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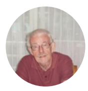

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Geological setting and styles of mineralization, north arm of Sulawesi, Indonesia

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Abstract—The north arm of Sulawesi consists of a Neogene island arc (North Sulawesi Arc) built upon Paleogene volcanic–sedimentary basement and underlain by oceanic crust, which is followed to the west by an arcuate, highly deformed terrane (neck of Sulawesi) characterized by metamorphic rocks and felsic granitoids belonging to the Sundaland continental margin. These two terranes have been contiguous during the Tertiary. The evolution of the North Sulawesi Arc is divided into two stages separated by collision of the north arm with the Sula Platform microcontinent in mid-Miocene time. During the Early Miocene a calc-alkaline andesitic arc developed in relation to west-directed subduction. Arc–continent collision resulted in back-arc thrusting, clockwise rotation of the north arm, and inception of subduction along the North Sulawesi Trench. Post-collisional magmatism in the North Sulawesi Arc produced felsic to mafic volcanic suites that are thought to be related primarily to rifting of the former arc rather than directly to subduction. In the neck of Sulawesi, LILE and LREE-element enriched, potassic granites (Dondo suite) of continental affinity (Sr^{87}/Sr^{86} 0.71) were generated.

The north arm of Sulawesi is comparatively well mineralized. Porphyry Cu–Au and porphyry Mo mineralization is approximately 2–4 Ma old based on preliminary K–Ar dating and geological relationships. The former developed in an oceanic terrane following collision-related arc reversal, whereas the latter developed in a continental terrane that underwent lower crustal melting during extension following the same collision. Porphyry Cu–Au mineralization in the North Sulawesi Arc is associated with clusters of small hornblende diorite or quartz diorite stocks, but the specific volcanic environment above these intrusions and their magmatic affinity remain unknown. Mineralization related to porphyry Cu–Au districts includes Cu–Au skarn, polymetallic vein and high sulphidation epithermal Au (+enargite). Porphyry Mo mineralization in the neck of Sulawesi is related to small stocks or roof apophyses of the Dondo batholith. Cogenetic granites are exposed over 5000 km^2 and are intruded in an arcuate belt, more than 400 km long, parallel to the Sula Platform collision zone. Unimodal felsic volcanics of Plio-Pleistocene age, which occur locally along the inner side of the north arm and further to the south, are probably the extrusive equivalents of the Dondo granites.

Epithermal Au mineralization (typically quartz–calcite veins ± adularia) is associated mainly with the Early Miocene andesitic arc but there are important exceptions, and in general the age of mineralization is poorly known. A district-wide correlation between epithermal Au mineralization and porphyry Cu–Au mineralization is not apparent. The most important epithermal Au district (Kotamobagu) is inferred to be associated with a long-lived volcanic center represented by the Moat caldera. Epithermal gold systems in the North Sulawesi Arc are generally eroded deeply, typically with chlorite–epidote wallrock alteration, and little is known about their associated volcanic environment.

In addition to high sulphidation Au mineralization related to porphyry systems, other styles and settings of Au mineralization in the north arm are exemplified by the Gunung Pani rhyolitic dome, the Patung diatreme breccia, the Mesel jasperiod, hosted partly by carbonate rocks, and sedimentary replacement Au-base metal mineralization at Doup. Diversity of mineralization in the north arm is further illustrated by VMS mineralization in volcanic basement to the Neogene arc, and by metamorphogenic quartz vein Au mineralization in the neck of Sulawesi.

INTRODUCTION

THE NORTH arm of Sulawesi is defined geographically as that part of the island extending north of 1° S. It encompasses the neck of Sulawesi and the North Sulawesi Arc (Fig. 1). Among Indonesian examples, this Neogene magmatic arc is comparatively well mineralized. Arc-related mineralization includes porphyry Cu–Au, porphyry Mo, volcanogenic massive sulphide Cu–Pb–Zn, magnetite skarn Cu–Au, epithermal Au of both high and low sulphidation type, and carbonate-hosted Au of possible Carlin-type. In addition, metamorphogenic Au is found in metamorphic basement rocks, west of the North Sulawesi Arc.

Between 1886 and 1931 the Dutch operated several hardrock gold mines (Fig. 2, Table 1), which in total produced 19.5 t of Au (Van der Ploeg 1945). Volcanogenic massive sulphide mineralization (VMS) was known from the turn of the 19th century (t'Hoen 1917). In the 1970s the region was the focus of extensive porphyry copper exploration, which led to the discovery of several subeconomic porphyry Cu–Au systems, a porphyry Mo deposit, and high sulphidation type Au (or Au-enargite) mineralization (Fig. 2; Trail *et al.* 1974, Taylor and Van Leeuwen 1980). In the early 1980s the old Dutch mining districts became the scene of a second Au rush by both local inhabitants and foreign mining companies. It is estimated that local miners have produced at least 10 t Au from Lanut, Mintu and Ratatotok, and 3 t Au from Taware ridge on Sangihe Island. The exploration activities of the foreign companies resulted in the identification of a number of prospects, some of which are close to mining feasibility (Table 2).

This study describes the general geology of the north arm of Sulawesi in plate tectonic terms. Mineral occurrences are listed and classified, and the styles of mineral-

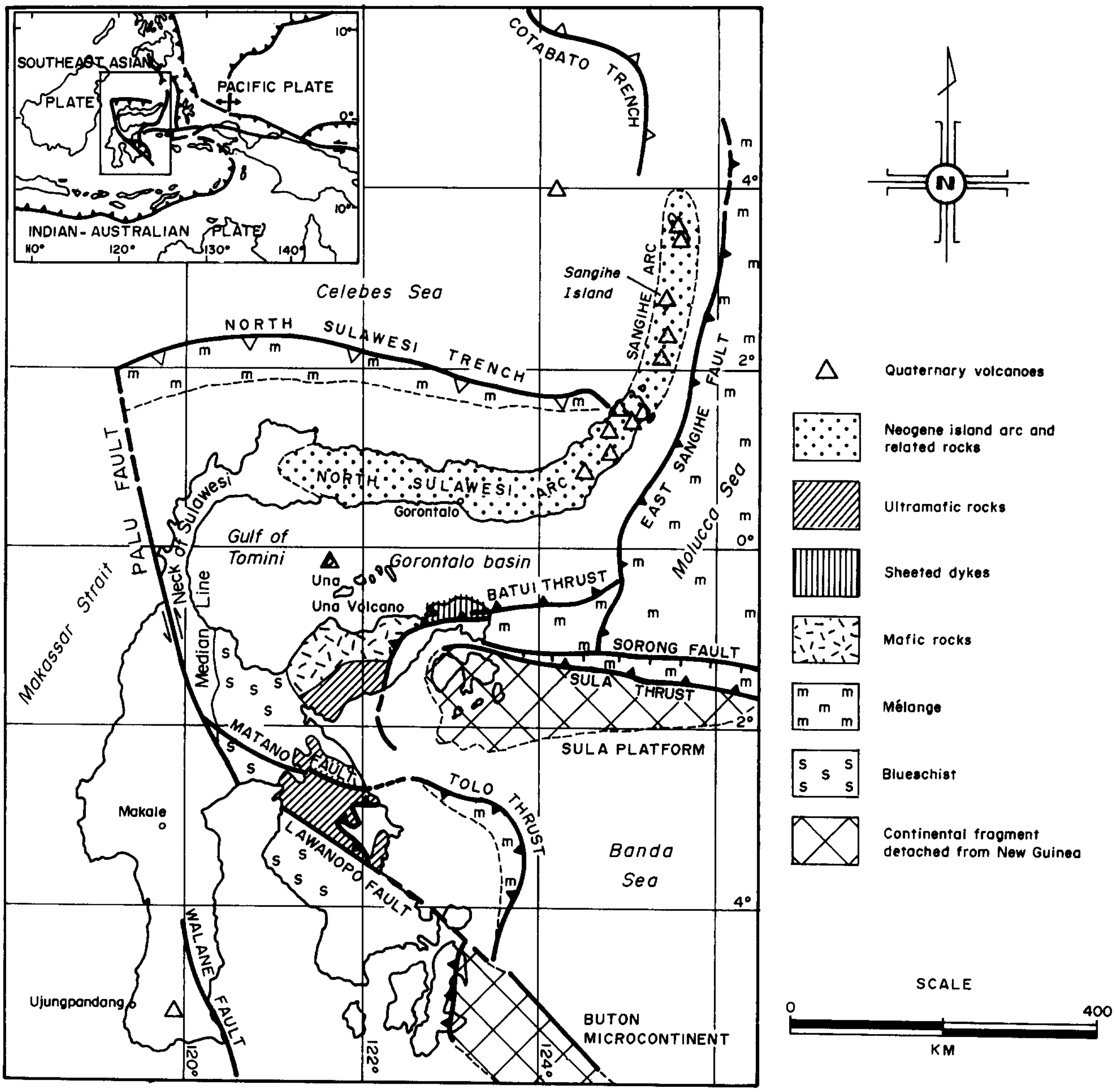

Fig. 1. Tectonic setting of the North Sulawesi Arc showing selected geology (after Hamilton 1979, Silver et al. 1983a). The north arm extends from 1° S and comprises the neck of Sulawesi and the North Sulawesi Arc. The inset shows the three mega plates which have contributed to the Cenozoic tectonic evolution of SE Asia.

ization are discussed with reference to the geological environments.

The geology of the north arm of Sulawesi has been reviewed using published 1:250,000 geological maps (Apandi 1977, Effendi 1972, Ratman 1976, Sukamto 1973, 1975), unpublished data on mineral exploration Blocks 2 (Trail et al. 1974) and 3 (Van Leeuwen 1980), literature, new data based on mapping by the authors, and data made available by exploration companies operating in the area. This has led to a compilation of a preliminary 1:1,000,000 scale map of the north arm of Sulawesi (unpublished), to complement a similar sheet to the south by Sukamto (1975). Prospects and mineral occurrences are from published and unpublished data, and are not claimed to be comprehensive. Many mineral occurrences of minor interest are omitted.

