Sandstones of arc and ophiolite provenance in backarc basin, Halmahera, eastern Indonesia

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Sandstones of arc and ophiolite provenance in backarc basin, Halmahera, eastern Indonesia

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Abstract: Analyses of sedimentary rocks from a late Neogene backarc basin on the island of Halmahera in eastern Indonesia show that the detrital mineral assemblages in the sandstones have distinctive characteristics. Quartz is extremely rare in the entire sequence of up to 4 km of basin sediments, clearly indicating that there has been no input from continental sources throughout the basin history. Sediments derived from two distinct provenance areas are recognized: sandstones dominated by volcanic rocks occur in the western half of the basin and in the eastern part there are black sands composed largely of ultrabasic debris interbedded with carbonate mudstones. These sandstone petrographies reflect the nature of the terrains which have bordered the Halmahera Basin throughout its history and other small basins formed in an ‘oceanic’ setting may show similar characteristics. Temporal changes in the volcaniclastic components are attributed to stages in the evolution of the adjacent volcanic arc and do not reflect the degree of dissection of an arc massif.

Numerous sedimentary basins of variable sizes have formed during the Cenozoic in the complex mosaic of small plates at the west Pacific margin (Fig. 1). These basins lie in forearc and backarc collisional settings and in strike-slip zones in areas of oblique collision. The nature of the fill of these sedimentary basins is controlled by the equatorial latitude (and hence high biogenic productivity) and the nature of the surrounding terranes. These include small pieces of continental crust detached by rifting and strike-slip faulting, old arc volcanic rocks and related sedimentary rocks, pieces of oceanic crust structurally imbricated with these arc massifs and active volcanic arcs. Each of these types of source area provide distinctive suites of mineral grains and lithic clasts to the adjacent basins and their contribution can be assessed from petrographic studies of the basin-fill sediments.

Sandstones with low quartz contents and a high proportion of volcanic lithic fragments are characteristic of undissected arc provenances (Dickinson & Suczek 1979). Dickinson (1982) demonstrates that forearc sandstones of the Circum-Pacific belt have similar compositions; variations in the detrital modes are interpreted to reflect varying degrees of dissection of the volcano-plutonic complexes of arc massifs. Dickinson (1982) notes that these sands have a consistent feldspar to quartz ratio of between 1:1 and 1:2 and that the petrology of these sands may serve as a reliable guide for the recognition of analogous sequences in other arcs.

In this paper, a small Neogene basin in a backarc setting adjacent to the Halmahera island arc in Eastern Indonesia is considered (Fig. 1). Throughout its history this basin received detritus only from arc and ophiolitic terranes. These terranes originated in the west Pacific, far from any continental crust and throughout the history of the basin there has been no influx of material from the Australian continental margin which lies to the south. The arenites of the Halmahera Basin are remarkable and distinctive because they are quartz-free; the clastic components are dominated by material derived from island arc volcanic and ultrabasic or gabbroic ophiolitic rocks. The sedimentary sequence in this basin is an interesting example of a basin formed in an ‘oceanic’ setting which may later become incorporated into an orogenic belt as collision proceeds.

Tectonic setting

The island of Halmahera lies in the middle of a number of small plates at the convergent triple junction where the Pacific, Eurasian and Indian/Australian plates meet (Hamilton 1979). It presently lies at the southwest corner of the Philippine Sea Plate (Nichols et al. 1990). To the
south, the Sorong Fault Zone is a strike-slip plate boundary with the Australian Plate; to the west convergence between the Philippine Sea Plate and the Eurasian margin is taken up in the dual subduction systems of the Molucca Sea Collision Zone (Silver & Moore 1978; Moore & Silver 1983).

During the late Neogene, the Halmahera Trench was the site of eastward subduction of the Molucca Sea Plate beneath Halmahera and there is still an associated active volcanic arc along the west side of the island (Hatherton & Dickinson 1969). Subduction at the Halmahera Trench commenced in the Late Miocene (Hall 1987; Nichols & Hall 1990). Up until this time, the Miocene had been a period of shallow marine carbonate sedimentation over most of Halmahera and adjacent areas. In the late Miocene uplift along the western edge of the island and downwarp to the east led to the formation of a basin, termed the 'Halmahera Basin' (Nichols & Hall 1990). The Halmahera Basin was a broad (at least 200 km perpendicular to the arc) back-arc basin from the Late Miocene until it was modified by east–west compression across the island at the end of the Pliocene (Nichols & Hall 1990).

