K-Ar DATING OF SELECTED IGNEOUS SAMPLES FROM THE SIBOLGA BASIN, MEULABOH AND SIMEULUE ISLAND, WESTERN SUMATRA

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ABSTRACT

As part of a general study of the sedimentation, structure and tectonic evolution of the northern part of the Sumatran forearc basin samples of igneous rock were collected for K-Ar dating from the eastern margin of the Sibolga Basin, and from the outer arc island of Simeulue.

A sample of biotite from a granodiorite in the Seumayam Complex in the Barisan Mountains yielded an age of 98.6 (±3.6) Ma (Mid-Cretaceous) and two samples of biotite from the Meuko River granodiorite yielded 56.2 (± 2.2) Ma and 53.2 (± 3.3) Ma (Palaeocene-Early Eocene) ages, respective ly. These ages are compatible with Cretaceous to Early Palaeocene granitic activity recorded elsewhere in northern Sumatra.

Gabbro from an ophiolite on the eastern side of Simeulue gave ages of 35.4 (± 3.6) Ma and 40.1 (± 2.7) Ma (Late Eocene). This age may represent the formation of the ophiolite as part of the Indian Ocean floor, which was accreted into the outer arc islands, but may have been modified by the later Mid-Oligocene accretion process.

Eight samples of basaltic and andesitic volcanic rocks from the Barisan Mountains on the eastern margin of the Sibolga Basin yielded K-Ar ages between 16 and 9 Ma (Mid- Late Miocene). The ages fall into two groups, one around the Early to Mid-Miocene boundary and the other around the Mid to Late Miocene boundary. The commencement of volcanic activity in the Mid-Miocene coincided with the uplift of the Barisan Mountains and the cessation of sedimentation along the eastern margin of the Sibolga Basin, as Early to Mid-Miocene sediments, showing only minor evidence of contemporaneous volcanic activity, are in fault contact with the volcanics and younger coarse clastic sediments contain abundant volcanic clasts.

I. INTRODUCTION

I.I. General

The Meulaboh area, the onshore part of the north- western Sumatra Forearc (Sibolga Basin), provides the opportunity to study forearc lithologies exposed along river sections in the foothills of the Barisan Mountains (Figure 1). Eleven of the thirteen samples selected for Potassium-Argon (K-Ar) analysis were from lithologies outcropping within the basin. Participation in a Royal Society Expedition to the islands of Nias and Simeulue which form part of the emergent outerarc ridge, enabled the geology along the southwestern margin of the basin to be studied. Two samples from Simeulue were analysed for K-Ar. Sample locations are shown in Figures 2 & 3.

The aim of the research programme was to establish the structural and stratigraphic evolution of the Sunda Forearc, and to determine the influence of factors such as the development of the accretionary complex, uplift of continental basement along the west margin of Sumatra, the growth of the volcanic arc and changes in sea level on the history of sedimentation in

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the region. These sedimentation patterns have been further complicated by movements along the major, dextral, transcurrent Sumatra Fault System.

I.2. Aim of Isotope Project

The primary aim of the isotope dating programme was to establish the timing of the episodes of volcanism that have occurred in North Sumatra. This is important as many of the younger sediments, particularly those of Plio-Pleistocene age, have been derived from the magmatic arc in the Barisan Mountains, either as a result of direct volcanic activity or indirectly as the continental basement was uplifted. As these sediments are predominantly terrestrial they cannot be dated directly from fossil evidence. Geochemical, petrographic and isotopic data, from both the volcanics and the sediments derived from them, may therefore help resolve the question of clast provenance and ultimately enable the amount of movement along the Sumatra Fault System to be determined more accurately.

II. REGIONAL TECTONIC SETTING

Sumatra lies on the western edge of Sundaland, a southern extension of the Eurasian Continental Plate. At the present day, the Indian Ocean Plate is being subducted beneath the Eurasian Continental Plate in a N20^{O} direction at a rate of between 6 and 7 cm a year. This zone of oblique convergence is marked by the active Sunda Arc- Trench system which extends for more than 5000 km, from Burma in the north to where the Australian Plate is in collision with Eastern Indonesia in the south (Hamilton, 1979).

Arc-related lithologies along the length of Sumatra suggest that the island has been at or near an active convergent plate boundary, at least intermittently, since Late Permian times (Katili, 1975, Cameron et al., 1980). The vast majority of ages for igneous rocks in North Sumatra have been inferred from field observations and not from direct analyses (Katili, 1962, Cameron et al., 1982, 1983). The North Sumatra Project (Kallagher, 1987) carried out five radiometric isotope ages on two selected igneous
bodies to the north and south of the Meulaboh
The Sikuleh batholith to the north yielded an averag
age (from two biotites and one hornblende) of 97
0.7 Ma. The Lassi granites, 150 km to the sou
yielded an average age of 112 ± 24 Ma from
biotites. Correlation of ages obtained from these
trusives together with some (less than 20 analy
from other regions of North Sumatra and field
dence, has led to the interpretation that many
sives observed at the present day are of Cretaceou
Palaeocene age. To establish more quantitative
for the Meulaboh area, three samples from two
sive bodies within the basin were selected
radiometric isotope dating (from biotite) as part of
study being described.

