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Age, petrology and mineralisation associated with two Neogene intrusive types in the Eastern Highlands of Papua New Guinea

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Abstract: Numerous Neogene porphyritic basic to intermediate intrusive rocks crop out as batholiths, stocks and dyke swarms in the eastern highlands of Papua New Guinea between 144°E and 146°E. Their radiometric ages range from 18 Ma to 7 Ma, and are consistent with known more definitive stratigraphic relationships. Our work has shown that within this time range, two distinct phases of plutonism occurred and that the second phase from 9 Ma to 7 Ma was often associated with magmatic-hydrothermal Cu-Au-Ag mineralisation. We have named the earlier phase *Akuna*-type, and the later phase *Elandora*-type.

Akuna-type intrusives tend to form large complexes (eg. Akuna Intrusive Complex, Bismarck Intrusive Complex) up to 800 km^2 in outcrop area, displaying a wide variety of fractionated compositions from pyroxenite, gabbro, diorite to granodiorite. Other smaller intrusions (Oipo and Kimil Diorites) are more homogeneous.

In contrast to *Akuna*-type, *Elandora*-type intrusives (Elandora Porphyry, Yandera porphyries) generally form microdioritic, often tabular stocks less than 10 km^2 in area, dykes and dyke swarms, some of which intrude *Akuna*-type masses. Many bodies and parts of individual bodies display propylitic alteration assemblages, with argillic, phyllic and silicic alteration being locally dominant. *Elandora*-type intrusives are apparently associated with either areas of outcropping basement or areas underlain at shallow depth by basement. Exposure of many *Elandora*-type intrusions at the present erosion surface is commonly a function of two fault sets trending 120° and 040°, which intersect to form elevated fault-bound basement blocks and areas of cover underlain at shallow depth by basement. Some *Elandora*-type intrusions occur in erosional basement highs.

The two intrusive types have calc-alkaline affinities. Analysed *Elandora*-type intrusives have a narrow compositional range between 60 and 70% SiO_2 compared with the wide range of SiO_2 values shown by analysed *Akuna*-type intrusives. *Elandora*-type analyses plot on or adjacent to *Akuna*-type major element variation diagram trend lines at 60% SiO_2.

However, at 60% SiO_2, *Elandora*-type intrusives have higher Sr (700 ppm) and lower K_2O (< 2%) than *Akuna*-type intrusives. These empirical geochemical features, coupled with field criteria, serve to distinguish the two intrusive types.

INTRODUCTION

Preamble

Neogene intrusives and their volcanic equivalents are common in the eastern highlands of Papua New Guinea (PNG). The area produces much alluvial gold recovered by Papua New Guineans using small petrol or diesel pumps to sluice river and creek banks. Many mineral Prospecting Authorities are held over the area by largely foreign-owned exploration companies searching for precious and base metal deposits. This large and small scale exploration activity prompted the Geological Survey of PNG to investigate mineral occurrences in an attempt to synthesise the relationships between regional geology and mineralisation. Detailed 1:50 000 mapping of part of this area (Rogerson *et al.*, 1982) has led to the recognition, using field-based criteria, of two Neogene intrusive types which we believe may be identified throughout the eastern highlands area. This paper attempts to outline the field occurrence, age and mineralisation associated with these two intrusive types. Whole-rock geochemical data supporting the initial field-based identification of the intrusive types are also presented.

The eastern highlands of PNG is a rugged, mountainous area generally exceeding 1500m in elevation and bounded approximately by longitudes 144°E and 146°E (Figure 1).

Regional geological setting

Pre-Late Triassic granites and Bena Bena Metamorphics, Goroka Formation and Omung Metamorphics, units dominated by multideformed, thin-bedded, low-grade regionally metamorphosed quartzose sediments, form basement to the area. Superimposed on the regional metamorphic pattern are schistose thermal aureoles surrounding foliated synkinematic granitic stocks of Middle Jurassic age (Dow and Plane, 1965; Tingey and Grainger, 1976; Page, 1976; Rogerson *et al.*, 1982). Late Triassic to Cretaceous fine-grained deep-water sediments and tuffaceous sediments unconformably overlie and surround two large basement highs, south of the Wahgi River (Kubor Anticline) and in the Goroka-Kainantu area respectively (Bain and Mackenzie, 1974 and 1975; Pigram *et al.*, 1983). Over most of the area, slow marine sedimentation and/or submarine erosion occurred until deposition of the Middle to Early Oligocene Chimbu and Nebilyer Limestones. These units ?unconformably underlie Late Oligocene to Early Miocene (P21-N5; Figure 2) Omaura Formation consisting of bathyal to upper bathyal fine-grained clastic sediments, with minor micrite units near its boundary with overlying Yaveufa Formation. The Yaveufa Formation, comprising volcanogenic clastic sediments, thick basaltic and andesitic agglomerates and flows, and minor limestones conformably overlies the Omaura Formation (Dow and Plane, 1965; Bain and Mackenzie, 1974; Tingey and Grainger, 1976; Rogerson *et al.*, 1982). Foraminiferids recovered from the Yaveufa Formation in many localities yield upper Te-lower Tf ages (Figure 2 - approximately equivalent to N6), suggesting that its age range is from Early to Middle Miocene. The Movi Beds (Bain and Mackenzie, 1974) are partly equivalent to, and partly overlie the Yaveufa Formation. Planktic foraminiferids yield N11-N12 ages (Middle Miocene) for the Movi Beds.