The island of Halmahera has a distinctive K-shape of four arms linked by a central zone (Fig. 2). This study has concentrated on the southeastern and southwestern arms of the island where late Miocene to Pliocene sedimentary rocks of the Halmahera basin form extensive areas of outcrop. Exposure on the island is limited to sections in deeply incised rivers in a rugged area which is totally covered by tropical rain forest and largely without tracks.

Stratigraphy

The stratigraphy of Halmahera is summarized in
Fig. 2. Outline of the geology of Halmahera. The Mio-Pliocene sedimentary rocks in the southern part of Halmahera form the Weda Group. The basement sediments in eastern Halmahera are the Buli Group and the volcanic basement of western Halmahera is the Oha Volcanic Formation. The central fold zone lies north–south across the centre of the island.

Fig. 3. The basement of the eastern part of the island is made up of a Mesozoic ophiolite imbricated with a complex of Upper Cretaceous and Eocene volcaniclastic rocks and limestones deposited in a forearc setting, the Buli Group (Hall et al. 1988a,b). This basement was deformed, uplifted and partly eroded before the beginning of the Miocene; basal conglomerates
of fluvial and littoral origin are found underlying a Miocene carbonate sequence up to 500 m thick. These carbonates from the Subaim Limestone Formation (Hall et al. 1988c) and they are dominantly shallow marine reef and reef-related deposits.

In western Halmahera the basement is a deformed association of volcanic and coarse volcaniclastic rocks of basaltic to andesitic composition, the Oha Volcanic Formation (Hall et al. 1988b; Hakim 1989). These rocks have not been dated, but they contain pebbles of Eocene limestone and they show similarities to the Upper Cretaceous to Eocene rocks of the Buli Group in Eastern Halmahera; the volcanic rocks of the Oha Volcanic Formation are very similar to the volcanic component of the Buli Group in their petrology, textures, mineralogy and chemistry (Hakim 1989). This suggests that western and eastern Halmahera formed an arc–forearc complex in the Late Cretaceous and Eocene.

Miocene limestones are found as abundant clasts within the Neogene rocks of the western arms of the island; a small outlier of limestone on the southwest arm may also be Miocene in age. These occurrences suggest that the Miocene limestone cover was largely stripped off when the western side of the island was uplifted in the Late Miocene. The Loku Formation lies unconformably on the basement (the Oha Volcanic Formation) and is exposed on the west side of the western arm of Halmahera. It is a sequence of turbiditic sandstones and siltstones which is strongly deformed and overlain by largely undeformed sedimentary rocks of the Weda Group. The nature of the contact is uncertain; it may be a thrust or an unconformity. The Loku Formation has not been included in this study.

Sedimentary rocks of late Neogene age on Halmahera were previously assigned to the Weda Series (Bessho 1944) and to the Weda Formation by Apandi & Sudana (1980), Supriatna (1980) and Yasin (1980). Most of these rocks are now assigned to the Weda Group (Fig. 3) which is subdivided into a number of formations by Hall et al. (1988b, c) and Nichols & Hall (1990). These formations have been dated as late Miocene to Pliocene in age on the basis of foraminifers and nannofossils. In western Halmahera the Superak and Akelamo Formations are Late Miocene in age; the Dufuk and
Gola Formations are early Pliocene in age. The Saolat Formation of eastern Halmahera is the stratigraphic equivalent of the western arm formations and is late Miocene to early Pliocene in age. In the Central Zone of Halmahera, Upper Miocene–Lower Pliocene and Pliocene sedimentary rocks are mapped as undifferentiated Weda Group because the tight folding and the nature of the exposure in this belt precludes division of the sequence into separate formations.

At the northern end of the SW arm, rocks assigned to the Kulefu Formation rest unconformably upon the folded rocks of the Weda Group. No fauna has been found in the Kulefu Formation and the formation is considered likely to be Pliocene in age (Nichols & Hall 1990).