The Eocene collision between India and
rasia at approximately 50 Ma, coincides wit
marked decrease in India's northward veloc
anomaly 22 (Patriat & Achache, 1984), and cor
sponds with much of the basin evolution in Sou
Asia. The Sumatran forearc basins are conside
be extensional in origin and to originate from th
(Daly et al., 1987). In the Meulaboh area, the
ments record the complex interaction betwee
tonic processes (including uplift of the Barisan
the continental basement), sedimentary enviro
and changes in sea level.

The timing for the commencement of
tion of the outerarc ridge is unresolved, althoug
data from Nias suggests that it was Pre-Mi
(Moore & Karig, 1980; Kallagher, 1987). The
oceanic crust being subducted beneath the
ridge can only be dated as Early Tertiary; a m
curate determination is precluded due to the
tion of available magnetic data and palaeoge
reconstructions of the Indian Ocean Plate
& Fisher, 1974; Karig et al., 1979). One of the
tives of the present research, therefore, is to de
isotopic dates from the ophiolite expose
outerarc island of Simeulue.

Oligocene agglomerates, lahars and
clastics in the Meulaboh area mark a period of
ral inversion of the forearc basins in Sum
Java. Stable, but oblique, convergence ra
cm/yr.) were established at about 30 Ma

1987), a period which coincides with a lowstand of sealevel (Pitman, 1978; Vail et al., 1977).

A major marine transgression, which began in Late Oligocene times, culminated in the Mid-Miocene (Cameron et al., 1980). In the Meulaboh area, Lower to Middle Miocene sandstone, siltstone and limestone represent a period when stable conditions existed across the Sunda shelf, with only sporadic volcanism.

No sedimentary record exists in northwest Sumatra for the Late Miocene (10 Ma), a period thought to correspond to uplift of the Barisan Mountains, possibly associated with renewed magma input (Cameron et al., 1980). If this hypothesis is true, then a significant number of the Tertiary volcanics sampled from the Meulaboh area should record ages within the Late Miocene.

Plio-Pleistocene sedimentation in the Meulaboh area marks a significant change from marine sedimentation during Lower Miocene times, to terrestrial. Thick sequences of inter bedded conglomerate, sandstone and mudstone were deposited in fluvial systems draining westwards, away from the Barisan Mountains.. A problem exists in determining the provenance of the volcanic and basement derived clasts of the conglomerates in an area complicated by movements along the dextral, strike-slip Sumatra Fault System. It is possible that part of the Meulaboh area originally lay up to 400 km south of its present position. The amounts of movement are disputed by numerous authors (Katili & Hehuwat, 1967; Posavec et al., 1973, Cameron et al., 1980, etc). By performing geochemical analyses together with isotopic dating of the igneous outcrops from within the area, provenance of the conglomerate clasts may be deter mined more accurately, and movements along the Sumatran Fault System may be resolved.

III. PRINCIPLES OF THE K-Ar METHOD OF DATING

III.1. General

Potassium is one of the eight most abundant elements in the crust of the Earth, and is a major constituent of many rock-forming minerals such as the micas, the feldspars and feldspathoids, clay minerals and certain evaporites (Heier & Adams, 1964). Potassium has three naturally occurring isotopes ^{39}K, ^{40}K and ^{41}K, of which ^{40}K is radioactive and undergoes branched decay to ^{40}Ca and ^{40}Ar (Von Weizsacker, 1937; Steiger & Jager, 1977). By measuring the concentration of potassium and the amount of radiogenic ^{40}Ar, the age of a rock or K-bearing mineral can be determined when the following assumptions are satisfied (Faure, 1986) :

1. No radiogenic ^{40}Ar produced by decay of ^{40}K in the mineral during its life has escaped;
2. The mineral became closed to ^{40}Ar soon after its formation, which means that it must have cooled rapidly after crystallisation, unless it formed at low temperatures;
3. No ^{40}Ar was incorporated into the mineral at the time of its formation or during a later metamorphic event;
4. An appropriate correction is made for the presence of atmospheric ^{40}Ar;
5. The mineral was closed to potassium throughout its life time;
6. The isotopic composition of potassium in the mineral is normal and was not changed by fractionation or other processes except by the decay of ^{40}K;
7. The decay constants of ^{40}K are known accurately and have not been affected by the physical or chemical conditions of the environment in which the potassium has existed since it was incorporated into the Earth;
8. The concentration of ^{40}Ar and potassium were determined accurately.

III.2. Sample Preparation

Samples of selected igneous rocks from the Meulaboh area and Simeulue island were crushed, sieved, and approximately 100 g of the 250-500 um fraction washed in distilled water and dried. This aliquot was then divided into two, and one half crushed to a fine powder in a 'tema' mill. For three of the samples biotite was separated for analysis. Approximately 0.2 g of the powdered sample was used to determine the potassium concentrations by conventional mixed-acid digestion and flame photometry; this was done in either duplicate or triplicate for each of the samples. The method is well established and so is not discussed in detail here.