Middle to Late Miocene plutons which form the subject of this paper are found intruding all the preceding units. The tectonism which began with the volcanism responsible for Yaveufa Formation and Movi Beds, continued with intrusion of Middle and Late Miocene plutons (Page, 1976) and resulted in a sedimentation hiatus from Late Miocene time until fluvial deposition of the undeformed Quaternary Kainantu Beds (Dow and Plane, 1965; Tingey and Grainger, 1976; Rogerson *et al.*, 1982). Extinct Quaternary strato-volcanoes are prominent topographic features of the area (Blake and Loffler, 1971; Mackenzie, 1976). Compressive deformation of the Tertiary and pre-Tertiary sequence resulted in open anticlines, homoclinal ramps, broad basins, and domes. Some of these structures reflect basement topography (Rogerson *et al.*, 1982). Formations younger than the Omaura

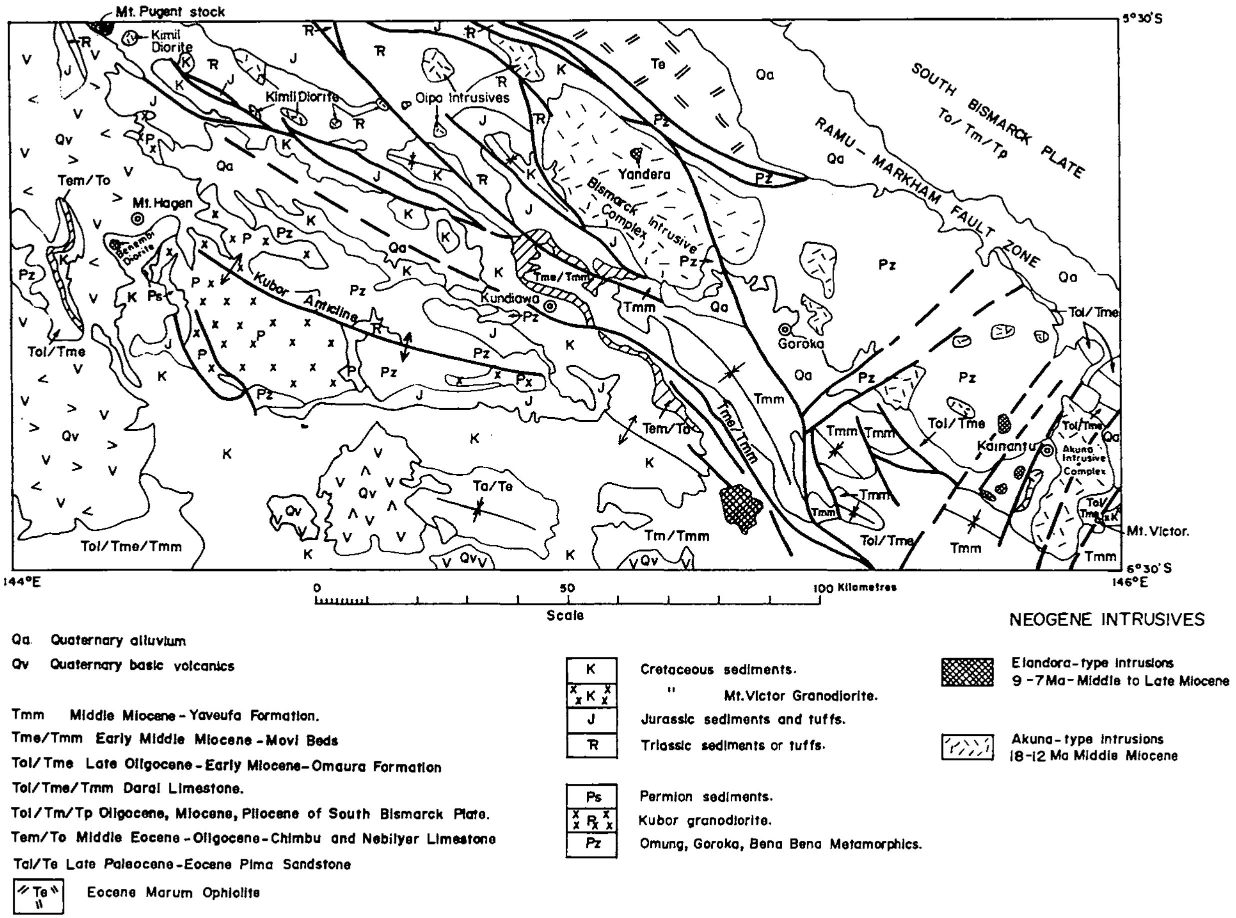
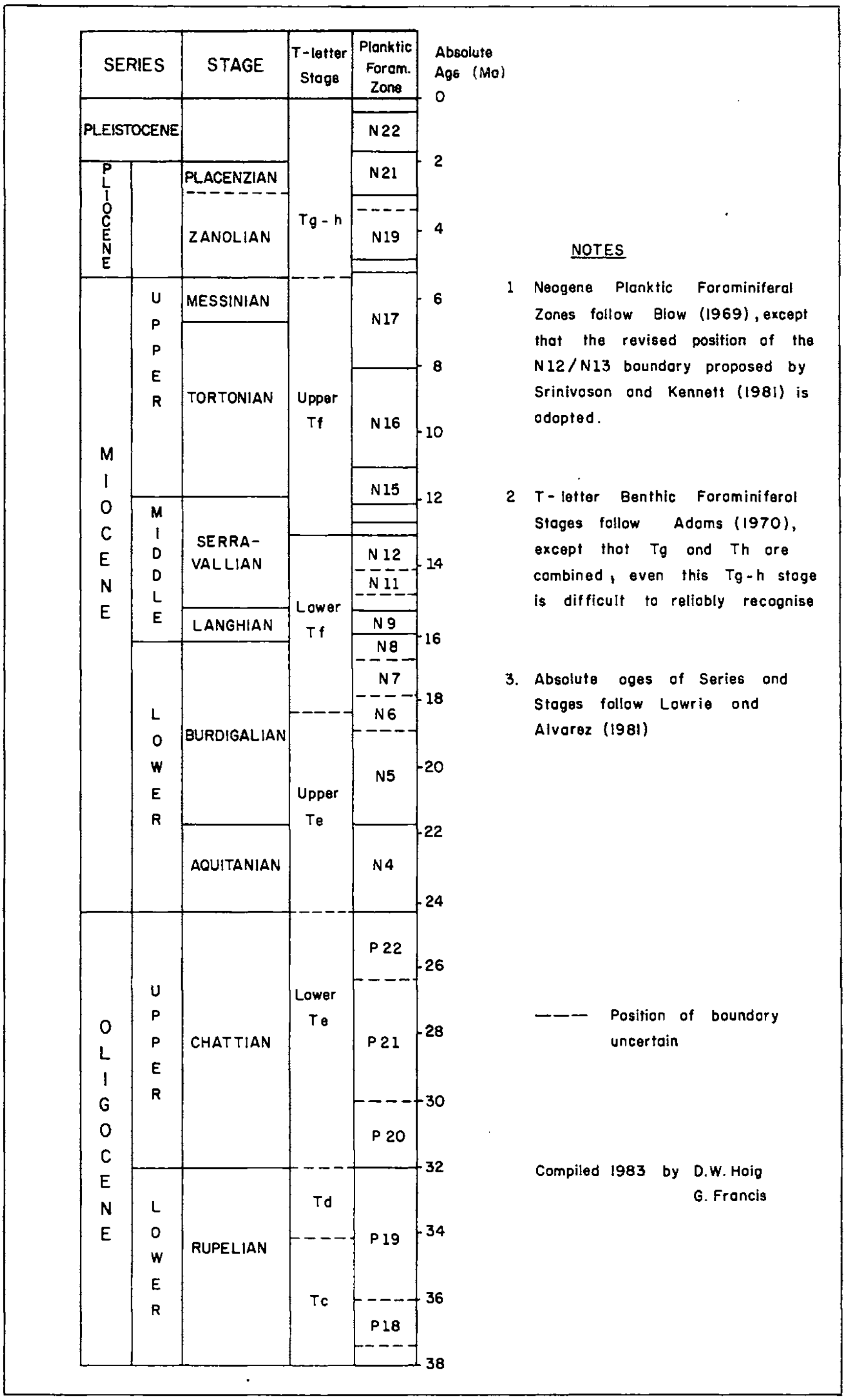