TECTONIC FRAMEWORK

The interaction of three mega plates, the Southeast Asian, Pacific and Indian–Australian plate (Fig. 1), has defined the Late Mesozoic–Cenozoic geological evolution of Eastern Indonesia (Hamilton 1979). During this period the eastern margin of the Southeast Asian plate (Sundaland) in Sulawesi was involved in at least three west-directed subduction events (polarity with respect to the present orientation of Sulawesi).

The earliest event is represented by Early Cretaceous (110 Ma) subduction complexes exposed near Ujung Pandang (Bantimala Mélange Complex) (Sukamto 1975, 1991, Hamilton 1979) and in Central Sulawesi near Lake Poso (Pompangeo Schist Complex) (Parkinson 1991). These rocks form the oldest basement in Sulawesi and may be correlatable with similar subduction complexes

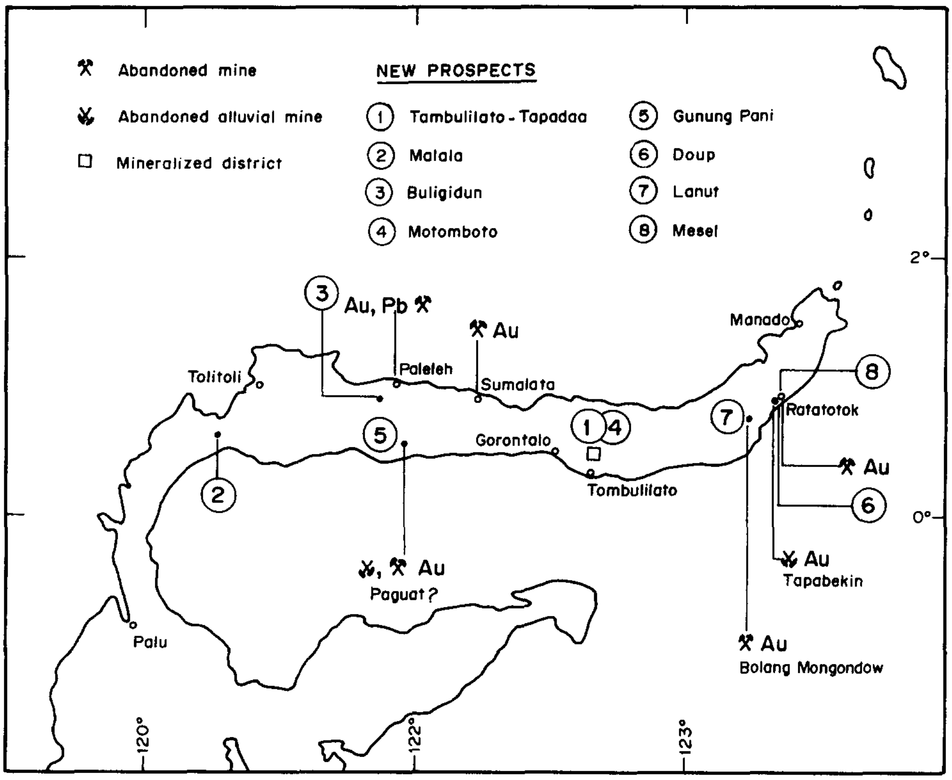

Fig. 2. Location of former gold, silver and base metal mines (Table 1), and newly discovered mineral resources (Table 2) in the north arm of Sulawesi.

in Eastern Kalimantan (Meratus Mts) and in Central Java (Luk Ulo Mélange Complex).

The second event is represented by blueschist and ophiolite complexes in Eastern Sulawesi (east and south-east arms). Blueschist metamorphism occurred during the mid-Oligocene (28–31 Ma) and was intimately related to ophiolite emplacement (Parkinson 1991, Helmers 1991). In Central Sulawesi blueschist and ophiolite mélange are thrust over the Early Cretaceous metamorphic basement, and Parkinson (1991) inferred they are products of east-directed subduction. In contrast Hamilton (1979), Helmers (1991), and Simandjuntak and Mubroto (1991) considered the subduction to be west-directed, a conclusion supported by this study. In the neck of Sulawesi basaltic and andesitic volcanics interbedded in the Tinombo Formation, which at least in part is of Eocene age (Brouwer 1947, Sukamto 1973), and numerous basaltic dykes of tholeiitic and calc-alkaline affinity (one of which was dated at 34.50 Ma; Priadi *et al.* 1991), which cut this formation and are considered by Sukamto (1973) to be coeval with the Tinombo volcanics, may be directly paired with this subduction event. Also probably related are Paleogene volcanics in southwest Sulawesi (Van Leeuwen 1981), felsic granitoids (29.9–31.0 Ma) near Palu and further to the south in Central Sulawesi (Priadi *et al.* 1991), and Paleogene volcanic and sedimentary rocks of the North Sulawesi Arc, which are of tholeiitic and calc-alkaline affinity (discussed below) and contemporaneous with the Tinombo Formation. The rift separation of Sulawesi from Kalimantan along the Makassar Strait also occurred at this time (Situmorang 1982).

The third event is represented by Lower Miocene calc-alkaline magmatic rocks in the north arm of Sulawesi. The related subduction was terminated south of the northern tip of Sulawesi by collision of the arc with the Sula Platform microcontinent in the mid-Miocene (Kundig 1956, Katili 1978, Hamilton 1979,

Table 1. Pre-World War gold, silver and base-metal production North Sulawesi (mine locations shown on Fig. 2)

Mine or prospect	Date	Production	Reference
Sumalata	1896–1908	1402 kg Au, 155 kg Ag	†
Totok‡	1900–1921	5060 kg Au, 19,267 kg Ag	†
Paleleh	1896–1929	8152 kg Au, 5419 kg Ag, 550 t Pb	†
Bolang Mongondou‖	1913–1931	4962 kg Au, 3989 kg Ag	†
Panguat concession¶	1912–1913	1 kg Au, 0.5 kg Ag	*
Tapabekin concession§	1938–1941	68 kg Au, 23 kg Ag	†

* Van Bemmelen (1970).
† Van der Ploeg (1945).
‡ Now known as Ratatotok.
‖ Now known as the Lanut mining area, and Mintu.
¶ Possibly the G. Pani prospect near Marisa.
§ Alluvial workings near Kotabunan.

Table 2. Mine resource estimates for advanced projects (locations shown on Fig. 2)

Project	Coordinates**	Crude ore (millions of tonnes)		Mo (%)	Cu (%)	Au (g/t)	Reference
Tombulilato	123°20′ E, 0°25′ N						
Cabang Kiri		Indicated	102		0.45	0.54	*
		Inferred	34		0.38	0.71	
Sungai Mak		Indicated	84		0.76	0.39	
Kayubulan		Inferred	75		0.62	0.33	
Total			295		0.57	0.46	
Tapadaa	123°12′ E, 0°33′ N	Inferred	4		0.4 oxide	0.065	§
			20		0.7 enriched	0.070	
			19		0.4 sulphide	0.086	
Total			43		0.54	0.074	
Buligidun	121°46′ E, 0°58′ N	Inferred	20		0.7		‡
Motomboto	123°17′ E, 0°28′ N	No resource calculated				High grade Au in enargite	‡
Malala	120°31′ E, 0°38′ N	Inferred	100	0.08			†
Gunung Pani	121°57′ E, 0°34′ N	Inferred	30			1+	‡
		Including	1.3			3+	
Doup	124°38′ E, 0°50′ N	Inferred	12			1.6	‖
Lanut	124°30′ E, 0°44′ N	Inferred	19			1.4	‖
Mesel	124°39′ E, 0°55′ N	Undisclosed Au resource					¶

* Utah International Inc., unpub. report by N. Schofield (1982).
† Van Leeuwen (1992).
‡ BHP–Utah Pacific Inc., unpub. data.
‖ Placer Dome Inc., unpub. data.
¶ Newmont Indonesta Ltd, J. Dow (pers. commun. 1991).
§ Kennecott Explorations Australia Ltd, unpub. data.
** Coordinates with respect to published 1:250,000 geological map sheets.

Silver *et al.* 1983a, b; Figs 1 and 4). This collision greatly modified the tectonics and subsequent magmatic history of Sulawesi.

The Sula Platform collision led to the reversal of subduction of the North Sulawesi Trench, clockwise rotation of the north arm (Hamilton 1979, Sasajima *et al.* 1980, Otofuji *et al.* 1981, Silver *et al.* 1983a, b) and Upper Miocene–Pliocene potassic–granite magmatism in the neck of Sulawesi (described below). In the east arm the East Sulawesi Ophiolite was thrust over the Sula Platform along the Batui Thrust (Fig. 1), and in eastern Central Sulawesi Lower Miocene oceanic rocks (Lamasi Volcanics) of MORB-like affinity were thrust together with continental shelf sediments (Toraja Formation) on to Western Sulawesi (Priadi *et al.* 1991).

Post-collision volcanicity along the North Sulawesi Arc is inferred to be related to rifting of the former arc, rather than directly to subduction along the North Sulawesi Trench. The active Una Una volcano in the Gulf of Tomini is believed to be rift-related (Cardwell and Isacks 1981; Fig. 1), but it is unclear to which subduction system it belongs (Hamilton 1979). Quaternary volcanicity at the north tip of Sulawesi and in the Sangihe Arc is related to west-directed subduction of the Molucca Sea plate.

The north arm of Sulawesi comprises two tectonic terranes based on the nature of pre-Tertiary basement (Taylor and Van Leeuwen 1980): (1) the Neogene North Sulawesi Arc, underlain by Paleogene arc assemblages and oceanic crust (possibly corresponding to the Celebes Sea plate), and (2) the neck of Sulawesi, characterized by metamorphic rocks belonging to the Sundaland continental margin. These two terranes are inferred to have been contiguous during the Tertiary based on the abovementioned correlation of Paleogene arc assemblages. To what extent continental rocks underlie the western margin of the North Sulawesi Arc is unclear, although it is suggested in the following text that the distribution of unimodal felsic, K-rich igneous rocks may be a guide.