Argon concentrations were determined by means of isotope dilution analysis. Approximately 2 g of sample from the 250-500 um fraction (or 0.02 g of separated biotite) was fused within a molybdenum crucible sealed within a vacuum system. A known quantity of spike argon enriched in ^{38}Ar was mixed with the gas extracted from the mineral and then purified by removing all chemically reactive gasses using a heated titanium sponge 'getter' and a liquid nitrogen trap, leaving only a mixture of the noble gases, including argon. The residual gas mixture was then introduced into the mass spectrometer and the ^{40}Ar/^{38}Ar and ^{36}Ar/^{38}Ar ratios of the mixture were determined. The measured value of the ^{36}Ar/^{38}Ar ratio was used to correct for the presence of atmospheric argon whose isotopic composition is known. The amount of radiogenic ^{40}Ar was calculated from measured ^{40}Ar/^{38}Ar ratio, using the known amount of spike argon that was added and its isotopic composition.

Minerals to be dated by the K-Ar method must have retained all of the radiogenic ^{40}Ar produced within them by decay of ^{40}K and they must not contain any excess ^{40}Ar. Argon loss may occur because argon is a noble gas and therefore does not from bonds with other atoms in a crystal lattice. If argon is lost, this will lead to under estimates of the age of the rock or mineral. In general, argon loss can be attributed to the following causes (Faure, 1986) :

1. In ability of a mineral lattice to retain argon even at low temperature and atmospheric pressure;
2. Either partial or complete melting of rocks followed by crystallisation of new minerals from the resulting melt;
3. Metamorphism at elevated temperatures and pressures resulting in complete or partial argon loss depending on the temperature and the duration of the event;
4. Increase in temperature due to deep burial or contact metamorphism causing argon loss from most minerals without producing any other physical or chemical changes in the rock;
5. Chemical weathering and alteration by aqueous fluids leading not only to argon loss but also to changes in the potassium content of minerals;
6. Solution and redeposition of water soluble minerals;
7. Mechanical breakdown of minerals, radiation damage and shock waves.

Alternatively, ^{40}Ar may be present in excess leading to over estimates of the ages of minerals dated by this method. Excess argon is most noticeable in minerals with a low potassium content (e.g. beryl, tourmaline, pyroxene, cordierite), in minerals that are young, or can be due to the presence of flued inclusions or older xenoliths or xenocrysts.

IV. INTERPRETATION OF K-Ar RESULTS

Data from the K-Ar analysis are presented in Table 1. Whole rock analysis was carried out on basaltic and andesitic samples; in samples, SEU 28, UKO 12 & 18, separated biotite was used.

The oldest age obtained from the analyses was from sample SEU 28, a granodiorite from the Semayam Complex towards the southern part of the Meulaboh area. The age of 98.6 (±3.6) Ma suggests that this complex is of Mid- Cretaceous age and therefore older than the Late Cretaceous-Palaeocene age ascribed to it by Cameron et al. (1983). However, only one sample was run and thus some caution should be ascribed to this result. Although only the freshest biotite was used in the analysis, some of the biotite was altered to chlorite. Nevertheless, the relatively high K content suggests that this was only a very minor effect and it is unlikely that this was a significant cause of argon loss.

Two samples of biotite from a granodiorite in the Meuko River in the central part of the Meulaboh area, UKO 12 & 18, yielded ages of 56.2 (± 2.2) Ma and 53.2 (± 3.3) Ma, respectively. The high potassium content of the biotites together with studies of the petrography indicate these samples are relatively fresh and thus it is unlikely that argon has been lost or is present in excess. Moreover, the good agreement between the duplicate samples suggests that the age of these rocks is probably reliable; a Palaeocene-Eocene age affirms that this intrusion is significantly older than (?) Middle/Late Miocene, the age tentatively suggested by Cameron et al. (1983), for this Bale Meuko granodiorite.

The ages of these three samples supports the hypothesis that widespread intrusive activity accompanied Late Cretaceous deformation (Cameron et al., 1982, 1983). In Cretaceous times (70 Ma), India separated from Africa and was converging on Eurasia in a north-north-west direction at a velocity of between 15-20 cm a year (Daly et al., 1987). A north-south spreading regime established in Late Cretaceous times, resulted in a system of oblique subduction beneath Sumatra. No sedimentary record exists on mainland North Sumatra for this period.

Two samples from the Sibau Gabbro Group on the island of Simeulue suggest that the ophiolite exposed in a small area in the east of the island is probably of Late Eocene age. MORB-type samples KM 4, 35.4 (± 3.6) Ma, and AIM 2, 40.1 (± 2.7) Ma have similar ages within the error range, despite the very different potassium contents (0.23% and 0.5%, respectively). Excess argon, often associated with ophiolites, is therefore unlikely and the ages are probably meaningful. These ages have important implications for the island's geological history; a simplified stratigraphic column is shown in Figure 4.