Fig. 1 Eastern highlands area showing distribution of *Akuna*-type and *Elandora*-type intrusions relative to regional stratigraphy and structure.



NOTES

1 Neogene Planktic Foraminiferal Zones follow Blow (1969), except that the revised position of the N12/N13 boundary proposed by Srinivasan and Kennett (1981) is adopted.

2 T-letter Benthic Foraminiferal Stages follow Adams (1970), except that Tg and Th are combined, even this Tg-h stage is difficult to reliably recognise

3. Absolute ages of Series and Stages follow Lowrie and Alvarez (1981)

---- Position of boundary uncertain

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G. Francis

Fig. 2 Oligocene and post-Oligocene correlation chart.

Formation display macroscale upright, open, non-plunging folds trending 120°, parallel to the Kubor Anticline and the Ramu-Markham Fault. The latter marks the Late Neogene-Quaternary collision zone between the South Bismarck and Indo-Australian Plates. Crustal deformation of the eastern highlands area was presumably a result of compression brought about by the approach of these plates (Ripper, 1977; Hamilton, 1979; Johnson, 1979; Falvey and Pritchard, 1983; Rogerson *et al.*, 1982). The main faults in the area trend northeast and west-northwest (Rogerson *et al.*, 1982) and regional evidence suggests that the final phase of faulting occurred during or after emplacement of Middle-early Late Miocene intrusives. Figure 1 shows the distribution of Neogene intrusives and the various stratigraphic units mentioned above.

Previous work

Early reconnaissance geological studies of the eastern highlands carried out by McMillan and Malone (1960), Dow (1962), Dow and Dekker (1963), Dow and Plane (1965) and Mackenzie and Bain (1972) described the field character, mineralisation, and petrography of many Neogene intrusions in the area. Later 1:250 000 geological sheet note compilations (Bain and Mackenzie, 1974 and 1975; Tingey and Grainger, 1976) summarized these earlier observations. Bain *et al.* (1975) also mentioned Neogene intrusions, but none of the previous authors presented whole-rock geochemical data for them. Lowenstein (1975) compiled the results of a geochemical investigation of porphyry-related mineralisation associated with the Oipo intrusives near Simbai. However, it was not until the late 1970's that whole-rock geochemical data were applied to the problem of differentiating plutonic rocks in the eastern highlands. Mason (1975, 1978) and Mason and Heaslip (1980) were the first authors who attempted to relate the occurrence of mineralisation with certain intrusive types on the basis of whole-rock geochemistry. Intrusive geochemistry and mineralisation of the Yandera porphyry copper prospect have been studied extensively by Watmuff (1978, 1979). Titley *et al.* (1978) presented further data and interpretations on Yandera prospect mineralisation, alteration and origin but did not list intrusive geochemical data. Griffin (1979) compiled published geochemical data from intrusions within PNG in an unsuccessful attempt to identify any major element variations between intrusions occurring in different structural-tectonic zones. Rogerson *et al.* (1982) presented data on the whole-rock geochemistry of intrusives in the eastern part of the eastern highland area.

Radiometric ages of some intrusions in the eastern highlands have been determined by Page and McDougall (1972), Grant and Nielsen (1975), and Page (1976).

NEOGENE INTRUSIONS

Intrusive types

Known Neogene intrusions (Figure 1) include the Kimil Diorite (Bain *et al.*, 1975), Oipo Intrusives (Dow and Dekker, 1964), Bismarck Intrusive Complex (McMillan and Malone, 1960), Yandera porphyries (Watmuff, 1978), Benembi Diorite, Michael Diorite (Bain *et al.*, 1975), Akuna Intrusive Complex (Tingey and Grainger, 1976), Elandora Porphyry (Dow and Plane, 1965) and the Mount Pugent stock. The Kimil Diorite and the Oipo Intrusives are group names given to many petrographically similar intrusions cropping out between the Bismarck Intrusive Complex and the Maramuni Diorite (Dow *et al.*, 1927). The latter does not crop out within the area discussed in this paper. Similarly the name Elandora Porphyry has been extended to include many small petrographically similar porphyritic microdiorite intrusions in the Kainantu area (Rogerson *et al.*, 1982). Table 1 summarises occurrence characteristics of the abovenamed intrusions.