BASEMENT OF THE NORTH ARM OF SULAWESI

North Sulawesi Arc

Geophysical studies (Silver *et al.* 1983a) show that oceanic crust underlies the Gorontalo basin (fore-arc margin), and therefore also likely underlies the north arm in this region. The exposed basement (Fig. 3) is composed of Eocene to (?)Oligocene submarine basalt, basaltic andesite, greywacke, shale, and minor limestone. All lithologies are considered to have formed in an oceanic island arc environment. Petrography by Trail *et al.* (1974) and this study suggest the basement volcanics may include calc-alkaline and tholeiitic rock suites. Limited radiometric dating of tholeiitic basalt from North Sulawesi by Villeneuve *et al.* (1990) indicates an age of about 50 Ma (Eocene).

Basic to andesitic submarine lavas, including pillow lavas with associated red pelagic sediments, predominate between 121° E and Gorontalo. According to Trail *et al.* (1974) these rocks are overlain by andesitic epiclastics and Lower Miocene volcanics. Near Kotamobagu, greywackes as well as submarine lavas and red siltstones are found.

Basement rocks east of Moutong and near Kotamobagu are highly deformed, and trend approximately east–west or parallel to the arc, and possess vertical dips. This deformation predates at least partly the Neogene arc, but it is uncertain to what it may be related. Possibilities include: deformation related to blueschist metamorphism and obduction of the East Sulawesi Ophiolite in the east arm or, more likely, inception of the subduction which generated the Early Miocene arc. The transformation of the Celebes Sea to a marginal basin at 23.4 Ma (Huang *et al.* 1991) may have occurred at roughly the same time.

Neck of Sulawesi

Low to medium-pressure, high-temperature (LP–HT), prograde metamorphic rocks, from chlorite zone to staurolite–kyanite zone (Egler 1947, Helmers *et al.* 1990) outcrop at the neck of Sulawesi (Fig. 3). Lithologically they may be divided into metapelites–psammites, metabasites and minor marble, corresponding probably to shallow marine turbidites with intercalated basic volcanics. Near Moutong, granitoids metamorphosed to greenschists are also found. In the neck of Sulawesi the high-grade metamorphics are enclosed by highly folded, weakly metamorphosed greywacke, shale and minor intercalated basic volcanics and limestone (Tinombo Formation; Alburg 1913), of Upper Cretaceous to Eocene age (Brouwer 1947, Sukamto 1973) and intruded by large volumes of Upper Miocene–Pliocene granites (Dondo suite).

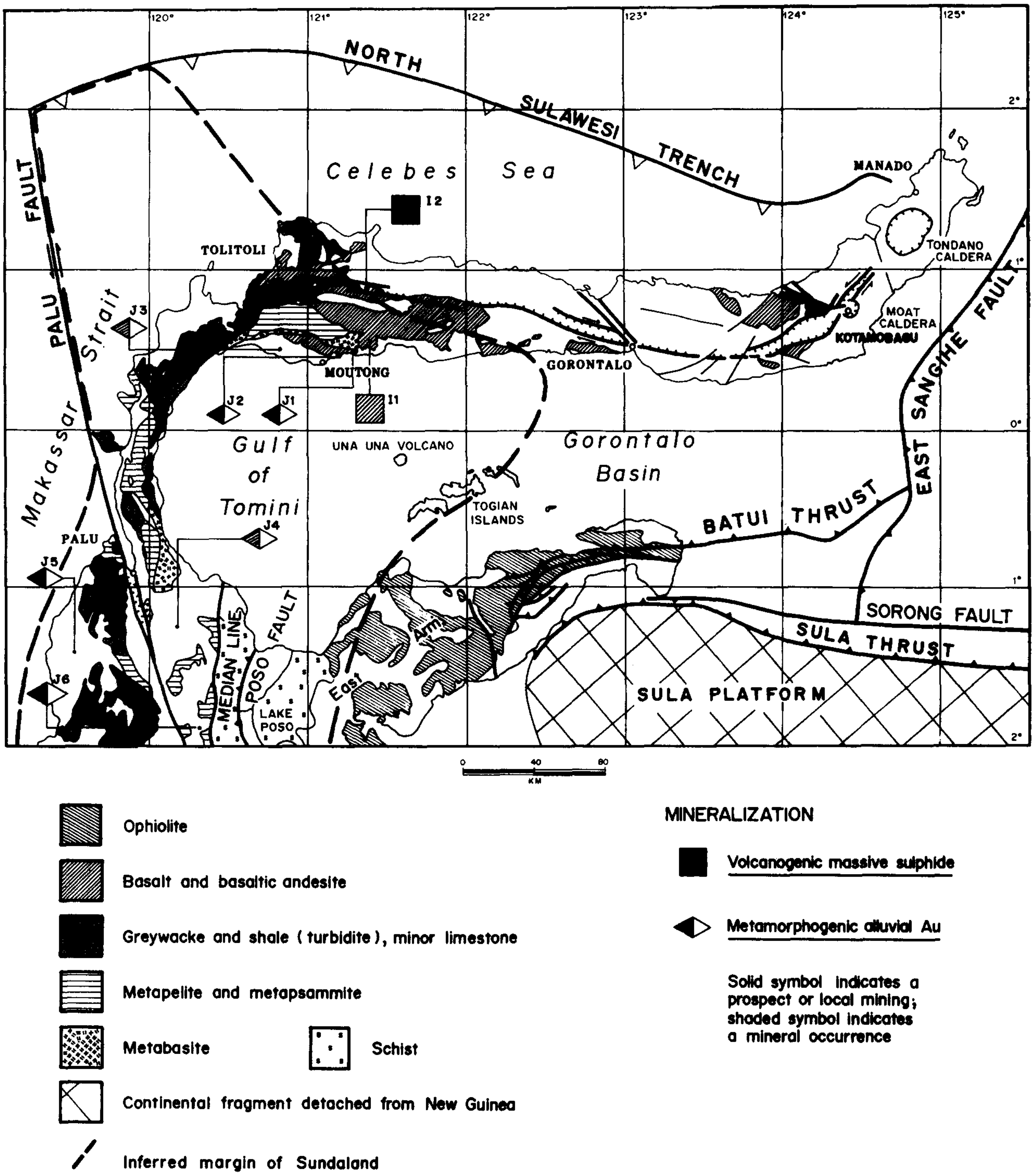

Fig. 3. Basement rocks to the North Sulawesi Arc. Neogene rocks are omitted for clarity.

The geological relationships of the metamorphic rocks in the north arm are poorly understood. At Moutong greenschist-facies metamorphic rocks marginal to the Malino metamorphic complex (informal name) are shown to be transitional to the Eocene–(?)Oligocene basaltic andesite basement (I.K., unpub. data). This relationship may be interpreted in several ways: (1) the Malino metamorphic complex is of post-Oligocene age, and not a window of older basement, or more likely (2) the greenschist rocks represent a ductile shear zone (detachment fault) to older rocks comprising a metamorphic core complex. Regional maps (Ratman 1976) show that greenschists form a discontinuous selvage around the Malino complex. It is therefore suggested that metamorphic core complexes may be a consequence of the Sula Platform collision in the north arm of Sulawesi. In this context, it should be noted that garnet peridotite and granulite facies rocks have been found near Palu. The garnet peridotite is derived from underlying mantle at a depth of about 60 km (Helmers *et al.* 1990).

NORTH SULAWESI ARC

The North Sulawesi Arc, defined primarily on the basis of distribution of Lower Miocene arc-related rocks (Figs 4 and 5a), extends for about 500 km onshore, from 121° E to 125°20′ E, and has a relatively constant width of 50–70 km, with elevations up to 2065 m. Higher elevations up to 3225 m are present at the neck of Sulawesi.

The evolution of the North Sulawesi Arc may be divided into two main stages, with respect to the mid-Miocene collision of the arc with the Sula Platform: (1) west-directed subduction during the Early Miocene, and (2) post-collisional rifting and uplift of the arc, and inception of subduction along the North Sulawesi