The age of the oceanic crust subducting along the Sunda Trench of North Sumatra has been dated as Early Tertiary (Karig et al., 1980). Some time after anomaly 17 (41 Ma), the spreading centre east of Ninety East Ridge ceased spreading and has since been partially subducted (Sclater & Fisher, 1974). At anomaly 13 (36 Ma), renewed spreading in the Indian Ocean (Scalar & Fisher, 1974), caused an increase in the subduction rate to appoximately 5-6 cm a year at Sumatra. In the Andaman sector, Karig et al. (1979), suggest "ophiolitic scraps' were accreted when thinly sedimented oceanic crust was subducted during Late Cretaceous to Early Tertiary times and subsequently deformed in the Mid-Oligocene. It is plausible, therefore, that the Simeulue ophiolite had a similar history, being emplaced in the Cretaceous and deformed in Eocene/Oligocene times. Alternatively the ophiolite may have been emplaced during Eocene times, perhaps reflecting a change from strike-slip motion to subduction in that sector of the Sunda Arc (D. Aldiss, 1989, pers. Comm.).

If the ophiolite was emplaced in Late Eocene times, this suggests that there has been very rapid uplift of the island, with emplacement of the Baru Melange Formation followed by deposition of the Pinang Conglomerate Member. The latter is a basal conglomerate dated on the basis of a shallow-water benthonic foraminiferal assemblage as Late Oligocene to Early Miocene in age. An alternative, more satisfactory explanation may be that the Baru Melange was emplaced along a major thrust in the Late Eocene, an event which 're-set' the geological clock of the Sibau Gabbro Group.

The remaining eight samples from the Meulaboh area have all yielded Miocene dates. There appear to be two clusters, the first around the Lower to Middle Miocene boun-dary, and the second around the Mid to Upper Miocene boundary (Figure 5). Duplicate argon analyses were performed on samples suffixed by the letter 'R'; SEU 19 (i) and (ii) were taken from different parts of the same igneous intrusion and are therefore treated as two separate samples.

Ages from Late Mid-Miocene times strongly support the hypothesis that uplift of the Barisan Mountains in Sumatra began at this time. These ages are probably meaningful as error ranges are relatively small and petrographic studies show that the samples are fresh. The mechanisms for uplift of the Barisans are not well understood but are thought to be associated with renewed magma input related to an increased subduction rate from 3-4 cm to between 5 and 7 cm a year (Karig et al., 1979). Uplift probably climaxed at the Mio-Pliocene boundary, and has continued intermittently until the Present (Cameron et al., 1980).

The earlier, more extensive, cluster around the Lower- Mid Miocene boundary is more difficult to explain as it has not been identified by previous authors. MIR 14 and SEU 19 have relatively small error ranges compared with those of CUT 34 and 45. These higher errors are due to the high proportion of atmospheric argon (90.95% for CUT 45 compared with 45.51% for SEU 19 (i), which reflects a low K content (0.2% for CUT 34 compared with 1.44% for SEU 19 (ii). However, both CUT 34 and CUT 45 are within the error ranges of each other and within those of MIR 14 and SEU 19; the mean age for the group is therefore probably meaningful.

Oligo-Miocene palaeogeography was dominated by an elongate landmass in the south and a chain of intermittently active volcanic islands in the north (Beaudry & Moore, 1985). It is possible that activity along this volcanic chain continued for longer than was previously thought. The sedimentary sequence of interbedded sandstones and siltstone, siltstones and limestones found in close proximity to the igneous lithologies have been dated on the basis of nannofossils and foraminifera as being of Lower to Middle Miocene age. At one locally, the siltstones are in depositional contact with a white tuffaceous sandstone, indicating that volcanic activity was occurring, if only sporadically, throughout this essentially stable period of deposition. Reasons for this continued volcanic activity are unclear at present as they do not seem to b directly related to regional tectonic events.

V. CONCLUSIONS

K-Ar dates obtained from the study describ above have been very useful in providing quantita evidence for previously proposed hypotheses. N only has the study helped resolve areas of specula as to when major episodes of volcanic activity t place in North Sumatra, it has also raised new q tions, such as those about Early-Mid Miocene vo ism in the Meulaboh area and the timing of geolog events on the island of Simeulue. This pilot also has wider implications for the use of isotopic ing in resolving the history of movement along Sumatra Fault System a multidisciplinary study p ently being carried out at the University of Lond

VI. Acknowledgements

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Sample No.	% K	% Error K	% Atm. Ar	Vol Rad Ar	Error Rad Ar	Age (Ma)	Error(Ma)
		(1 Sigma)		(nl/g)	(1 Sigma %)		(2 Sigma)
BAT 9	1.36	1.00	73.22	0.5956	3.01	11.2	0.7
BAT 15	1.12	1.00	59.02	0.4493	1.81	10.3	0.4
MIR 9	1.18	2.40	79.28	0.403	4.08	8.74	0.82
MIR 14	1.31	1.37	46.47	0.908	1.44	17.7	0.7
MIR 14R	1.31	1.37	64.86	0.873	2.15	17.1	0.9
SEU 19 i	1.31	1.00	45.51	0.8408	1.38	16.4	0.6
SEU 19 ii	1.44	1.00	72.81	0.8941	2.90	15.9	1.0
CUT 34	0.20	1.07	89.73	0.105	9.97	13.7	2.7
CUT 45	0.30	2.39	90.95	0.19	11.79	16.1	3.9
KM 4 *	0.23	3.33	77.91	0.313	3.98	35.4	3.6
AIM 2 *	0.50	1.26	73.88	0.795	3.10	40.1	2.7
UKO 12 ▲	7.38	1.00	54.99	16.3732	1.69	56.2	2.2
UKO 18 ▲	6.57	1.00	68.23	13.7957	2.96	53.2	3.3
SEU 28 ▲	6.01	1.00	52.16	23.6649	1.56	98.6	3.6

Table 1. K-Ar data from selected samples from the Sibolga Basin & Simeulue (marked by an *), Indonesia. All analyses were performed on whole rock, except those marked by a solid triangle, where separated biotite was used.