Microsyenite constituting the Mount Pugent stock (Mason, 1978) is geochemically distinct from any other analysed eastern highlands intrusion. At 60% SiO_2 it has nearly 12% total alkalies (Mason, 1978). A high alkali igneous suite occurs in the Milne Bay area (Smith and Davies, 1976) where they are presumably related to deep crustal fracturing and lithospheric rifting. The petrology and origin of this stock is beyond the scope of this paper but it does constitute another as yet un-named intrusive type.

Intrusion characteristics summarised in Table 1 suggest that two intrusion-types can be initially recognized on the basis of petrography, alteration and field character. Elandora Porphyry intrusions, Michael Diorite and the Yandera porphyries are all variably altered, porphyritic microdiorites or dacite porphyries forming relatively small stocks but mostly dyke swarms. They are frequently associated with gold (-copper) mineralisation. Conversely, the Akuna and Bismarck Intrusive Complexes, Oipo Intrusives and Kimil Diorite form larger intrusive bodies and are not generally altered unless intruded by younger porphyry dykes. At least in the case of the Bismarck and Akuna complexes, the second type consists of a fractionated suite of plutonic rocks ranging from ultramafics to granodiorites. We refer to the first named group of intrusions as *Elandora*-type and the second named as *Akuna*-type.

One apparent anomaly in Table 1 is the occurrence of minor Cu-Au-Mo mineralisation within the Kimil Diorite and Oipo Intrusions. In part, we believe that such mineralisation may be due to unrecognized Elandora-type intrusions which are known to be associated with Au-Cu mineralisation in the Kainantu area (Rogerson *et al.*, 1982), Mount Michael (Bain and Mackenzie, 1974) and Yandera (Watmuff, 1978 and 1979; Titley *et al.*, 1978). Other support for this contention comes from the Simbai area, where alluvial gold has been traced to source within Oipo Intrusives (Dow, 1962). However, Lowenstein (1975) showed conclusively that the primary mineralisation in the area occurs within altered quartz diorite and diorite-porphyry dyke swarms which have been mapped by Bain and Mackenzie (1975). In the Simbai area at least, as Oipo Intrusives. We believe these altered dykes are *Elandora*-type intrusives and that similar dykes may not be recognized during reconnaissance mapping, particularly within larger *Akuna*-type plutons.

Intrusive/envelope relations

Table 1 suggests that from approximately 17-7 Ma, intrusive calc-alkaline igneous activity occurred extensively in the eastern highlands of PNG, resulting in the emplacement of large intrusive complexes, stocks and dyke swarms. Most of the known intrusions are found emplaced within pre-Triassic basement and Mesozoic sequences but some, such as the Elandora Porphyry, Michael Diorite and Akuna Intrusive Complex, are found intruding rocks as young as Middle Miocene. Small hornfelsic contact aureoles less than 100m wide surround larger intrusions. It is probable however, that other intrusions may have intruded younger sequences now removed by erosion. The area (Figure 1) is cut by many macroscale 120° trending faults and in the Kainantu area, Rogerson *et al.* (1982) recognized a further fault

TABLE 1
NEOGENE INTRUSIVES

NAME OF PLUTON	AGE	ROCK TYPE(S)	MESOSTRUCTURE/ ALTERATION	INTRUSIVE FORMS	COUNTRY ROCKS	COMMENTS/REFERENCE
Mount Pugent stock	Miocene	Microsyenite		Elliptical plug 1km x 1.5km	Early Cretaceous	Petrographically and geochemically different from other intrusions in the area. Mason (1979).
Elandora Porphyry	7-9 Ma (K-Ar; Page 1976).	Porphyritic microdiorite and quartz microdiorite	Highly feldspar porphyritic, Au mineralisation	Dykes, dyke swarms plugs, stocks up to 4km².	Basement (? Permian) to Middle Miocene in age. Intrudes Akuna Intrusive Complex.	Group name for petrographically similar small intrusions in Kainantu area. Many seem to be associated with basement (Rogerson *et al.*, 1982)
Michael Diorite	6-8 Ma (k-Ar; Page 1976)	Porphyritic microdiorite	Feldspar porphyritic, has chalcopyrite.	Oval stock 60km² in area.	Early-Middle Miocene Movi Beds	Bain and Mackenzie (1974).
Yandera Porphyries	7-9 Ma Rb-Sr and K-Ar; Page and McDougall (1972)	Dacite porphyries, quartz microdiorite porphyries.	Altered, copper gold mineralisation Vesicles in some, intrusive breccias.	Dykes, intrusive breccias.	Bismark Intrusive Complex (granodiorites)	Watmuff (1978, 1979), Titley *et al.*, (1978), Grant and Nielsen (1975), Page (1976), Page and McDougall (1972).
Benembi Diorite	? Miocene	Diorite	Much alluvial gold in area	Small 1km² stock but may only be partly unroofed.	Cretaceous	Bain and Mackenzie (1975).
Kimil Diorite	16 Ma K-Ar on on hornblende Page (1976)	Microdiorite often porphyritic	Cu, Au, Mo occurences shown on Ramu 1:250 000 geological sheet	Elongate stocks up to 10km x 3km	Triassic and Jurassic	Bain and Mackenzie (1975) Similar to Oipo intrusives
Oipo Intrusives	15-18 Ma K-Ar Page (1976)	Porphyritic microdiorite for stocks. Porphyritic quartz microdiorite for dyke swarms.	Cu, Au, Mo occurrences shown on Ramu 1:250 000 geological sheet	Sub-circular stocks up to 10km in diameter, some dykes and dyke swarms.	Triassic, Jurassic, Cretaceous	Dow and Dekker (1964)
Bismarck Intrusive Complex	12-13 Ma Rb-Sr and K-Ar, Page (1976)	Granodiorite, diorite gabbro ultramafics	Altered where intruded by Yandera porphyries. Plutonic microstructure	Elongate 45km x 20km main outcrop area; consists of a fractionated complex of intrusions.	Mainly basement (? Permian), some Mesozoic	Bain *et al.*, (1978)
Akuna Intrusive Complex	13-17 Ma K-Ar; Page (1976)	Granodiorite, diorite gabbro, ultramafics	Plutonic microstructure	Main outcrop is approx. 900km² consists of a fractionated complex of intrusions	Basement (? Permian), Omaura Formation and Yaveufa Formation	Tingey and Grainger, (1976), Rogerson *et al.*, (1982).

set trending 040°. Intersection of these two fault sets and the effects of 120° open folds, produces in the Kainantu area at least, fault-bound blocks exposing areas of elevated basement. Some erosional basement highs also occur. Rogerson *et al.*, (1982) showed that Elandora porphyry intrusions are apparently more common in areas of pre-Triassic basement and in areas affected by 040° trending faults. Some intrusions themselves are faulted and Rogerson *et al.*, (1982) concluded that faulting and intrusion was complementary but that faulting continued with regional uplift after intrusion had ceased.