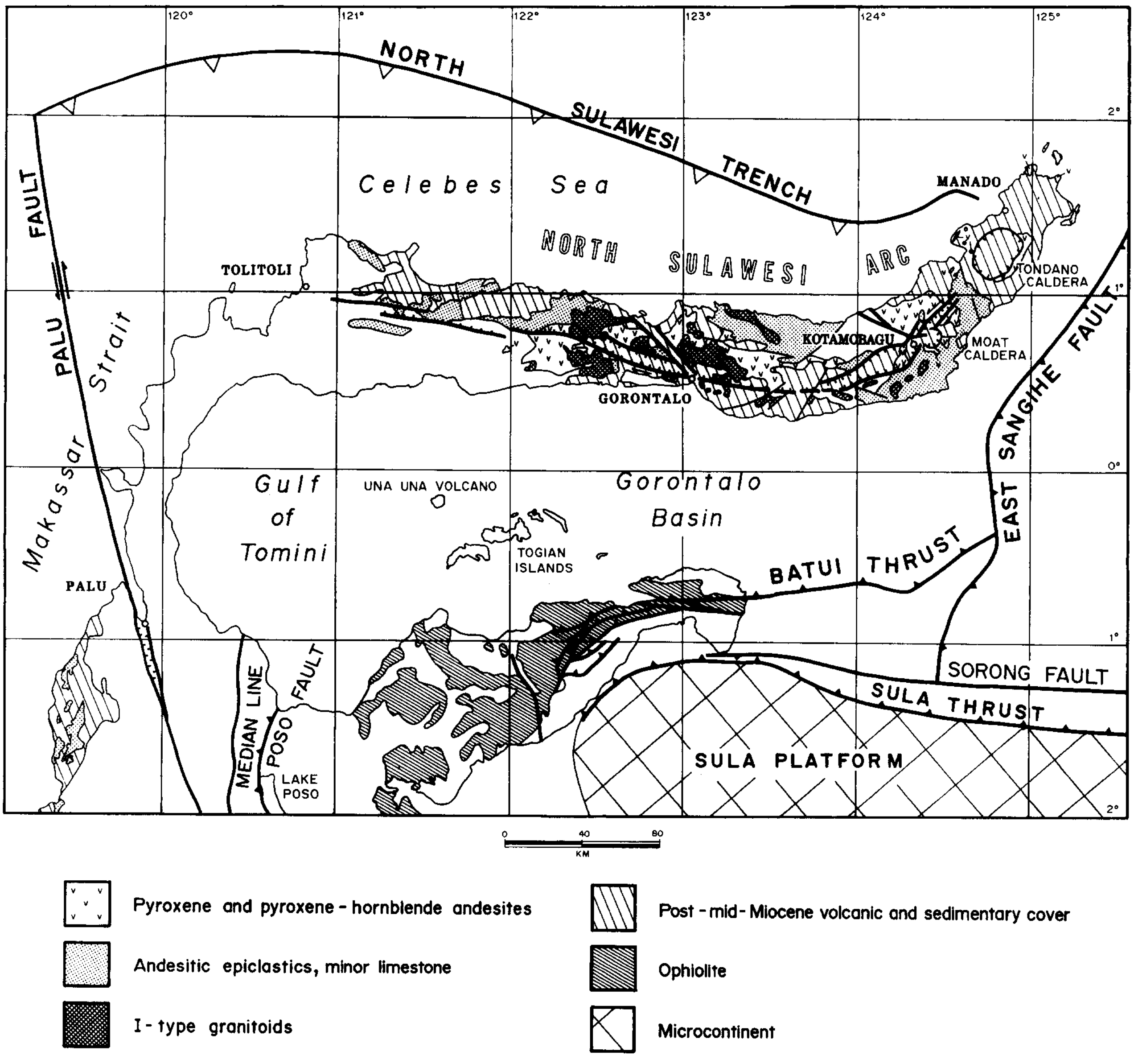

Fig. 4. The Neogene North Sulawesi Arc. Basement rocks are omitted for clarity. Also shown are certain geological features of the surrounding area.

Trench during the Late Miocene to Quaternary. Geological relationships, paleontology (summarized on published 1:250,000 maps) and preliminary K–Ar dating (Lowder and Dow 1978, Villeneuve *et al.* 1990, Perello 1992, Priadi, pers. commun. 1991) suggest two main periods of magmatic activity during the Neogene and Quaternary, namely, 22–16 Ma (Early Miocene) and younger than 9 Ma (Late Miocene–Quaternary), i.e. pre- and post-collision of the arc with the Sula Platform.

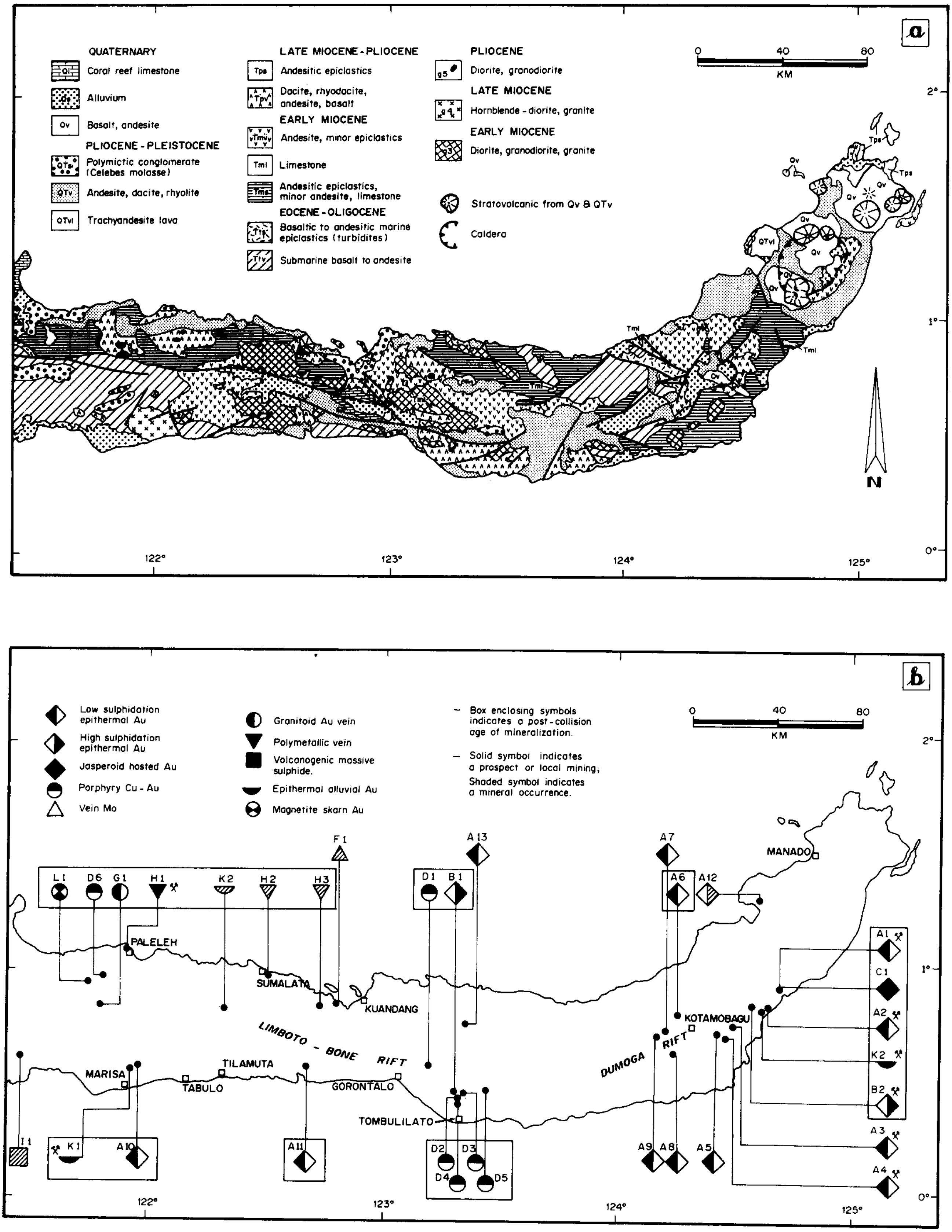

Fig. 5. Geology (a) and mineral occurrences (b) of the north arm of Sulawesi east of 121° E.

Pliocene and active Quaternary volcanicity belonging to the Sangihe Arc (Fig. 1) conceals much of the Early Miocene geology near Manado (Fig. 4). Small exposures of andesite and diorite below Quaternary volcanic cover on the Sangihe islands, north of Manado, suggest that older arc volcanics continue offshore, possibly to Mindanao (Fig. 1), and form the basement to the present-day Sangihe Arc.

Neogene arc-related volcanic rocks are absent between Tolitoli and Palu in the neck of Sulawesi (Fig. 4), partly due to high uplift rates and deep erosion. Lower Miocene granitoids are not known, and there seems to be little evidence that the Early Miocene arc extended into the neck. Despite this, it is still inferred that the Early Miocene Benioff zone extended beneath the neck, and south to an intersection with the paleo-Palu–Matano transform fault (Fig. 1). In Western Sulawesi, south of Makale (Fig. 1), potassic alkaline (or shoshonitic) magmatism related to rifting rather than subduction was dominant during the Neogene (Yuwono *et al.* 1985, Leterrier *et al.* 1990, Priadi *et al.* 1991).

The Early Miocene arc

The Early Miocene arc comprises typical calc-alkaline volcanics and shallow marine sedimentary rocks, mainly pyroxene andesite, pyroxene-hornblende andesite basalt, andesitic greywacke and minor limestone. Co-magmatic granitoids (g3; Table 3 and Fig. 6) are typically fine- to medium-grained and vary in composition from diorite to granite. Mineralogically they correspond to the I-type granitoids of Chappell and White (1974).

This arc may have developed in an environment similar to the present day Sangihe arc (Hamilton 1979), that is, initially as a chain of partly submarine stratovolcanoes. This interpretation is supported by the general stratigraphy (Table 4) observed near Gorontalo and Kotamobagu, where shallow- to deep-water marine sedimentary rocks including carbonates are overlain by, and intercalated with, andesitic volcanics.

On the north coast, marine sedimentary rocks are typically turbidites and are moderately to strongly folded subparallel to the arc. Inland, near Sumalata, subvertical turbidites (Dolokapa Formation after Molengraaf, Vide Rutten 1927) trend N 120 E and N 60 E, young to the south, and are overlain conformably by a polymictic conglomerate that contains granitoid clasts derived from contemporaneous erosion of the Early Miocene arc.

The Early Miocene arc is deeply eroded, and partly covered by younger rocks. Erosion to a deep level is indicated by the extensive exposure of granitoids (g3) constituting some of the highest mountains near Gorontalo. These plutons have dimensions comparable to the Tondano Caldera (Fig. 3), and during the Early Miocene a similar but largely removed volcanic superstructure above these granitoids may be envisaged. Near Kotamobagu, the Early Miocene volcanics form a flat-topped volcanic field centered mainly on the Moat caldera (Fig. 3), a possible long-lived volcanic centre located on major graben faults (Dumoga Rift) parallel to the arc.