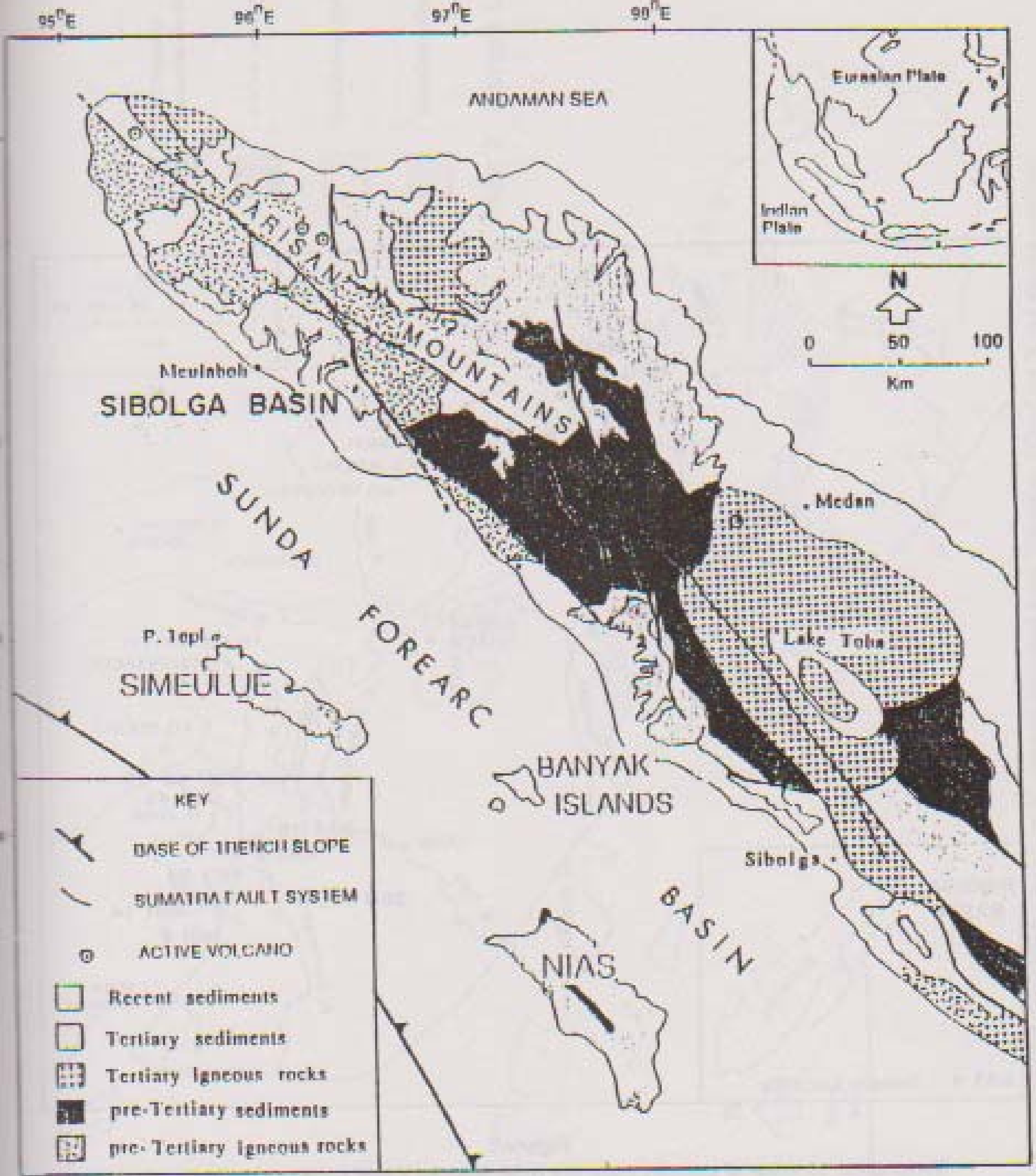

Figure 1

Simplified geological map of North Sumatra (from Stephenson & Aspden, 1982), showing geographic location of the Sibolga Basin and Simeulue and Nias Islands