Age

Table 1 summarizes radiometric age data for plutons in the area. A clear age distinction can be made between *Akuna*-type and *Elandora*-type plutons on the basis of available age data. The latter were emplaced between 9-7 Ma using results obtained by Page (1976). Experimental errors for Page's (1967) ages were generally less than 1 Ma. Independent corroboration of the 7-9 Ma Rb-Sr and K-Ar dates which Page and MacDougall (1972) determined for the Yandera porphyries is provided by Grant and Nielson (1975), who reported new K-Ar dates of between 6 and 7 Ma. *Akuna*-type plutons which are in places intruded by *Elandora*-type dykes, show radiometric ages ranging from 18-12 Ma (Page and MacDougall, 1972; Grant and Nielsen, 1975; Page, 1976). The 17-13 Ma age range shown by the Akuna Intrusive Complex (Page, 1976) reflects the intrusion of multiple, fractionated magma pulses. Only a small age range (13-12 Ma) is shown for the Bismarck Intrusive Complex, but Page (1976) only sampled granodiorites. Granodiorites from the Akuna Intrusive Complex gave ages of 13.2 and 13.5 Ma (Page, 1976) and it is here suggested that Bismarck Intrusive Complex gabbros and diorites would yield older K-Ar ages.

Yaveufa Formation (upper Te-lower Tf in part) and Movi Beds (Nll-N12) contain basic to intermediate lavas and volcanic detritus, and overlie non-volcanogenic Omaura Formation of P21-N5 age. The age overlap of the beginning of *Akuna*-type intrusive activity at approximately 18 Ma and the influx of volcanism in the Yaveufa Formation at about N6 (18 Ma) suggests that some *Akuna*-type intrusives vented.

Elandora-type intrusions are clearly younger than *Akuna*-type intrusions on stratigraphic grounds. Michael Diorite intrudes Movi Beds, Yandera porphyries intrude the Bismarck Intrusive Complex and many Elandora Porphyry bodies intrude the Yaveufa Formation.

Petrology

Table 2 lists published and unpublished whole-rock geochemical data on intrusive rocks from the eastern highlands area and the Appendix lists analytical details. Rogerson *et al.*, (1982) have shown that the Akuna Intrusive Complex as a whole lacks intermediate-SiO_2 iron enrichment and has geochemical characteristics intermediate between sub-alkalic and calc-alkaline island arc igneous suites. AFM ratios for the Akuna Intrusive Complex and other analysed rocks in Table 2 are plotted on Figure 2 which demonstrates that all analyses have major element ratios which approach those of calc-alkaline plutonic rocks. In addition, major element abundances are similar to those listed by Jakes and White (1972) for the calc-alkaline association with the exception of K_2O within *Elandora*-type intrusions. For rocks with 60-70% SiO_2 *Akuna*-type intrusions have 2.16-2.87% K_2O. *Elandora*-type intrusions in the same SiO_2 range show K_2O from 0.7-1.94%.

TABLE 2
NEOGENE INTRUSIVE WHOLE ROCK GEOCHEMISTRY

	Akuna Intrusive Complex					Bismarck Intrusive Complex			Elandora Porphyry		Yandera Porphyries		Michael Diorite		
ANALYSIS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	45.8	47.4	49.2	52.5	63.6	62.31	67.39	64.64	61.0	64.1	63.22	69.33	65.54	60.10	60.42
TiO_2	0.86	0.74	0.47	0.95	0.74	0.73	0.48	0.61	0.66	0.48	0.54	0.33	0.43	0.65	0.64
Al_2O_3	14.60	12.60	2.90	15.60	15.60	16.38	15.26	15.76	15.90	15.60	16.25	16.23	16.09	17.50	17.42
Fe_2O_3	5.90	4.40	2.80	2.10	1.58	2.30	1.62	2.03	3.47	0.70	2.16	1.19	4.59	1.67	2.22
FeO	6.90	9.10	8.90	8.40	5.10	2.93	1.84	2.32	2.90	4.70	2.40	1.40	4.59	3.48	3.02
MnO	0.17	0.20	0.18	0.16	0.12	0.07	0.06	0.07	0.09	0.05	0.08	0.05	0.04	0.14	0.13
MgO	8.04	10.30	17.10	5.65	1.94	2.82	1.70	2.28	2.98	2.50	3.24	1.07	1.72	1.81	1.77
CaO	15.90	13.40	17.90	8.94	4.18	4.98	3.32	4.30	4.84	3.38	4.77	2.53	3.77	6.43	5.71
Na_2O	1.00	1.56	0.23	2.93	3.88	4.74	4.61	4.62	4.92	4.80	5.09	5.70	5.69	4.46	4.36
K_2O	0.01	0.01	0.01	1.09	2.81	2.16	2.68	2.33	1.76	1.60	1.15	1.33	0.70	1.27	1.94
P_2O_5	0.02	0.02	0.01	0.32	0.25	0.22	0.14	0.19	0.43	0.24	0.18	0.10	0.16	0.33	0.34
H_2O+ (LOI)	0.4	0.3	0.2	1.2	0.3	0.55	0.75	0.63	0.6	0.6	1.05	0.99	1.37	1.26	1.19
H_2O-	0.2	0.1	0.2	0.5	0.1	0.55	0.75	0.63	0.6	1.2	1.05	0.99	1.37	0.24	0.31
Total	99.08	100.13	100.10	100.34	100.20	100.19	99.85	99.78	100.15	99.95	100.13	100.29	99.95	99.34	99.47
Cr	295	375	670	185	195	39	37	NC	95	160	ND	ND	ND	0	0
Ni	90	85	137	43	7	12	13	NC	27	27	ND	ND	ND	2	1
V	510	490	285	370	187	110	68	NC	27	27	ND	ND	ND	117	107
Sr	825	570	55	595	545	634	504	589	1400	895	833	1001	953	701	763
Rb	< 5	< 5	< 5	30	87	45	68	50	33	5	17	22	17	25	38
Nb	< 5	< 5	< 5	< 5	< 5	ND	ND	ND	5	5	ND	ND	ND	25	9
Zr	< 5	< 5	7	103	165	167	250	168	130	5	94	94	97	139	134
Ba	ND	ND	ND	ND	ND	370	395	423	ND	ND	268	347	ND	366	348
Y	10	5	5	25	20	19	15	16	10	5	11	7	8	21	22
Ga	ND	ND	ND	ND	ND	24	17	NC	ND	ND	ND	7	ND	23	21
Cu	ND	ND	ND	ND	ND	48	43	NC	ND	ND	ND	ND	ND	3	1
Pb	ND	ND	ND	ND	ND	20	13	14	ND	ND	13	9	A	5	4
Zn	ND	ND	ND	ND	ND	48	65	NC	ND	ND	ND	ND	ND	71	71
$Al_2O_3/(K_2O + Na_2O + CaO)$	0.86	0.84	0.16	1.2	1.435	1.38	144	14	1.38	1.595	1.48	1.70	1.54	1.44	1.45
Sr/Rb	165	114	11	20	6.3	14.1	7.4	11.8	42.4	179	49	45.5	56	28	20
K/Rb	NC	NC	NC	NC	269	400	328	116	58	2667	564	504	343	423	425