**Weda Group and younger sedimentary rocks**

The Weda Group constitutes the fill of the Halmahera Basin which developed behind the Halmahera Arc by crustal downwarp during the late Neogene (Nichols & Hall 1990). The basin was at least 200 km across from east to west and up to 400 km long, parallel to the Halmahera Trench (Fig. 4). Reconstructions of the Halmahera Basin take into account at least 60 km of late Pliocene east–west shortening across the fold and thrust belt of the Central Zone (Hall et al. 1988b; Nichols & Hall 1990). The samples discussed in this study are arenites from the Superak, Dufuk and Saolat Formations of the Weda Group, undifferentiated Weda Group of the Central Zone, and the Kulefu Formation.

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**Fig. 4.** Palaeogeographic reconstruction of the Halmahera Basin in the late Miocene to Pliocene. 60 km of late Pliocene shortening, calculated by restoring balanced cross-sections through the central fold zone, has been taken into account.
### Table 1. Percentages of the detrital components of 84 sandstones from the Halmahera Basin calculated from point-counting of thin sections

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The Superak Formation is a sequence of conglomerates and sandstones interpreted as fan-delta and shallow marine deposits (Hall et al. 1988b). The Akelamo Formation is a poorly exposed sequence of calcareous mudstones found in discontinuous outcrops above the Superak Formation and is devoid of arenaceous material. Overlying the Superak and Akelamo Formations is the Dufuk Formation; this is a shallow marine sequence of bioturbated and cross-bedded sandstones, siltstones, calcareous mudstones and intraformational conglomerates. The Gola Formation is poorly exposed and is composed of limestone and calcareous mudstones without any sandy beds. The Saolat Formation is exposed over a large area on the southeastern arm of Halmahera. It is a mainly thick bedded calcareous mudstone and marl with some limestone beds. There are also beds of distinctive black sandstone and fine conglomerate. The arenites and rudites are well sorted, the clasts are well rounded and the beds display low angle cross stratification; this suggests deposition in a littoral environment (Hall et al. 1988b; Nichols & Hall 1990). The Kulefu Formation includes cross-bedded and bioturbated tuffaceous sandstones.

Data set

The data presented in Table 1 and used in the generation of the triangular plots and graphs in this paper were obtained by point counting thin sections of sedimentary rocks. The material under the cross wires of the microscope was identified at 0.2 mm intervals in ribbons across the slide and for each thin section between 500 and 600 counts were made. Fixed interval counting was used in preference to grain counting to reflect the relative volume of each constituent; as the selected arenites are all moderately to well sorted, the differences between the results obtained by the two methods are likely to be minor. The data presented are from 80 fine- to medium-grained sandstones selected from the Weda Group. The sandstone samples selected are generally fresh with only very minor alteration of feldspars and ferromagnesian minerals. In places the edges of the grains have been slightly corroded and replaced by calcite. With the exception of some of the aphyric volcanic lithic clasts the lithic fragments are usually easily identifiable.

Points in the count were classified into the 11 categories described below. These were chosen after petrographic examination of samples from each of the formations. As quartz is very rare it is not identified as a separate category; lithic fragments are divided into four groups to reflect the types of rock fragments present. Cement and voids are excluded from the totals.

(i) Porphyritic volcanic lithic clasts are an important component of many of these sandstones. They are volcanic rocks which occur in pieces ranging from fine sand in the sandstones to boulders in conglomerates. They are typically pyroxene and hornblende andesites with large plagioclase phenocrysts.

(ii) Aphyric volcanic lithic clasts are most common in Superak Formation arenites. They are typically basaltic in composition. Volcanic glass, which occurs in the Kulefu Formation, is included in this category.

(iii) Plagioclase feldspars with compositions in the range of andesine to labradorite (determined optically) are very common. Alkali feldspar is absent. The degree of alteration of the feldspars varies; many feldspar grains show complex zoning and inclusion patterns. The freshest feldspars occur in the Kulefu Formation.

(iv) Dark green to brown pleochroic hornblende grains are common, particularly in the Kulefu Formation, where the crystals are very fresh.

(v) Pyroxenes in these sedimentary rocks are principally clinopyroxenes with smaller amounts of orthopyroxenes: they occur in small amounts in many of the samples.

(vi) Sedimentary lithic clasts are mainly mudstones, fine siltstones and limestones and they occur in almost all the samples examined.