The effect of collision with the Sula Platform on the Early Miocene arc, apart from uplift, is not understood. The strong deformation of the Dolokapa Formation on the north coast is related tentatively to the inception of subduction by back-arc thrusting at the North Sulawesi Trench. In the Kotamobagu area, Early Miocene marine

Table 3. Characteristics of granitoid suites shown on Fig. 6

Suite	Distribution	Composition	Age	Comment
g1	121°E to 124°15′ E	Diorite or gabbro	Paleogene	Too small to be shown on maps. Small bodies related to Paleogene basic volcanics.
g2	Small body west of Palu	Hornblende–biotite granodiorite (Sukamto 1975)	mid-Oligocene 31.0 Ma	
g3	121°20′ E to 124°25′ E	Diorite, granodiorite and granite Hornblende is the main ferromagnesian phase. Syenite recorded near Molosipat (Ratman 1976) is tentatively included	Early Miocene *Bone diorite*; 16 Ma (Lowder and Dow 1978)	Assumed to be co-genetic with Early Miocene calc-alkaline volcanics.
g4	South coast near Marisa and at Tilamuta	Hornblende–biotite granodiorite	Late Miocene	Assumed to be co-genetic with the Pani Volcanics.
g5	121°E to 124°E	Quartz diorite	Pliocene	Small stocks on the north coast west of Kuandang, and in the Tombulilato district.
g6	From 121°15′ E, along the neck of Sulawesi, west of the Median Line to at least Palopo	Porphyritic biotite granite	Upper Miocene–Pliocene *Dondo granite suite* (Priadi *et al.* 1991, OTCA 1971, Van Leeuwen 1992)	Mineralogically coherent suite characterized by plagioclase and K-feldspar crystals up to 5 cm, and biotite.

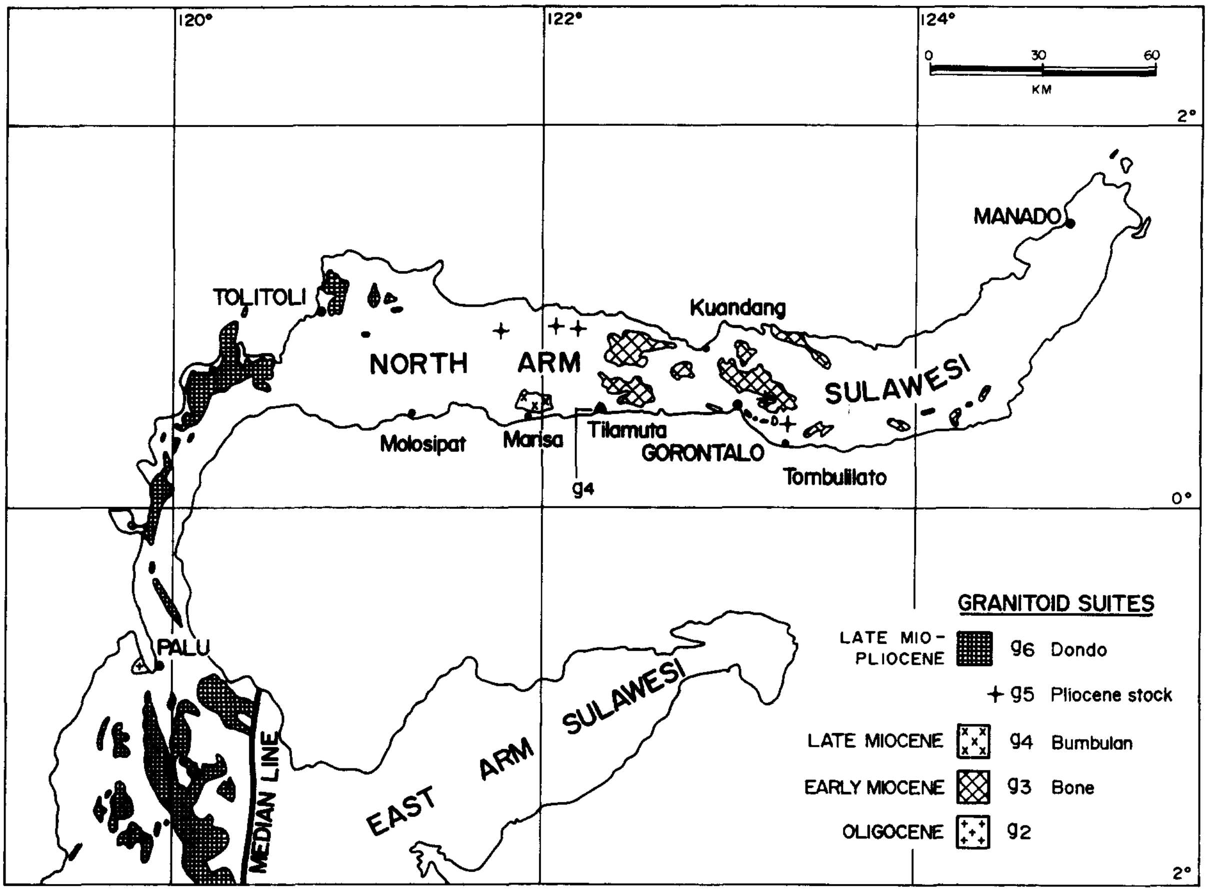

Fig. 6. Distribution of granitoids in the north arm of Sulawesi.

sedimentary rocks are less deformed, but are folded in several directions.

Post-collision volcanicity

Post-collision magmatism involving the neck of Sulawesi is described separately. However, along the south coast of the north arm, there are poorly studied igneous rocks that may belong to either the North Sulawesi Arc or to the neck, i.e. island arc vs continental margin affinity.

In the North Sulawesi Arc post-collision volcanicity (Fig. 7) is not well known, but believed to be typified by felsic to mafic volcanic suites related to major rifting of the arc, uplift and caldera formation. Extensional structures parallel to the North Sulawesi Trench are traced from near Kotamobagu to Gorontalo, and west almost to Tolitoli. However, although the rifting may be related to the North Sulawesi Trench, magmatism is not necessarily related to subduction of the Celebes Sea plate (see below).

Two major Plio-Quaternary calderas are present in NE Sulawesi at Kotamobagu (Moat caldera) and Tondano (Fig. 3). Magmatism there is related to the East Sangihe subduction system (Fig. 1), but is likely also to be controlled by rifting of the Early Miocene arc leading to unroofing of high-level and differentiated magma chambers. Ignimbrites from the Tondano caldera are andesitic, but subsequent and still active volcanicity located on the caldera margin includes olivine basalts (Lokon and Soputan), which must be tapped from a deep source. The Moat caldera is characterized by extracaldera dacitic ignimbrites and intracaldera Quaternary hornblende andesite domes. Both calderas have associated hot springs and fumarolic activity.

In the Gorontalo–Kotamobagu area, (?)Upper Miocene to Pliocene volcanics include basalt, andesite and dacite or rhyolite. North of Tombulilato (Fig. 5), intermediate and basic volcanics are overlain by rhyolite, and intruded by small stocks of quartz diorite with associated porphyry Cu–Au mineralization. North-directed thrusting is identified in the Tombulilato area

Table 4. Details of Early Miocene sedimentary–volcanic stratigraphic sections

Locality	Coordinates	Description
Bolangitang river	123°20′ E, 0°45′ N	Green shale, siltstone and interbedded andesitic pyroclastics are overlain conformably by pyroxene andesite lava in excess of 300 m in thickness, striking N 60 E and dipping southwest.
Lanut	124°37′ E, 0°38′ N	Shallow-dipping shale and andesitic sandstone with thin intercalated andesitic and basaltic volcanics and limestone are overlain by pyroxene–hornblende andesite lava 300 m thick.
Lobong	123°15′ E, 0°46′ N	Red and black shales, greywacke, conglomerate, sandstone and limestone are overlain by massive andesitic volcanics.

(Perello 1992). This deformation is related to the Sula Platform collision and ongoing convergence on the Batui Thrust (Fig. 1) (Silver *et al.* 1983a). Plio-Pleistocene volcanics (Pinogu volcanics of Trail *et al.* 1974) fill the Limboto–Bone Rift (Fig. 5), east and west of Gorontalo; they include basalt, dacite and rhyolite. The felsic volcanics are characterized by the presence of biotite and hornblende phenocrysts.

Mineralogically similar but unimodal felsic volcanics of Plio-Pleistocene age occur intermittently along the inner side of the north arm, most notably between Molosipat and Tilamuta, and near Ongka, and in the Palu valley (Gimpu), and at Una Una in the Gulf of Tomini (Fig. 7). In addition, Quaternary biotite–hornblende rhyolitic ignimbrites (Barupu Tuff) are present further to the south in Central Sulawesi, near Makale (Fig. 1).