ND Not determined
NC Not calculated

Appendix lists analytic methods.

* Contains more basic rocks but these not analysed.

Similarity also exists between trace element abundance ratios in analysed eastern highland intrusives and those for the calc-alkaline association (of Table 2 and Jakes and White, 1972). However Sr abundances within analysed *Elandora*-type intrusions are always greater than 700 ppm, which is almost double those Sr values quoted by Jakes and White (1972) as being typical of the calc-alkaline association. The combination of unusual K_2O and Sr values for the *Elandora*-type intrusions suggests that their evolution may have been a function of feldspar controlled fractionation. Figure 4 suggests there may be a trend of increasing Sr with increasing SiO_2, similar to that found in high K_2O calc-alkaline rocks of eastern Papua (Jakes and Smith, 1970).

Mineralisation

Precious/base metal mineralisation and alteration are generally associated with phases of *Elandora*-type intrusives. The common occurrence of the mineralising phase of the *Elandora*-type as dykes and dyke swarms of limited extent often localised within mineralised *Elandora*- or *Akuna*-type intrusives suggests they generally constitute small targets.

Mineralisation in the Simbai and Kainantu areas is associated with *Elandora*-type intrusives which display pervasive propylitic alteration (Lowenstein, 1975; Rogerson *et al.*, 1982). Lowenstein (1975) also recognised a preceding phase of secondary biotite development. Metal values within the intrusives are generally lower than those in the adjacent country rocks, exo-skarns or veins related to the intrusive. Intrusion invariably results in local fracturing of the host rocks, usually accompanied by weak, though pervasive propylitic alteration. These features are enhanced when intrusion takes place in areas of pre-existing faults. Minor, local argillic alteration assemblages characterised by the occurrence of clay-pyrite may develop in areas of these pre-existing structures. Precious/base metal mineralisation is best developed in the country rocks and ranges from locally developed, thin, randomly-oriented networks of pyritic fractures, through small veins and stringers, to more pervasive, extensive stockwork veining. Skarn lenses hosting pyrite, pyrrhotite, gold, sphalerite, chalcopyrite, magnetite and minor galena with various combinations of pyroxene, epidote, garnet and quartz, may develop within calcareous strata adjacent to the intrusives. Examples of calcium exoskarns within the Kainantu area include the Mount Victor and Aifunka Hill prospects (Rogerson *et al.*, 1982).

At Yandera, Au-Cu-Mo mineralisation and attendant alteration is associated with, though overprints porphyritic intrusives (Watmuff, 1978). Overprinting and peripheral to the quartz vein swarm and breccia dykes is a phyllic/argillic alteration zone carrying the highest metal values. Using oxygen and hydrogen isotope analysis of alteration minerals in this zone, Chivas *et al.*, (1984) have shown that both magmatic and meteoric waters generated the alteration assemblage. Therefore, where an intrusion, or magma-hydrothermal centre is sufficiently accessed or large enough, not only will more pervasive alteration and mineralisation ensue as a consequence of the magmatic fluids, but meteoric waters will also become involved.

Little mineralisation is known to be genetically related to *Akuna*-type intrusives. Where capital mineralisation occurs within or adjacent to *Akuna*-type intrusions such as at Aifunka Hill (Rogerson *et al.*, 1982) or Yandera, it can be shown to be spatially and temporally (in the case of Yandera) related to *Elandora*-type intrusions. The only known mineralisation