(vii) Clasts of serpentinite and other ultrabasic lithic fragments form an important component of the sandstones of eastern Halmahera, making up over 70% of some of the arenites from the Saolat Formation. Ultrabasic lithic clasts are absent from arenites of the SW arm and Central Zone.

(viii) Planktonic and benthic foraminifers are a very common bioclastic component of the sandstones examined. In the Saolat Formation there are thick beds of foraminiferal mudstone, wackestone and packstone. Other bioclastic components in the arenites are fragments of coralline algae, corals, echinoids, polyzoans and molluscs.

(ix) Organic material (wood, spores and resin) constitutes up to 10% of the sand size clasts, but occurs more commonly as finer material disseminated in the matrix.

(x) Clay minerals and micrite are the main components of the matrix to these sandstones. Fine silt-sized feldspars, ferromagnesian minerals, lithic fragments and disseminated organic matter also form part of the matrix.
(xi) The final category of miscellaneous material includes a wide variety of heavy minerals, including chrome spinel in the Saolat Formation, olivine and opaque minerals.

**Data presentation**

It is usual to present modal analyses of arenites in the form of triangular diagrams. The most commonly used diagram is the quartz–feldspar–lithic (QFL) plot as these three components usually make up the bulk of the clasts. However, because of the extreme scarcity of quartz, either as mineral grains or in lithic fragments, this standard plot is inappropriate for the arenites of the Halmahera Basin. A plot of lithic components is used by Dickinson & Suczek (1979) and Dickinson (1982) for comparison of circum-Pacific sandstones; a similar plot, using sedimentary, volcanic and ultrabasic rock fragments as the three components, is shown in Fig. 5 for the arenites of the Halmahera Basin. A drawback of this method of presentation is that other important and abundant components, particularly feldspar and other mineral grains, are excluded; this plot is hence not truly representative of the composition of the rock. As an alternative to triangular diagrams, a series of stacked bar charts (Fig. 6) has been used to present the modal compositions of arenites from the Weda Group of the SW arm and the Central Zone. These diagrams allow the variations in more than three components (or groups of components) to be displayed together. In Fig. 6 hornblende and pyroxene crystals have been grouped together and organic debris has been grouped with bioclastic material. The samples in each formation have been ranked in order of abundance of porphyritic volcanic lithic clasts, which is the commonest grain type in these arenites.

**Spatial and temporal variations in the framework modes**

**Spatial variations**

The lithic components plot (Fig. 5) shows clearly that the arenites from the eastern part of the island, the Saolat Formation, have a different provenance from those of western Halmahera. Lithic clasts of serpentine, the main ultrabasic lithic component, are abundant in the Saolat Formation, constituting up to 80% of the rock for some samples. Notably lacking in the arenites of the Saolat Formation in the SE arm is the volcanic mineral and lithic debris typical of the Weda Group in the SW arm, such as zoned

Fig. 5. Ternary plots of the lithic components (lithic fragments of sedimentary, ultrabasic and volcanic rocks) for arenites from the Weda Group and the Kulefu Formation.
plagioclase feldspars, fresh hornblende, and porphyritic volcanic lithic clasts.

In contrast, ultrabasic lithic clasts are entirely absent from the Weda Group arenites of the Central Zone and southwest arm. The Superak arenites are dominated by volcanic debris (crystal and volcanic lithic grains) with considerable variation in the proportions of each (Fig. 6). The Dufuk arenites are composed mainly of volcanic debris (crystal and volcanic lithic grains), sedimentary lithic grains and bioclastic debris. Tightly folded and thrust faulted Upper Miocene to Pliocene sedimentary rocks in the Central Zone of the island have the same provenance as the Weda Group arenites of western Halmahera. The Central Zone arenites are very rich in volcanic mineral and lithic grains with some variation in the proportions of crystals and volcanic lithic grains. On the basis of their clastic components the Central Zone arenites may be equivalent to either the Superak Formation or the Dufuk Formation or both.

**Fig. 6.** The principal components of the main arenaceous formations in the SW arm and the Central Zone presented as stacked bar charts. See text for discussion.