Between Molosipat and Tilamuta, Paleogene basaltic andesite basement is intruded intensively by felsic dykes, commonly trending N 120 E and N 60 E. A felsic ring dyke complex, 10 km in diameter, is located near Tilamuta (Kavalieris 1984). The ring dyke is mineralogically and geochemically correlated with the Pani Volcanic Complex (after Trail *et al.* 1974), located 35 km to the west near Marisa. This complex is an eroded volcanic center, about 3.5 km in diameter, consisting of rhyodacitic pyroclastics and lavas, which hosts low-grade epithermal gold mineralization (Kavalieris 1984,

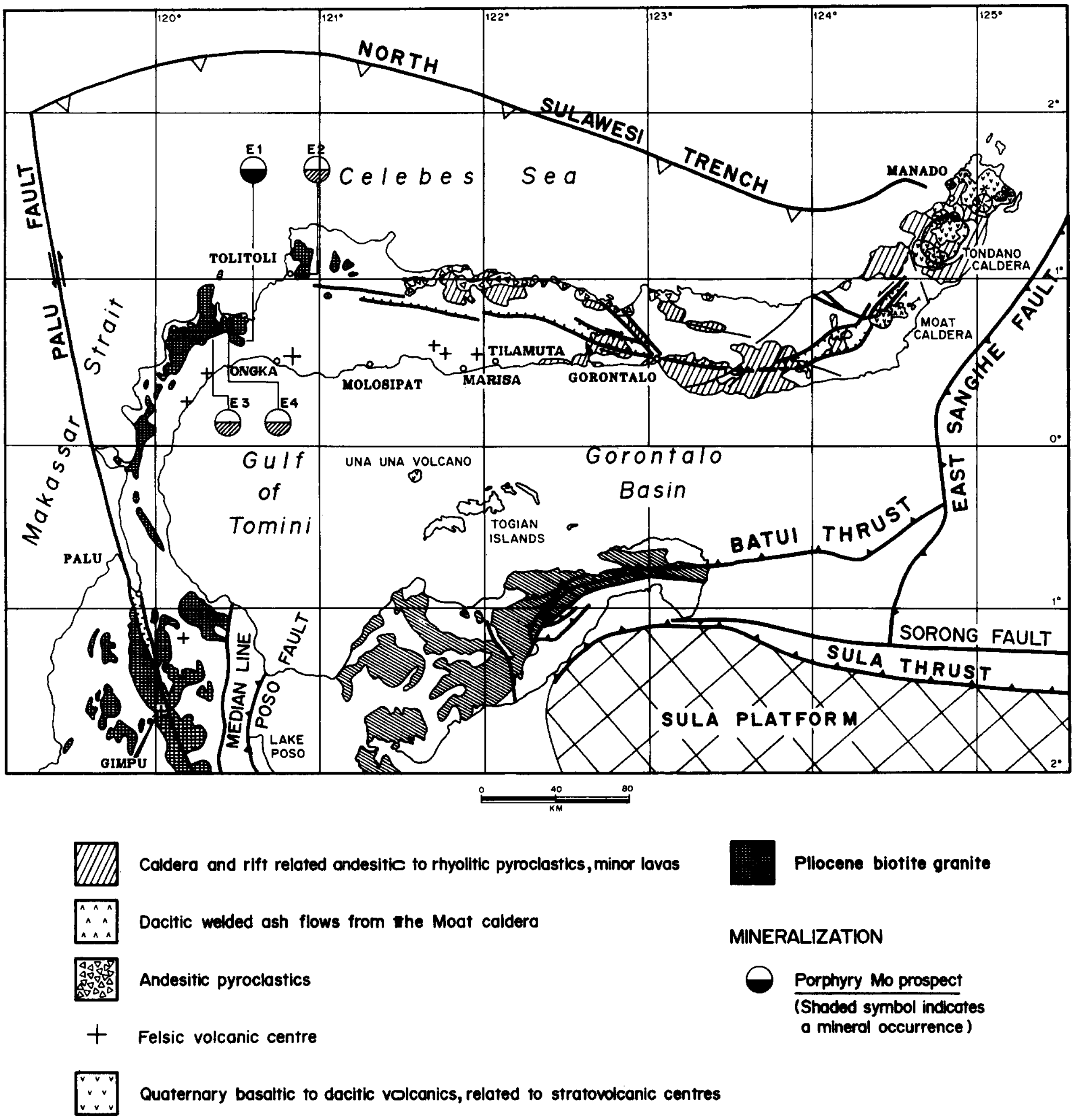

Fig. 7. Distribution of Upper Miocene–Pliocene granites belonging to the Dondo suite, and post-collision volcanics. Older rocks are omitted for clarity.

Kavalieris *et al.* 1990). At Ongka similar volcanics overlie basaltic and metamorphic basement, covering an area of about 220 km^2.

The unimodal felsic volcanics may have a different origin from those found in association with intermediate and basic volcanics in the North Sulawesi Arc. Their distribution along the inner side of the north arm and extending into Central Sulawesi suggests: (1) a relationship to an Early Miocene Benioff zone, although subduction had ceased prior to their emplacement, and (2) that this area, including the Gulf of Tomini (Una Una) is underlain by Sundaland continental margin (Fig. 3).

In contrast to felsic volcanics on the south coast, Pliocene andesitic pyroclastics (Wobudu Breccia, Trail *et al.* 1974) are dominant on the north coast of Sulawesi, between 121°30′ E and 123°30′ E. The Wobudu Breccia overlies unconformably highly folded Lower Miocene turbidites and mainly caps high ranges along the north coast. Remnants of stratovolcanoes are present to the west of Kuandang (Fig. 5). Widespread dioritic stocks and dykes on the north coast are considered to be comagmatic with the Wobudu Breccia.

The age of massive andesitic volcanics, inland from Paleleh (Fig. 5), is uncertain; they may correlate with Lower Miocene volcanics in the upper Paguyaman valley or may be part of a younger volcanic sequence (Fig. 7).

PLIOCENE MAGMATISM IN THE NECK OF SULAWESI

The Dondo suite (informal name) comprises mineralogically and texturally uniform biotite granites (g6, Table 3) lacking basic or intermediate end members and characterized by porphyritic textures with K-feldspar phenocrysts up to 5 cm in length. This suite extends in a 400 km long arcuate belt around the neck of Sulawesi to near Tolitoli (Fig. 7). K–Ar dating indicates that these granites are Upper Miocene–Pliocene (Priadi *et al.* 1991, Van Leeuwen 1992, OTCA 1971), that is, post-collision with the Sula Platform.

Van Leeuwen (1992) has shown that geochemically these granites correspond to I-type granitoids (Chappell and White 1974), are compatible with orogenic magmas from continental–margin settings (Ewart 1979), and show a number of features typical of post-collision granitoids. The granites are characteristically potassium-rich, are enriched in large ion lithophile elements (LILE), K, Rb, Sr, Ba, and light rare earth elements (LREE), as well as being characterized by high initial Sr^{86}/Sr^{87} ratios (0.71). The general lack of strong foliation, and minimal displacement of these granites along the active Palu Fault suggest the granites were emplaced after rotation of the north arm. They are inferred to be generated from lower crustal igneous sources by anatexis following collision of the Sula Platform and cessation of subduction.

The previous importance of co-magmatic volcanics cannot be assessed because the neck is deeply eroded. However, similarities in mineralogical and chemical characteristics between the Dondo suite and the felsic volcanics at Pani (Kavalieris 1984), Ongka (Van Leeuwen, unpub. data), Gimpu and Makale (Priadi *et al.* 1991) suggest that felsic pyroclastic volcanicity may have been widespread. This interpretation is supported by the presence of felsic dykes cutting Dondo granites at Malala (Van Leeuwen 1992) and the occurrence of a few isolated rhyodacite outcrops along the east coast of the neck.

PLIOCENE–QUATERNARY EXTENSION AND UPLIFT

Post-collisional uplift and erosion of the North Sulawesi Arc resulted in coarse polymictic conglomerates (Celebes Molasse; Sarasin and Sarasin 1901) that fringe parts of the coast and cap ridge crests up to 500 m in elevation (Fig. 5a). Lacustrine and fluvial deposits of similar age fill axial rift valleys southeast of Tolitoli. Although the Celebes Molasse possibly dates from mid-Miocene in the Palu area (Sukamto 1973), much of the molasse sedimentation associated with erosion of the North Sulawesi Arc probably took place during Late Pliocene–Quaternary time. Rapid uplift at 2 Ma is recorded by an increased sedimentation rate in the Celebes Sea (Huang *et al.* 1991). The Gulf of Tomini and Gorontalo basin (Fig. 1) have water depths up to 5 km and contain 3–4 km of sedimentary fill, much of which may be Quaternary (Hamilton 1979). Uplift in the Palu Fault valley is 4.5 mm/yr (Tjia 1981). At Gorontalo, Lake Limboto, now a shallow swamp, was once connected to the sea in the 16th century and provided port facilities as shown by ruins of Portuguese harbor fortifications.

Preserved remnants of the Celebes Molasse and Quaternary reefal limestone up to 500–1000 m elevation in the north arm (Rutten 1927) suggest Pliocene–Quaternary uplift of at least that order. Uplift of several kilometers is suggested for the neck. The high uplift rate, especially in the Palu area, resulted in increased geothermal gradients with related hot-spring activity along major faults.

MINERALIZATION

Mineral occurrences are listed in Table 5 and shown on Figs 3, 5b and 7. The styles of mineralization are denoted by letter codes and symbols. Prospect names and letter codes are used in the text that follows. Most mineral occurrences, with the possible exception of VMS mineralization and metamorphogenic gold, are Neogenic in age. The mineralization is classified with respect to pre- and post-collisional magmatic events (Fig. 5b), but due to a lack of radiometric dates this convention must be regarded as tentative.

Epithermal Au mineralization (Fig. 5b)

Epithermal Au mineralization of low sulphidation type (Hedenquist 1987) is hosted mainly by Lower Miocene andesitic volcanics, and in several cases (A2 and

Table 5. Summary of prospects and mineral occurrences in North Sulawesi (excluding Sangihe Island)