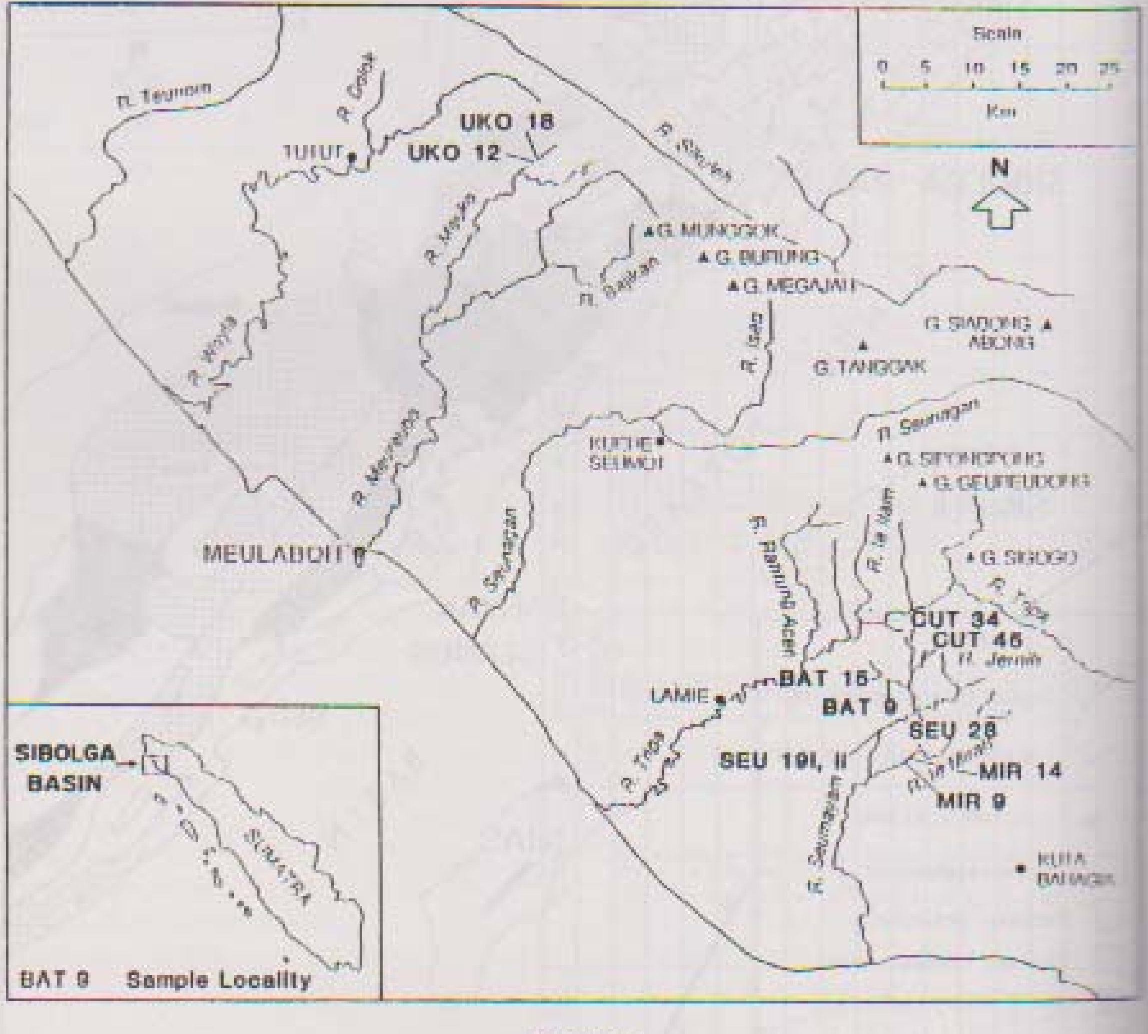

Figure 2
Geographic location of samples collected from Sibolga Basin for K-Ar dating analysis