**Temporal variations**

The main differences between the Superak, Dufuk and Kulefu Formations of the SW arm can be seen on Fig. 6. The older sedimentary rocks (the Superak Formation) are generally richer in volcanic lithics than the overlying Dufuk Formation which has a higher crystal component. The volcanic lithic fragments in the Superak Formation include both porphyritic and aphyric rocks of andesitic and basaltic compositions. In the Dufuk Formation aphyric volcanic lithic clasts are less abundant. Compared to the Superak Formation, the Dufuk Formation includes samples with greater proportions of matrix and greater proportions of non-volcanic debris, reflecting the overall fining-upward trend of the Weda Group. Organic and bioclastic material occur in variable proportions in both the Superak and Dufuk Formations. Arenites from the Kulefu Formation are dominated by volcanic material and they are strikingly different from the older SW arm arenites of the Weda Group. Distinctive features of the Kulefu Formation arenites include the abundance of fresh ferromagnesian minerals, the presence of small quantities of biotite and quartz, abundant pumice and rare dacite clasts. The implications of these temporal variations in the framework components in the western Halmahera sedimentary rocks are discussed in the following section.
Source areas

Eastern Halmahera

The principal source of detritus for the eastern part of the Halmahera Basin were ultrabasic, volcanic and sedimentary rocks from the Ophiolitic Basement Complex. Many of the sandstones in the Saolat Formation are almost exclusively composed of grains of serpentinite. These sandstones are an interesting example of a sharp contrast between the textural and compositional maturities of the sediment. Texturally many of these sandstones are very mature: the grains are well-rounded, they are well to very well-sorted into layers and contain little or no matrix. However, the absence of quartz, the low proportion of feldspars and the high proportion of lithic fragments would normally indicate a very immature sediment on compositional criteria. Serpentinite, as a mineral species, is not even mentioned as a possible component of sandstone by other authors (e.g. Pettijohn 1975; Pettijohn et al. 1973). In the Saolat Formation the textural maturity is determined by the environment of deposition (a littoral setting), whereas the composition is determined by the available material, in this case a terrain composed of the ultrabasic part of an ophiolite.

Western Halmahera

The sandstones in the western part of the Halmahera Basin contain a very high proportion of material derived from a volcanic source area, including volcanic lithic fragments, plagioclase feldspars, pyroxenes and amphiboles. There are two likely sources for this detritus, the Late Cretaceous to Eocene volcanic basement of the Oha Volcanic Formation or contemporary volcanic rocks from the evolving Halmahera Arc. These two volcanic sources can be distinguished on both textural and compositional grounds (Hakim 1989). The Oha Volcanic Formation rocks are typically aphyric basalts; plagioclase feldspar and clinopyroxene are the principal phenocrysts. The Neogene arc volcanics are generally porphyritic andesites; hornblende and plagioclase are the most common phenocrysts together with minor amounts of clinopyroxene and orthopyroxene.

Conglomerates and sandstones in the Superak Formation include basaltic lithic clasts derived from the Oha Volcanic Formation, but the younger sedimentary rocks of the Weda Group contain many volcanic lithic clasts with an andesitic composition. This indicates that the older volcanic basement was supplying detritus in the early stages of development of the Halmahera Basin, but contemporaneous volcanism in the Halmahera Arc was the principal source of volcaniclastic detritus for most of the Weda Group sedimentary rocks.

A change in the volcanic character of the Halmahera Arc is indicated by the composition of arenites of the Kulefu Formation. The presence of biotite and quartz, pumice and dacite clasts indicates that they are the products of a distinct phase of volcanism in the Halmahera Arc. They are exceptionally rich in volcanic lithic and crystal debris, and the character of the debris suggests an explosive interval of acid volcanism.

Late Miocene to Pliocene palaeogeography

Two provenance areas are recognized for the clastic detritus in the Halmahera Basin in the late Neogene (Fig. 4). Sediments in the western part of the basin were mainly derived from a volcanic terrain of andesitic rocks. The coarsest sediments lay in the central part of western Halmahera with finer sediments to the south and east. This indicates that the source area lay to the west or northwest of the central part of the Halmahera. This area is currently an area of intense volcanic activity related to subduction at the Halmahera Trench.

The western Halmahera basement consists of island arc basalts belonging to the Oha Volcanic Formation which has been uplifted since the Miocene, resulting in the erosion of Miocene limestone cover and the elevation of the basement rocks to over 1000 m above sea level. However, the volcanic lithic fragments in the Weda Group sedimentary rocks are typically andesitic in character and are more similar to the volcanic rocks which form the present day Halmahera Arc (Hakim 1989). This suggests that the volcanism associated with the subduction of the Molucca Sea Plate generated the volcanic rocks which were eroded into the adjacent parts of the south Halmahera sedimentary basin. Once the Halmahera Arc became established, volcanic and volcaniclastic rocks of the arc mantled the Oha Volcanic Formation and these basement rocks were not an important source of detritus after the deposition of the Superak Formation.