Map Ref.	Name	Status[1]	Mineralization[2]	Description	Reference
Code A: Low sulphidation epithermal Au					
A1	Ratatotok	X, P	Au, (Ag)	Quartz veins in limestone and palaeokarst breccia fill.	¶
A2	Doup	P	Au, (Ag, Cu, Pb, Zn)	Quartz–rhodochrosite–base metal veins, and quartz–pyrite stockwork. Base metal-Au replacement mineralization in sedimentary rocks.	*
A3	Mintu	X	Au, (Ag)	Quartz veins.	*
A4	Lanut	X	Au, (Ag)	Quartz veins and stockwork.	*
A5	Tobongan	P	Au, (Ag)	Quartz veins.	*
A6	Lobong	P	Au, As, Hg	Active hot spring with solfataric alteration, calcite veins, minor chalcedonic quartz veins, and stockwork in limestone and sedimentary rocks.	*
A7	Patung	P	Au, (Ag)	Gold mineralization in structures, minor quartz–Mn calcite veins, breccia dykes and mineralized breccia clasts. Hosted by diatreme breccia.	*
A8	Tanoyan	P	Au, (Ag, Cu, Pb, Zn)	Quartz veins and stockwork.	*
A9	Pusian	P	Au, (Ag)	Quartz–Mn calcite veins.	*
A10	Gunung Pani	P	Au, (Ag, Cu, Pb, Zn)	Quartz–adularia–pyrite encrustations on fissure and breccia zones; hosted by a rhyolitic dome complex.	†‡
A11	Totopo	P	Au, (Ag)	Quartz veins.	‖
A12	Paslaten	M	Au, Ag	Quartz veins.	¶
A13	Bolangitang	P	Au, Ag, (Cu, Pb, Zn)	Quartz–carbonate veins and stockwork.	‡
Code B: High sulphidation epithermal Au					
B1	Motomboto	P	Au, Cu, As, (Ag, Te, Cu, Pb, Zn, Hg)	Pyrite–enargite–quartz veins and breccias on an E–W structure over 5 km long.	‡
B2	Simbalang	M	Au, Cu, As	Pyrite-rich veins, extensive kaolinitic alteration; vuggy silica float; enargite recorded.	
Code C: Jasperoid hosted Au					
C1	Mesel	P	Au, (As, Sb)	Jasperoid body in limestone or in limestone at contact with andesitic volcanics.	§§
Code D: Porphyry Cu–Au					
D1	Tapadaa	P	Cu, (Au)	D1 to D5 (Tapadaa–Tombulilato district) are generally stock-like quartz diorite intrusions < 500 m diameter. Early biotite–magnetite alteration overprinted by chlorite–albite–sericite–quartz–pyrite–chalcopyrite. Extensive late advanced argillic alteration overprints Cu–Au mineralization. Sungai Mak is supergene-enriched prospect.	§
D2	Cabang Kanan	P	Cu, (Au)		
D3	Kayabulan Ridge	P	Cu, (Au)		
D4	Cabang Kiri	P	Cu, (Au)		
D5	Sungai Mak	P	Cu, (Au)		
D6	Buligidun	P	Cu, (Au)	Dioritic intrusive; 2 alteration assemblages, similar to Tapadaa–Tombulilato district. Tourmaline up to 10%. High grade mineralized breccias at intrusive contacts (2–4 ppm Au; 1–2% Cu).	‡‡
Code E: Porphyry Mo					
E1	Malala	P	Mo, (Cu, Pb, Zn)	Contact zone between biotite granite and sedimentary host rocks. Mo is associated with K-feldspar–biotite alteration overprinted by quartz–sericite, pyrite and carbonate.	§**
E2	Anomaly C	M	Mo, Cu, Pb, Zn		
E3	Anomaly K	M	Mo, (Pb)		
E4	Anomaly A	M	Pb, Zn, (Mo)		
Code F: Vein Mo					
F1	Molamuhu	M	Mo	Quartz veins in (?) dacitic volcanics; with chalcopyrite and molybdenite.	‖
Code G: Granitoid Au vein					
G1	Petulu	P	Au, (Cu, Pb, Zn)	Sulphide-rich veinlets in basaltic andesite.	‖
Code H: Polymetallic vein					
H1	Paleleh	X	Au, Ag, Cu, Pb, Zn	Quartz–calcite–pyrite–chalcopyrite galena–sphalerite in veinlets and breccia zones at the contact between andesitic volcanics and a dioritic dyke.	‡‡‖‖
H2	Sumalata	M	Cu, Pb, Zn, (Au, Ag)	Galena–sphalerite–chalcopyrite–quartz–calcite-bearing shear zones in andesitic volcanics.	‖‖
H3	Ilangata	M	Pb, (Zn, Au, Ag)	Galena–sphalerite–pyrite–quartz veins in andesitic volcanics near granitoid contact.	‖

continued

Table 5. *continued*

Map Ref.	Name	Status[1]	Mineralization[2]	Description	Reference
Code I: Volcanogenic massive sulphide					
I1	Papayato	M	Cu, (Pb, Zn, Mo, Au, Ag)	Massive pyrite lens in felsic pyroclastics.	**
I2	Bukal	M	Cu, Pb, Zn	Chalcopyrite–sphalertie–pyrite lens, up to 2 m thick and 130 m long (Dixon Lode), in felsic pyroclastics rhyolitic lava.	**¶¶
Code J: Alluvial Au from a metamorphogenic source					
J1	Molosipat River	P	Au	Relatively coarse, high-purity gold worked by local miners.	§§
J2	Moutong River	P	Au	As above; alluvial gold in river and Pleistocene terrace.	§§
J3		M	Au	High-purity gold in streams from metamorphics.	§§
J4	Lindu	M	Au	Idem	§§
J5	Lariang	P	Au	Very fine, high purity gold intermittently worked by local people.	§§
J6	Upper Lariang	P	Au	Coarse, high-purity gold worked by local miners.	§§
Code K: Alluvial Au of epithermal origin					
K1	Taluduyunu River	X, P	Au	Alluvial gold derived from the Pani prospect; 750 fineness. 100 kg produced by Marisa Alluvial Mining during 1989, average grade 150 mg/m^3. Local mining also nearby in Batudulanga and Balayo Rivers.	***
K2	Tapabekin	X, P	Au	Pre-World War II Dutch sluicing operation working very coarse gravels. Coarse Au in quartz vein pebbles.	*
Code L: Magnetite skarn Au					
L1	Matinan	P	Au, Ag, Cu, (Pb, Zn)	Magnetite and epidote skarn with pyrite and base-metal sulphides replacing shallowly dipping carbonate rocks up to 3 m thick; >500 m strike length; proximal to a dioritic intrusion.	‡

[1]X: Old Dutch mine, P: Prospect, M: Mineral occurrence.
[2]Minor minerals in brackets.
* Placer Dome Inc., unpub. data.
† Kavalieris *et al.* (1990).
‡ BHP–Utah Pacific Inc., unpub. data.
‖ New Hope Min. Grp, unpub. data.
¶ Effendi (1972).
§ Taylor and Van Leeuwen (1980).
** Van Leeuwen (1980).
†† Van Bemmelen (1970).
‡‡ Carlile *et al.* (1990).
‖‖ Trail *et al.* (1974).
¶¶ t'Hoen (1917).
§§ Observations by the authors.
*** Cambridge Mining Group, unpub. data.

A4) also partly by underlying shallow-marine sedimentary rocks. Pusian (A9) and Patung (A7) are in pillowed basaltic andesite and greywacke which form the basement to the Neogene arc. In general, epithermal systems in North Sulawesi are assumed to be related to coeval volcanic activity, and due to erosion they are now exposed to deep levels. Most systems are characterized by chlorite–epidote (propylitic) wallrock alteration. Lanut (A4) is one of the few vein systems in North Sulawesi that is not deeply eroded, or alternatively it may be comparatively young. Lobong (A6) is a possible example of a still active system with solfataric alteration anomalous in Au (up to 1 ppm), Hg and As.

Andesitic lavas exceeding 200 m in thickness at Mintu (A3), Lanut (A4) and Bolangitang (A13) suggest host rocks at these prospects are proximal to volcanic centers, or are part of domes. Three examples of low sulphidation epithermal Au mineralization clearly hosted by volcanic centers are known. At Taware on Sangihe Island, quartz-base metal veins occur in a dioritic core of a deeply eroded andesitic stratovolcano. Mineralization controlled by structures, minor veins and breccia dykes is hosted by a diatreme breccia at Patung (A7), and at Gunung Pani (A10) low-grade disseminated Au mineralization is hosted by a rhyolitic dome complex (Kavalieris *et al.* 1990).

The importance of major structures in controlling mineralization is illustrated by Tanoyan (A8), where epithermal mineralization is related to a dilational offset on the Dumoga Rift. Other Au occurrences (not listed) occur in the same tectonic environment to the southwest.

Most low sulphidation epithermal mineralization in North Sulawesi is typified by quartz vein systems, which have limited grade and tonnage potential. All known vein type prospects in North Sulawesi are subeconomic, and historic production nowhere exceeded 10 t Au.

High sulphidation Au mineralization hosted by andesitic volcanics is known at Motomboto (B1) (Carlile *et al.* 1990) in the Tapadaa–Tombulilato porphyry Cu–Au district, at Mt Simbalang (B2) in the Kotamobagu area, and possibly also at Sangihe Island (Fig. 1), where quartz–enargite has been found as float. Weak porphyry Cu mineralization in diorite at Taware on Sangihe Island could be related to this occurrence. At Motomboto, vuggy silica–enargite and alunite alteration extends 5 km east–west, apparently controlled by rift faults parallel to the Neogene arc. This occurrence is proximal to the Tombulilato Cu–Au prophyries, and both types of mineralization are likely to be related genetically to the same magmatic system.

Gold mineralization in jasperoid at Mesel (C1) is hosted by Miocene limestone, carbonaceous sedimentary rocks and hornblende andesite, and may be of Carlin-type. Nearby, sedimentary replacement Au-base metal mineralization is found at Doup (A2). A distinctive feature of the geological setting is the occurrence of small hornblende andesite volcanic plugs and domes intruding shallow-marine sedimentary rocks, including limestone. A similar volcanic environment is found in the Bau district, Sarawak, where Carlin-type Au mineralization is described (Sillitoe and Bonham 1990). The age of the plugs and domes in the Mesel area is unclear, but preservation of related pyroclastic block-ash deposits suggests they are relatively young, possibly post-Miocene. Based on a comparison with the Bau district (I.K., unpub. data), it is suggested that the jasperiod Au mineralization is genetically related to concealed intrusions subvolcanic to the andesitic plugs and domes. High sulphidation mineralization at Mt Simbalang (B2) may also be related to the same magmatic–hydrothermal system.

Porphyry Cu–Au mineralization (Fig. 5b)

Two porphyry Cu–Au districts (D1–5 and D6), excluding Sangihe Island, are known in North Sulawesi: (1) Tapadaa and Tombulilato (Lowder and Dow 1978, Taylor and Van Leeuwen 1980, Carlile and Kirkegaarde 1985), and (2) Buligidun (Carlile *et al.* 1990).