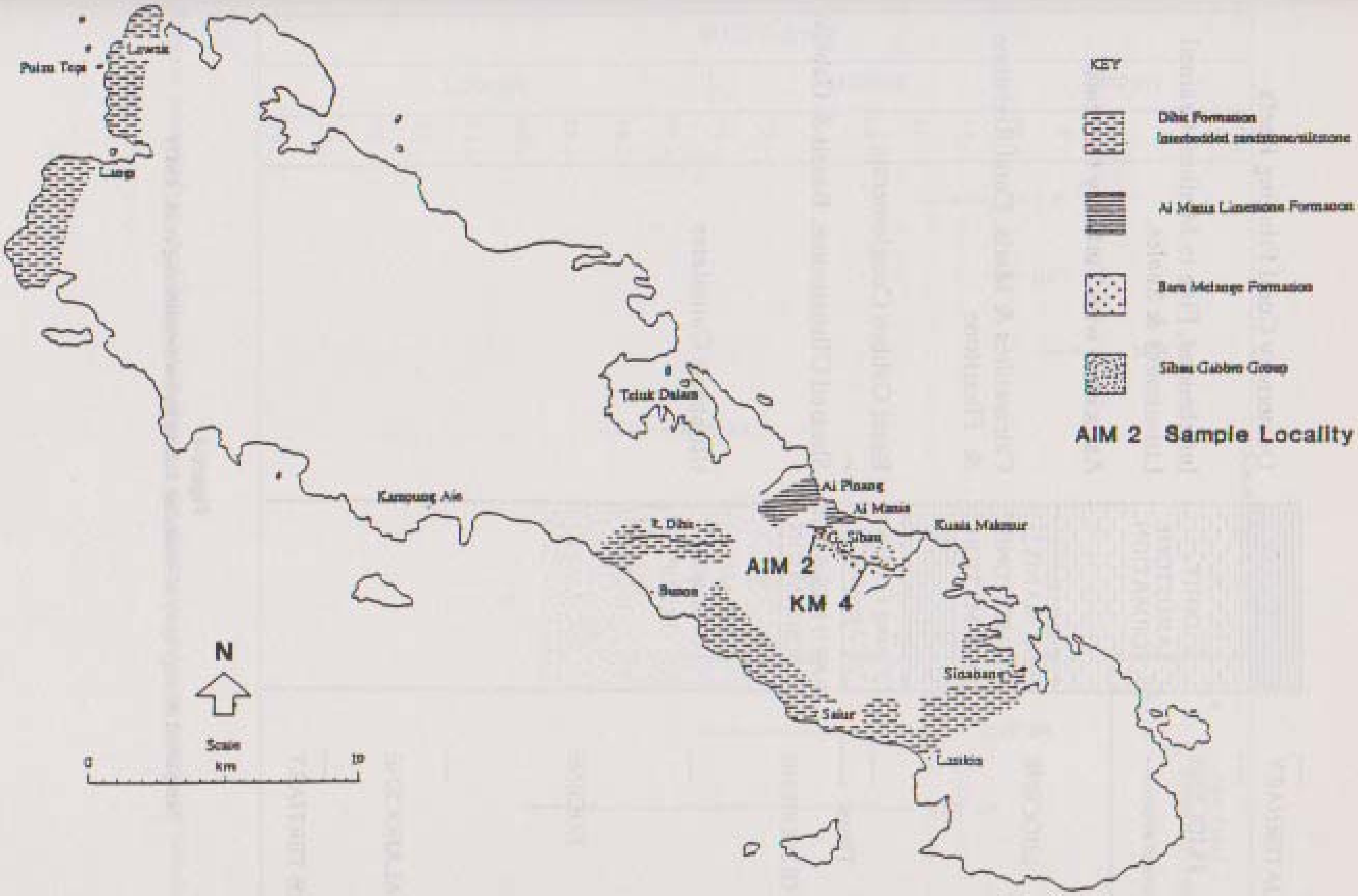

Figure 3. Geographic location of samples collected from Simeulue Island for K-Ar dating analysis