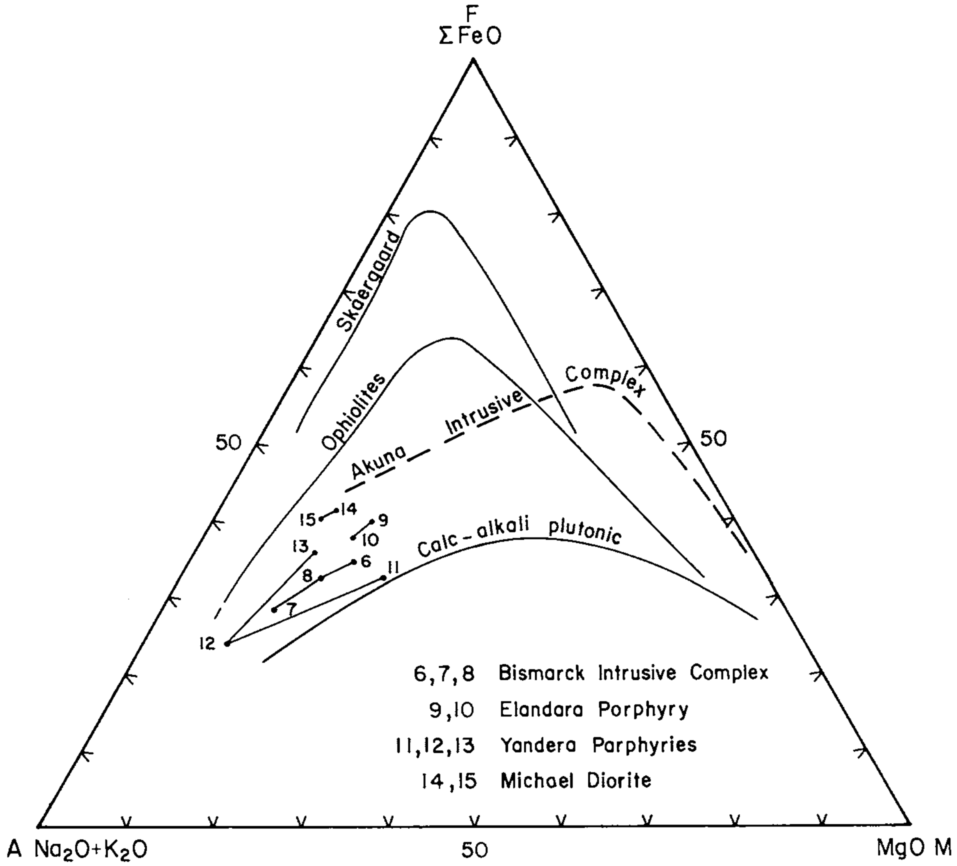

Fig. 3 AFM diagram showing similarity of different suites and their calc-alkaline affinity.

related to *Akuna*-type intrusions is at the eastern margin of the Akuna Intrusive Complex near Yonki. There, magnetite- garnet skarn mineralisation, related to gabbro intruding limestone, contains up to 3 ppm Au, but mineralisation occurs in pods of limited extent. No *Elandora*-type intrusives were noted at surface adjacent to the pods. It is possible that similar mineralisation could occur in other areas where *Akuna*-type intrusives have invaded calcareous strata. Unless tonnage of such deposits proved to be large, they have limited exploration potential.

DISCUSSION

Geochemical differences recognized between relatively unaltered *Akuna*- and *Elandora*-type intrusions supplement previously outlined field and radiometric age data used initially to define the two intrusive types. Figure 4 contains Harker diagrams illustrating Table 2 data. Within the range 60-70% SiO_2 the two intrusive types can be clearly distinguished using K_2O and Sr Harker diagrams (Figure 4a, b). Figure 4c shows that the ratio Sr/Rb can also be used with SiO_2 to distinguish intrusive types. Various authors have sought methods to distinguish potentially barren and potentially mineralised intrusions on the basis of factors such as tectono-structural setting, intrusive geometry, petrography, mafic mineral geochemistry, alteration, intrusive structure, and intrusion geochemistry (for example: Chappell and White, 1974; Kestler *et al.*, 1975; Feiss, 1978; Mason, 1978; Mason and Feiss, 1979; Titley and Beane, 1981; Sillitoe and Gappe, 1984). Methods based on geochemistry of relatively unaltered plutons thought to be prospective for porphyry Cu-Au mineralisation were outlined by Kestler *et al.*, (1975), Feiss (1978), Mason (1978) and Mason and Feiss (1979) on the assumption that economic elements (generally Cu) were originally present in the melt. However, oxygen and hydrogen isotope data on alteration minerals from porphyry copper deposits (for example: Sheppard *et al.*, 1969 and 1971; Sheppard and Taylor, 1974) suggested that the water responsible for porphyry alteration had mixed magmatic/meteoric origins. The possibility was then raised that the metal source could exist in the meteoric water path-way, either within or without the pluton. Hydrogen isotopic data suggest that mixing of magmatic and meteoric waters occurred in the formation of sericite and kaolinite in the Yandera deposit (Chivas *et al.*, 1984).

Mason and Feiss (1979) applied to PNG intrusives Feiss' (1978) earlier theory that whole-rock $Al_2O_3/(Na_2O + K_2O + CaO)$ ratios could be used to distinguish potentially barren from potentially mineralised intrusions. High magmatic values of that ratio were linked with high Cu levels in octahedral sites because a high octahedral/tetrahedral site ratio is generally favoured by a high alumina to alkali ratio (Feiss, 1978). Mason and Feiss (1979) found that samples from 10 sites in PNG supported Feiss' (1978) findings. However, in the eastern highlands area (Figure 4d), that ratio does not apparently distinguish barren and mineralised intrusions. Our earlier mentioned empirical observation that low K_2O is apparently a feature of mineralised intrusives supports Mason and Feiss (1979).

CONCLUSION

At least two Neogene intrusive types can be distinguished in the eastern highlands of PNG on the basis of petrography, age, petrology and associated mineralisation. *Akuna*-type intrusives are generally large composite intrusive complexes displaying separate basic to acidic plutons. K-Ar and Rb-Sr cooling ages range from 18-12 Ma for *Akuna*-type intrusives as a whole and also within the Akuna Intrusive Complex itself. Little mineralisation is associated with *Akuna*-type intrusives. *Elandora*-type intrusives are generally smaller dykes or dyke swarms, which intrude *Akuna*-type intrusives. They are often conspicuously altered and are associated with precious metal (+ copper) mineralisation in adjacent country rocks. Magnetite-garnet exoskarns hosting Au-Ag mineralisation occur where *Elandora*-type intrusions occur within calcareous strata. Dated *Elandora*-type intrusions have Rb-Sr and K-Ar cooling ages ranging from 9-7 Ma.