A generalized stratigraphy for the Tapadaa–Tombulilato district consists of andesitic volcanics overlain subhorizontally by several hundred meters of dacite or rhyolite (welded pyroclastics ?), that outcrop on the highest summits in the area. Gold-rich, porphyry Cu mineralization is related to small (500 m diameter), sub-circular, elongate stocks which intrude the andesite sequence and capping felsic volcanics. Porphyry Cu mineralization in the Tapadaa–Tombulilato district is characterized by extensive hypogene acid overprinting. Limited available K–Ar age dates suggest that the mineralizing event took place approximately two to three million years ago (Lowder and Dow 1978, Perello 1992).

The Limboto–Bone Rift transects the Tapadaa–Tombulilato district, and Tombulilato is uplifted 300 m relative to Tapadaa. However, the timing of the uplift in relation to the mineralizing event is uncertain. The preservation of hypogene acid overprinting in both areas indicates that post-mineralization erosion was minimal.

Porphyry Cu–Au mineralization at Buligidun (D6) is also related to small dioritic intrusions in andesitic volcanics (Carlile *et al.* 1990). Alteration is also comparable, except for the abundant tourmaline. Polymetallic vein and skarn mineralization on the north coast near Buligidun is associated with post-Miocene dioritic intrusions that are likely to be co-genetic with the Cu–Au porphyries.

The Buligidun porphyry Cu–Au district is poorly explored, but probably includes the granitoid-related Au mineralization at Petulu.

Porphyry Mo mineralization (Fig. 7)

At Malala (E1), porphyry Mo mineralization of Pliocene age is related to biotite granite. The molybdenite mineralization is present in quartz–pyrite–Kfeldspar–biotite–apatite veins or hairline veinlets in altered wall-rock, and is overprinted by a carbonate–sericite–chlorite–base metal sulphide assemblage. The mineralization is disseminated in a narrow contact zone between granite and Eocene basic volcanics and sedimentary rocks, but also occurs in higher concentrations in a steeply dipping fault zone (Van Leeuwen 1992). The Malala porphyries may be apical intrusions at the roof of a larger pluton.

Vein Mo mineralization (Fig. 5b)

An occurrence of vein molybdenite is recorded at Molamuhu (F1). Molybdenite and chalcopyrite occur in quartz veins hosted by (?) dacitic volcanics. The genetic significance of the occurrence is not known.

Intrusion-related vein mineralization (Fig. 5b)

This mineralization type includes Au mineralization at Petulu and base metal–minor Au mineralization at Paleleh, Sumalata and Ilangata. Polymetallic vein mineralization at Paleleh (H1) is related to a dioritic dyke post-dating the Wobudu Breccia Formation (Rutten 1927). Paleleh may be representative of other small base-metal mineral occurrences of Pliocene age on the north coast west of Kuandang.

At Petulu (G1) (I.K., unpub. data), quartz–chalcopyrite–bornite–magnetite veins intersecting a zone of magnetite alteration are inferred to be related to a deeper granitoid. Gold is present in pyrite-rich veins peripheral to the magnetite zone. Shallowly and vertically dipping dacitic dykes related to the inferred intrusion are considered to be of post-Miocene age.

Magnetite skarn mineralization (Fig. 5b)

Gold-bearing magnetite and epidote skarn developed after carbonate rocks is associated with a (?)Pliocene dioritic stock of matinan (L1). Host rocks are mainly shallow-marine shale and greywacke of probable Lower

Miocene age. The sequence was moderately to strongly folded before intrusion. The Matinan prospect is 7 km west southwest of the Buligidun Cu–Au porphyry and dioritic intrusions in both areas are likely to be co-magmatic.

Volcanogenic massive sulphide mineralization (*Fig.* 3)

Two occurrences of VMS mineralization (Bukal and Papayato) are present in Paleogene volcanic and sedimentary basement rocks to the Neogene arc. The VMS mineralization in the north arm is interpreted to be the same age as VMS mineralization at Sangkaropi near Makale (Fig. 1), which occurs stratigraphically below the Makale Formation (Upper Oligocene–Middle Miocene). As at Sangkaropi VMS mineralization at Bukal (I2) and Papayato (I1) is related to local felsic volcanicity, but virtually nothing else is known about its geological setting.

Metamorphogenic gold mineralization (*Fig.* 3)

High-purity alluvial gold derived from metamorphic quartz veins is widespread in the neck of Sulawesi, but the two most important areas are Moutong–Molosipat (J1 and J2) and the Upper Lariang River, 100 km south of Palu. Source rocks in the Upper Lariang River comprise mica schist, gneiss and amphibolite of amphibolite–facies grade. Similar metamorphics are present at Moutong–Molosipat, but greenschists are the main host rock. In both areas quartz occurs as lenses along foliation and as cross-cutting veins. Layers of quartz up to several meters thick are present at Molosipat; veins are generally less than 0.5 m wide. The metamorphogenic Au is comparable to mineralization in the Otago Schist, New Zealand (Henley *et al.* 1976), Central Kalimantan, Sumatra, and other similar terranes in the Circum-Pacific region.

DISCUSSION

This synthesis of the geology of the north arm of Sulawesi provides some insights into the relationship between plate tectonics, volcanicity and mineralization in modern magmatic arc terranes. However because the basic geology and age relationships in North Sulawesi remain poorly known, the conclusions are only tentative.

Porphyry-type mineralization (Cu–Au and Mo) in North Sulawesi (excluding Sangihe Island) is approximately 2–4 Ma old. For the porphyry Cu–Au mineralization a simple geometric relationship to the North Sulawesi Trench is apparent, namely that the perpendicular distance between the trench and the porphyry Cu–Au mineralization at Tapadaa–Tombulilato and Buligidun is approximately the same. However, because Late Miocene–Pliocene magmatism in the north arm extends along the neck and because the depth of the south-dipping subduction zone below the arc is relatively shallow (< 100 km; Cardwell *et al.* 1980), it is equivocal whether porphyry Cu–Au mineralization is linked to subduction-related magmatism along the North Sulawesi Trench, whereas the porphyry Mo mineralization certainly is not. In more general terms it is concluded that porphyry Cu–Au mineralization has occurred in an oceanic arc above two opposed subduction zones. This could also apply to Sangihe Island, which may be located above the Cotobato and East Sangihe trenches (Fig. 1). The Pliocene ages of the mineralized intrusions imply that they were emplaced following the reversal of subduction polarity. Porphyry Cu development following arc reversal is proposed for other southwest Pacific regions by Solomon (1990). The importance of arc reversal, cited by Solomon (1990), is that it may generate second stage gold-enriched melts. However, other tectonic processes may also control generation of these melts (Jones and Thompson 1991), including late intra-arc extension, which is an important feature of the evolution of the north arm of Sulawesi during the Pliocene. The porphyry Cu–Au mineralization and plate tectonic environment in the north arm may be compared most closely with Luzon in the North Philippine Arc.

In the Tapadaa–Tombulilato district and probably also in the less explored Buligidun area, Cu–Au porphyries occur in clusters. However, the specific volcanic environment and magmatic affinity of porphyry intrusions remains unknown. The porphyry Cu–Au districts are also typified by other intrusion-related mineralization. At Buligidun this includes skarn-type mineralization and polymetallic veins, whereas at Tapadaa–Tombulilato high sulphidation epithermal Au mineralization is present.

Upper Miocene–Pliocene granites associated with porphyry Mo mineralization in the neck of Sulawesi are emplaced in a post-collisional, extensional tectonic environment. The granites are intruded in an arcuate belt which parallels the shape of the Sula Platform collision zone in Eastern Sulawesi. Intense deformation of the neck, and high-temperature metamorphism (anatexis) at depth may be related to this collision. In Western Sulawesi this collision is between a microcontinent and the Sundaland continental margin, whereas elsewhere in the north arm it is between a microcontinent and an island arc. This fact may help to explain the high initial Sr isotope signature and K-rich felsic composition of the granite (Van Leeuwen 1992). However, the collision zone now undergoing extension overlies an Early Miocene Benioff zone, and the young magmatism is at least geometrically related.

The age of low sulphidation epithermal Au mineralization relative to the age of volcanic host rocks in the north arm of Sulawesi is poorly known. The epithermal systems are assumed to be coeval with their host volcanic field, which in most cases is believed to be Early Miocene. However, this assumption and the age of volcanics may be erroneous.

A district-wide relationship between porphyry Cu–Au mineralization and low sulphidation epithermal Au is not clearly evident in the North Sulawesi Arc, although there are epithermal Au occurrences in the Tombulilato district (J. Perello, pers. commun. 1991), which are unlisted in this compilation.

The most important area of epithermal mineralization related to andesitic volcanicity is the Kotamobagu district. This mineralization may be centered on the pre-Moat caldera volcano, which may be a long-lived volcanic system spanning 20 Ma. Similarly, the epithermal mineralization could also have a wide range of ages, as young as Recent (Lobong solfatara).

Volcanogenic massive sulphide mineralization of possible Late Oligocene age in the north arm and at Sangkaropi formed before the inception of the Neogene arc. The VMS mineralization is interpreted to be related to sea-floor magmatism during rift separation of Sulawesi from Kalimantan. This environment is likely to have been back arc to an east-facing Paleogene arc which now includes blueschist in the east arm of Sulawesi. Intense deformation of the basement to the Neogene arc, blueschist metamorphism and obduction of the East Sulawesi Ophiolite sugest that the Paleogene arc was terminated by collision.

In the north arm, the geology of the metamorphic terranes remains very poorly known. Although this study concurs with previous interpretations that the metamorphic terranes represent pre-Tertiary basement, a post-collisional age of emplacement of some of these rocks as metamorphic core complexes together with felsic magmatism may be suggested. This interpretation would imply that the metamorphogenic Au mineralization could be of Pliocene age.

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