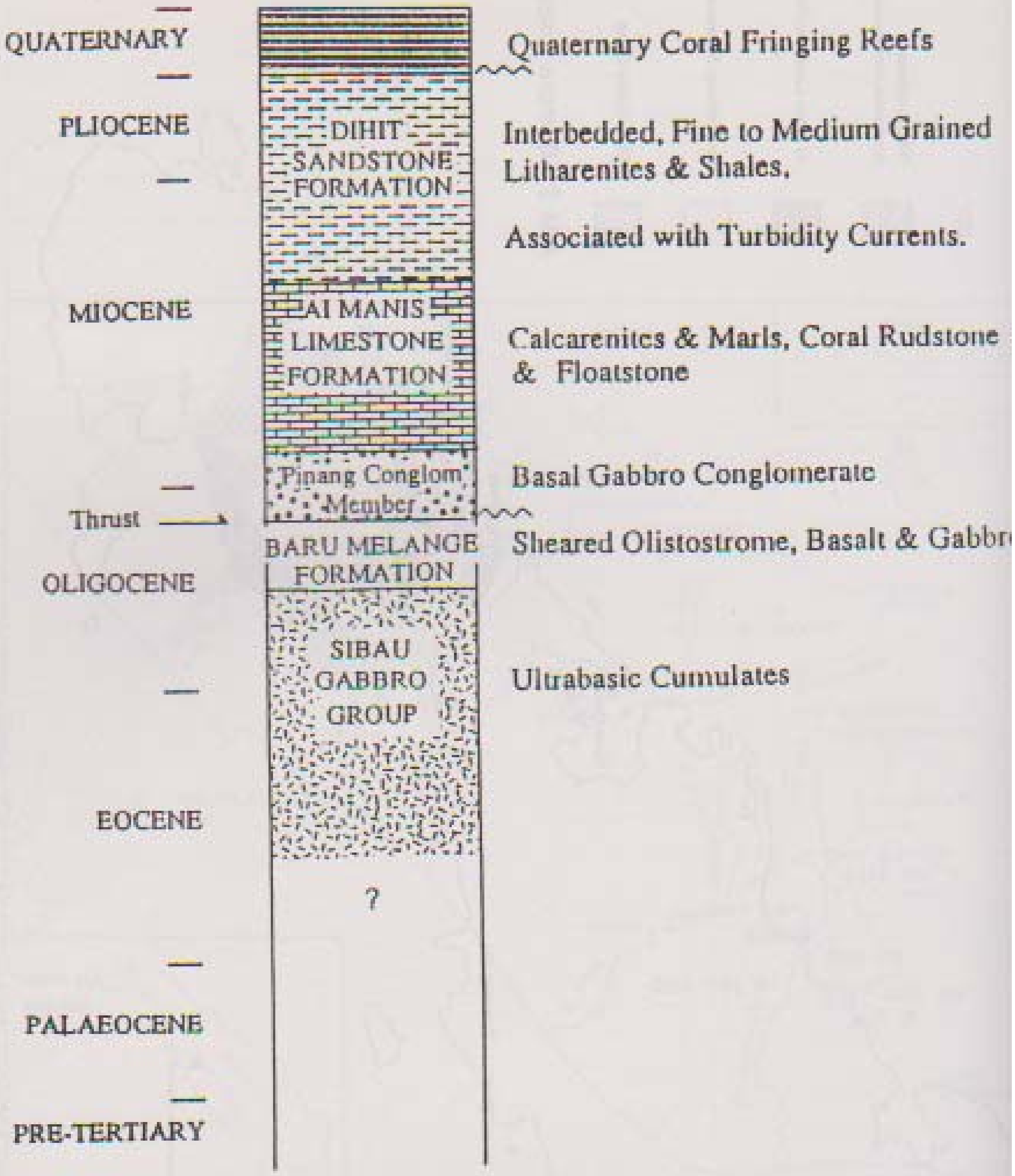

Figure 4
Simplified stratigraphy of Simeulue Island (from Situmorang et.al., 1987)

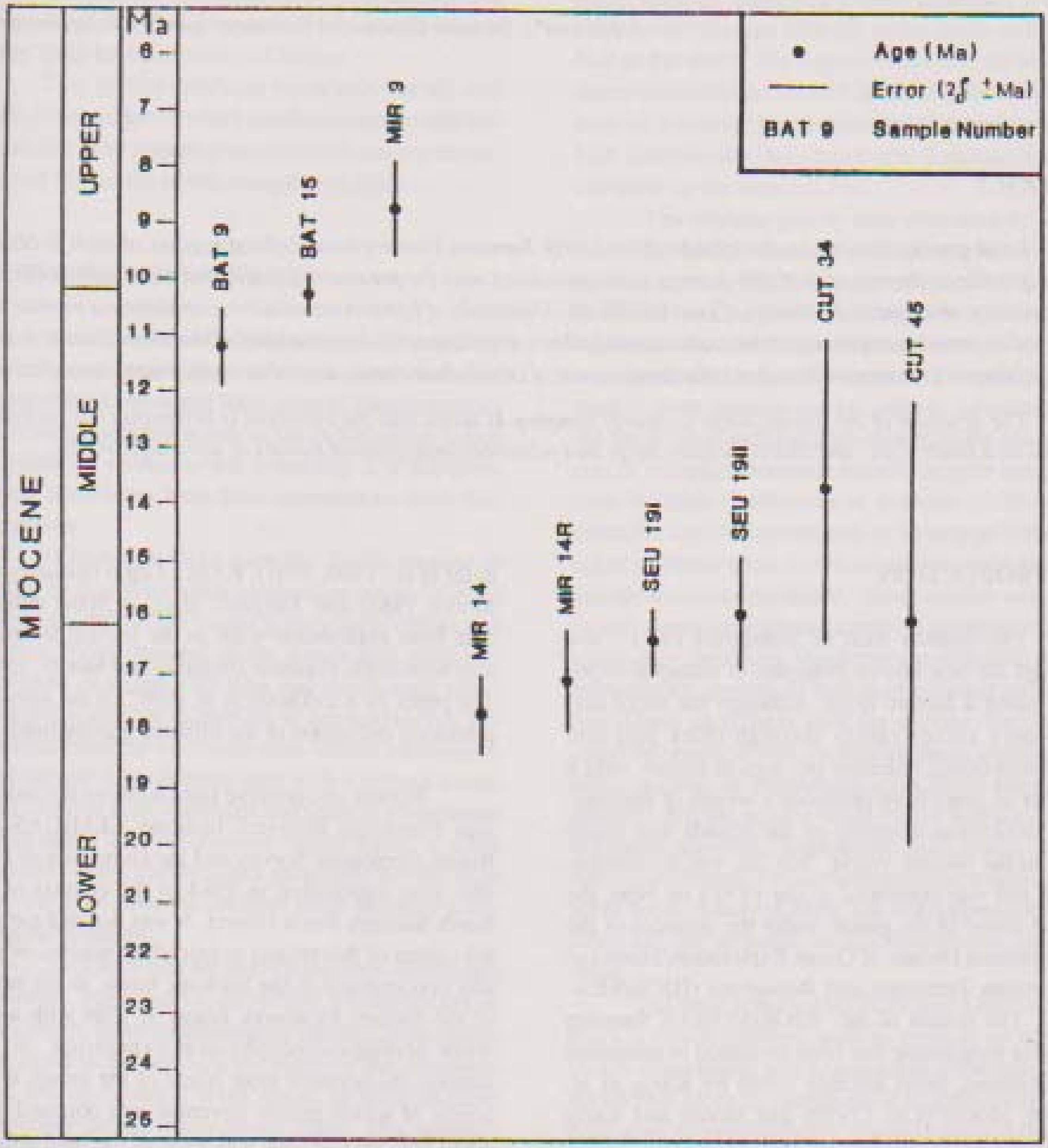

Figure 5
Miocene volcanics from the Sibolga Basin, showing age of samples and error margins on calculations