The Mount Pugent syenite with nearly 12% total alkalies at 61% SiO_2 is geochemically distinct from both *Akuna*- and *Elandora*-type intrusions. Both the latter show calc-alkaline affinities but analysed *Elandora*-type intrusions show lower K_2O and much higher Sr than *Akuna*-type intrusions. Our empirical observations suggest that in the eastern highlands at least, barren and potentially mineralising intrusions corresponding to *Akuna*- and *Elandora*-types (respectively) can be distinguished on the basis of the latter possessing less than 2% K_2O and more than 700 ppm Sr at 60-70% SiO_2.

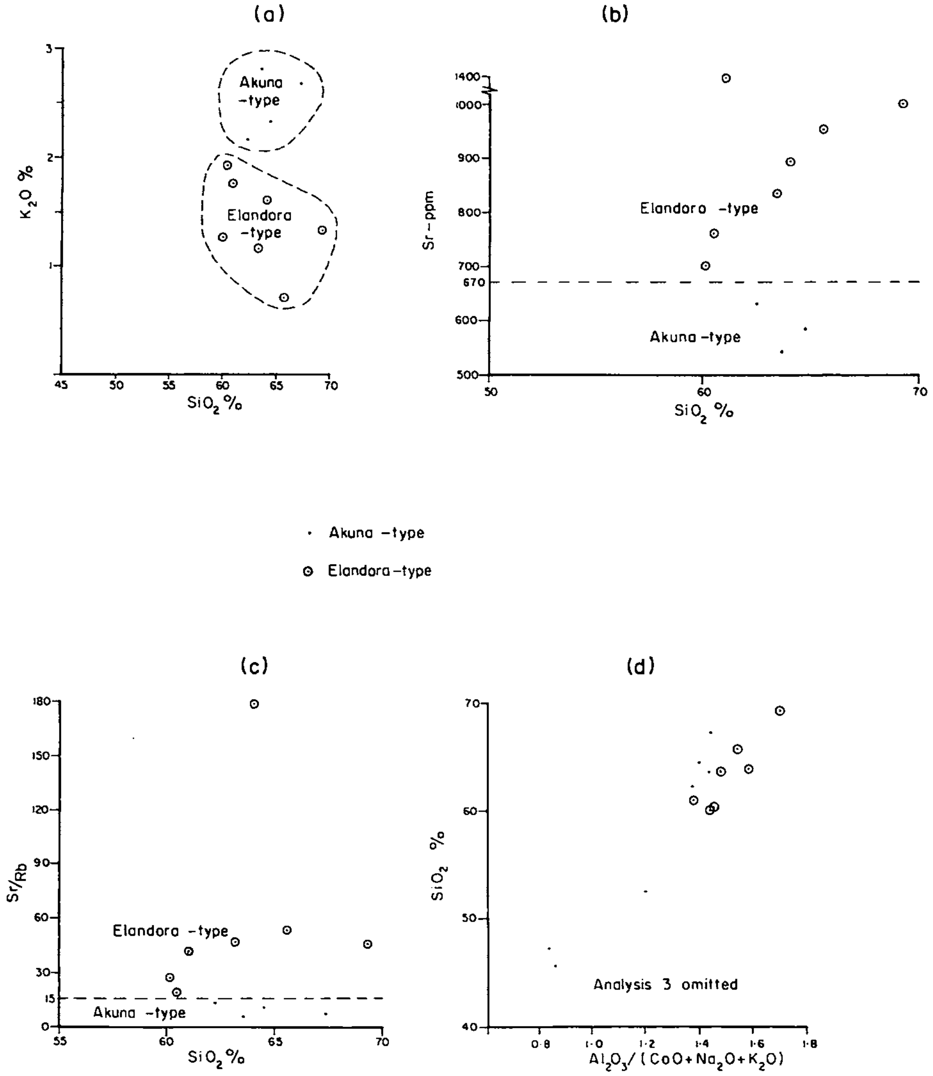

Fig. 4 Geochemical differentiation of *Akuna*-type and *Elandora*-type intrusions using Harker diagrams.

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APPENDIX

ANALYSIS DETAILS

Analysis 1. Hornblende gabbro. Rogerson *et al.*, 1982
2. Biotite-orthopyroxene-olivine gabbro. Rogerson *et al.*, 1982
3. Plagioclase-olivine pyroxenite. Rogerson *et al.*, 1982
4. Olivine dolerite. Rogerson *et al.*, 1982
5. Biotite-hornblende-quartz diorite. Rogerson *et al.*, 1982
6. Quartz monzodiorite. Watmuff, 1979
7. Granodiorite. Watmuff, 1979
8. Average of 13 (including 6 and 7 above) Bismarck Intrusive Complex rocks. Analyses 6 and 7 are the extremes of the analysed rock compositions. Watmuff, 1979.
9. Porphyritic biotite-hornblende-quartz microdiorite Rogerson *et al.*, (1982)
10. Porphyritic biotite-hornblende-quartz microdiorite Rogerson *et al.*, (1982)
11. "Older porphyry". Watmuff, 1979
12. "Intermediate porphyry". Watmuff, 1979
13. "Younger porphyry". Watmuff, 1979
14. Porphyritic hornblende diorite. Mason, 1975
15. Prophyritic hornblende diorite. Mason, 1975

Analytical methods

1-5, 9, 10	SiO_2, Al_2O_3, TiO_2, Fe_2O_3 (tot), MnO, MgO, CaO, Na_2O, K_2O, P_2O_5 by ICP FeO volumetric Cr, Sr, Zr, V, Ni, by ICP Rb, Y, Nb by XRF
6, 7, 8, 11, 12, 13	Major and trace elements by XRF FeO not stated
14, 15	Si_2O, TiO_2, Al_2O_3, Fe_2O_3 (tot), MnO, MgO, CaO, K_2O, P_2O_5 by XRF Na_2O by flame photometry FeO volumetric Trace elements by XRF