and they form a remarkably concordant group in the range 1.11 to 1.24 m.y. The K values of the whole rocks range from 4.5% to 8.7%. Note that the duplicate determinations on the whole rock samples are in excellent agreement; the biotite age of 6013 is also in accord with the whole rock measurement. The concordance of the dates is convincing evidence that the ages are geologically meaningful, and represent the time of hydrothermal alteration and mineralziation of the Ok Tedi porphyries. It is surmised that hydrothermal activity began and ended within the 0.1 m.y. interval indicated by the total age spread. The ages of 1.1 to 1.2 m.y. are consistent with the known stratigraphic control and correspond to a time in the mid Pleistocene.

These data relate only to the mineralization, and the age of initial intrusion in the Ok Tedi prospect porphyries remains undertermined. Although there is no direct evidence, it is conceivable that one or both of the unmineralized intrusions to the north, dated at 1.9 and 4.9 m.y., are phases of theoriginal porphyry of the Ok Tedi Prospect. The present K-Ar data unequivoca indicate the extreme youthfulness of the Ok Tedi deposit, the youngest yet discovered, but further detailed geochronological work, now being undertaken, is necessary to better delineate the age relationships between intrusion and mineralization.

Generalization on Mineralization in the New Guinea Region

Isotopic dating of rocks and minerals associated with the emplacement and mineralization of five mineral deposits in the New Guinea region, reveal ages from mid Miocene through to Pleistocene. These ages, together with the Panguna, Bougainville, data (Page and McDougall, 1972), are summarized in Table 6. All of the mineralized bodies are genetically associated with fractured, hydrothermally altered subvolcanic porphyries and other high level intrusives, whose compositions from granodioritic to dioritic. In the two bodies where ages of emplacement and mineralization have been determined, the discernible time intervals between the two processes are about 1 m.y. at Panguna, and possibly 5 m.y. in the Yanderra area. Recent K-Ar measurements (Moore and Lanphere, 1971) on hydrothermal biotite from the Bingham porphyry copper deposit, Utah, show that a time interval of 1 to 2 m.y. separated the emplacement of the composite stock and its subsequent mineralization. Previous attempts (Laughlin and others, 1969a; 1969b; Moore and others, 1968 Ohmoto and others, 1966) to delineate age differences between igneous intrusion and hydrothermal alteration/mineralization in other mid Tertiary and early Tertiary mineral provinces in North America, have been mainly inconclusive. Unless the age studies are detailed enough, the experimental uncertainties of measurements in this age range (Laramide-mid Tertiary) probably mask any real differences. Nevertheless these studies indicated that time intervals between intrusion and mineralization were generally less than a few million years.

The foregoing data and discussion demonstrate that six of the principal gold and porphyry copper depositis in New Guinea and Bougainville are related to magmatic events that are mid Miocene or younger in age. Geological constraints on several other copper prospects in Papua New Guinea, West Irian, Manus Island, New Britain, and Guadacanal are also suggestive of late Tertiary or Quaternary ages. Hence this general region of the Southwest Pacific can be thought of as a late Tertiary-Quaternary copper-gold metallogenic province. Within the province mineralization appears to have occurred at different times at different localities. At this point of our knowledge it is not possible to define any unique metallogenic age or "epoch", but rather the mineralization processes in the region appear to have been fairly continuous from the mid Miocene, perhaps to the present day. Mineralization activity occurring over discrete periods of time is also found in other porphyry copper provinces, e.g. the Laramide (55-75 m.y.) deposits of Arizona (Livingston and others, 1968), and the Chilean-Argentinian deposits (Clark and others, 1970; Caelles and others, 1971) which, in pulses, span much of the Mesozoic and Tertiary.

Recent geological mapping (Dow, 1969; Dow and others, 1972) and the general study of ages of plutonism and volcanism in the New Guinea Highlands (Page and McDougall, 1970; Page, 1971, and in prep.) indicate an upsurge in magmatism and other tectonic activity in the Miocene, and to a lesser extent, in later time. The fact that the New Guinea mineral deposits so far studied are also mid Miocene or younger in age points to the likelihood that regional geothermal gradients were much higher during this period than at any other time in the Phanerozoic. In general terms, this tectonic upsurge is identifiable with the culmination of the Papuan Geosyncline development in the New Guinea

Table 5   K-Ar ages from the region of Ok Tedi Copper Prospect

No.	Sample	K %		Rad. Ar^{40} $x10^{-6}$ cc NTP/g	$\frac{100\ Rad.Ar^{40}}{Total\ Ar^{40}}$	Calculated age (m.y.) ± 2 s.d.
5996	Biotite	7.747) 7.720)	7.734	0.571 0.638	37.3 28.4	1.85 ± 0.03 2.07 ± 0.05
5997	Hornblende	1.031) 1.018)	1.025	0.200	34.0	4.88 ± 0.11
6009	Whole rock	4.539) 4.528)	4.534	0.221 0.221	71.8 68.9	1.22 ± 0.04 1.22 ± 0.02
6010	Whole rock	8.722) 8.707)	8.715	0.390 0.390	72.0 68.8	1.12 ± 0.02 1.12 ± 0.02
6012	Whole rock	6.288) 6.240)	6.264	0.299 0.304	54.2 66.3	1.19 ± 0.02 1.21 ± 0.02
6013	Whole rock	5.857) 5.854)	5.856	0.290	61.9	1.24 ± 0.02
	Biotite	8.204) 8.236)	8.220	0.364	17.6	1.11 ± 0.05

Table 6 Age summary of some New Guinea mineral deposits

District	Main type of Mineralization	Age of Emplacement of associated igneous rocks (m.y.)	Age of Mineralization (m.y.)	(Epoch
Frieda Prospect	Cu	13 -16	? Same	Mid Miocene
Kainantu Goldfields	Au, Cu	7 -10, (15)	? Same))	Late Miocene
Yanderra Prospect	Cu, Au	12.5	7 - 8))	to
Morobe Goldfield	Au, Mn	3.1 - 3.8	Same)	Plicone
Ok Tedi Prospect	Cu		1.1 - 1.2	Pleistocene
Panguna ore body, Bougainbille Island	Cu	4 -5	3.4	Pliocene

Highlands area, and was possibly triggered by interaction and collision between the Pacific plate and the northward-moving Australian plate, which has New Guinea as its leading northern edge. Assuming that the mineralized late Tertiary-Quaternary calc-alkaline intrusives examined in this paper are indeed products of a zone of plate interaction, it is tantalizing, but quite realistic, to consider that other potential ore bodies are probably in the process of formation beneath New Guinea and other currently active island arc environments.

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