Episodes in the activity in the Halmahera Arc and changes in the chemistry of the material erupted can be identified in the Weda Group sedimentary rocks. A period of volcanism in the Pliocene which produced an assemblage of
minerals characteristic of more silicic rocks is represented by the Kulefu Formation. Periods of low clastic input are represented by the muddy and calcareous Akelamo and Gola Formations. These are interpreted as periods when the volcanic activity in the southern part of the Halmahera Arc was reduced and uplift to the west of the basin was not sufficient to generate large quantities of detritus.

Although large quantities of volcanic material were shed into the Halmahera Basin at its western edge, very little (if any) of this material was transported as far east as the present outcrops of the Saolat Formation. Taking the late Pliocene east–west shortening into account, these outcrops would have been around 100 km away from the western margin of the basin. In the eastern part of the Weda Group Basin most of the late Miocene to Pliocene sedimentary rocks are intrabasinal carbonates of bioclastic material, principally foraminiferal mudstones and wackestones. Beds of sandstone and conglomerate interbedded with these carbonates were derived from an uplifted block of ophiolite and deposited in a littoral environment. These uplifted blocks within the basin must have been similar to the islands of ophiolitic rocks seen at the present day on the eastern coast of Halmahera.

This pattern of sedimentation persisted until the Halmahera Basin was modified by late Pliocene east–west compression.

Discussion

A sedimentary basin filled by clastic sediments which are almost devoid of quartz, and with serpentinite as an important clastic component in some areas, is clearly unusual but may not be unique in terms of the detrital composition. The west Pacific has been a region of subduction and arc activity throughout the Cenozoic. The oceanward shift of the subduction system currently at the Mariana Trench has resulted in linear remnant arcs within the Philippine Sea Plate. These old arc massifs are now being transported westward as the Philippine Sea Plate converges on the Eurasian margin. Small ocean basins bounded by older arc terrains have also formed to the north and east of New Guinea. As convergence between the Pacific and Eurasian plates has proceeded, some of these arc massifs have become amalgamated with each other and with slices of ophiolitic rocks to form complexes like the basement of Halmahera. Halmahera has clearly not been close enough to continental crust to receive any quartz detritus at any time in its history, and other regions of the west Pacific have had similar histories. Continental crust has only arrived adjacent to Halmahera (to the south) relatively recently as a result of the oblique convergence between the Pacific and Australian plates.

Basins have formed within the convergent zone of the west Pacific by spreading or downwarp in the backarc region, as forearc basins, intra-arc basins or as pull-apart basins between strike-slip faults. Volcaniclastic debris from contemporaneous or older arc terrains will be the principal clastic component of these basins and quartz may be absent where they are not close to any continental margin or continental fragment. Ultrabasic rocks will also contribute detritus where ophiolitic rocks have been imbricated with the arc massifs. When these basins become incorporated into an orogenic belt at the Eurasian or Australian margin their sedimentary infill will clearly show whether the basin formed (or resided) close to continental crust or if it was always surrounded by terrains of exclusively 'oceanic' origin.

The data presented here have implications for the interpretation of arc-related basin sediments. Dickinson (1982) suggested that an upward trend in arc-related sediments from volcanic lithic sandstones to feldspathic sandstones indicates a progressive dissection of the arc. However, the changing volcanic component of arenites in the Halmahera Basin reflects stages in the evolution of the volcanic arc. A pre-existing volcanic basement was uplifted and eroded in the early stages of subduction at the Halmahera Trench, but as the volcanic arc became established, the basement was mantled by younger volcanic rocks; this relationship can be seen today in the north west arm of Halmahera where Plio-Quaternary volcanic rocks overly an older volcanic basement (Fig. 2). Variations in the proportions of volcanic lithic fragments and feldspar crystals in the Halmahera Basin sediments reflect changes in the contemporaneous arc volcanism and in this case does not indicate the degree of dissection of the arc massif.

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References


