The geological history of the Latimojong region of western Sulawesi

Lloyd T. White[1∞]*, Robert Hall[1], Richard A. Armstrong[2], Anthony J. Barber[1], Marcelle BouDagher Fadel[3], Alan Baxter[4, 5], Koji Wakita[6], Christina Manning[7], Joko Soesilo[8]

1. Southeast Asia Research Group, Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey, TW20 0EX
2. Research School of Earth Sciences, The Australian National University, Canberra, Australia, 0200
3. Department of Earth Sciences, University College London, Gower Street, London, WC1E 6BT, UK
4. School of Environmental and Rural Sciences, University of New England, Armidale, New South Wales, Australia, 2351
5. Department of Earth and Planetary Sciences, McGill University, Montreal, Canada
6. Department of Earth Sciences, Yamaguchi University, Yamaguchi, Japan
7. Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey, TW20 0EX
8. Faculty of Mineral Technology, UPN Veteran Yogyakarta, Jalan SWK104, 52283, Yogyakarta, Indonesia

* Corresponding Author
∞ Present address: School of Earth and Environmental Sciences, University of Wollongong, Northfields Avenue, Wollongong, NSW, Australia, 2522

Keywords: Biostratigraphy, geochronology, granite, carbonate, zircon, mapping

Abstract

We present an updated geological map and revised stratigraphy of the Latimojong region of central–western Sulawesi. This work includes new biostratigraphic ages from the Latimojong Metamorphic Complex, Toraja Group, Makale Formation and Enrekang Volcanics, together with whole-rock geochemical data and sensitive high-resolution ion microprobe (SHRIMP) U-Pb analyses from zircons extracted from igneous rocks in the region. Previous work on the study region and in other parts of Sulawesi have discussed the age and character of two different rock sequences with similar names, the Latimojong Complex and the Latimojong Formation. One would assume that the type location for these two sequences is in the Latimojong Mountains. However, there is considerable confusion as to the character and location of these sequences. We make a distinction between the Latimojong Formation and the Latimojong Complex, and propose that the Latimojong Complex be renamed the *Latimojong Metamorphic Complex* to minimise the confusion associated with the current nomenclature. The Latimojong Metamorphic Complex is an accretionary complex of low- to high-grade metamorphic rocks tectonically mixed with cherts and ophiolitic rocks, while the Latimojong Formation consists of Upper Cretaceous weakly deformed, unmetamorphosed sediments or very low-grade metasediments (previously interpreted as flysch or distal turbidites that unconformably overlie older rocks). Our work indicates that the Latimojong Formation must be restricted to isolated, unobserved segments of the Latimojong Mountains, or are otherwise not present in the Latimojong region, meaning the Latimojong Formation would only be found further north in western Sulawesi. Radiolaria extracted from chert samples indicate that the Latimojong Metamorphic Complex was likely assembled during the Cretaceous (Aptian-Albian) and was later metamorphosed. Ages obtained from benthic and planktonic foraminifera were used to differentiate and map the Toraja Group (Ypresian to Chattian: 56–23 Ma), Makale Formation (Burdigalian to Serravallian: 20.5–11.5 Ma) and Enrekang Volcanic Series (8.0–3.6 Ma) across the study area. U-Pb isotopic data collected from magmatic zircons record several phases of volcanism (~38 Ma, ~25 Ma and 8.0–3.6 Ma) in the region. Each phase of magmatism can be distinguished according to petrology and whole-rock geochemical data. The isotopic ages also show that dacites from the Enrekang Volcanic Series are contemporaneous with the emplacement of the Palopo Granite (6.6–4.9 Ma). Miocene to Proterozoic inherited zircons within these igneous rocks support earlier suggestions

that Sulawesi potentially has a Proterozoic–Phanerozoic basement or includes sedimentary rocks (and therefore detrital zircons) derived from the erosion of Proterozoic or younger material. Some earlier work proposed that the granitic rocks in the region developed due to crustal melting associated with plate collision and radiogenic heating. Our observations however, support different interpretations, where the granites are associated with arc magmatism and/or crustal extension. The region was cross-cut by major strike-slip fault zones during the Pliocene. This deformation and the buoyancy associated with relatively young intrusions may have facilitated uplift of the mountains.

1. Introduction

The study area, herein referred to as the Latimojong region, comprises the Latimojong Mountains of central-west Sulawesi and the surrounding areas, including Tanah Toraja to the west (Fig. 1 and 2). This mountainous area includes the highest peaks found on Sulawesi, with some exceeding 3,400 m a.s.l (e.g. Rante Mario). The region is considered to include part of a Cretaceous accretionary complex and records several phases of deformation potentially associated with continent collision (Bergman et al., 1996). Existing geological maps of the region vary in quality and there is poor age control for many of the sequences in the area. We present the results of a geological study of the Latimojong Mountains. This included the collection of new age, geochemical and structural information to re-evaluate existing geological maps as well as the stratigraphy and deformation history of the region.

2. The geological framework of Sulawesi

Sulawesi is a region of amalgamated continental blocks and island arc crust that records a Cretaceous to recent history of continent-continent collision, ophiolite obduction, arc volcanism, strike-slip faulting and significant crustal extension (e.g. Katili, 1970, 1978; Audley-Charles, 1974; Hamilton, 1979; Parkinson, 1998; Spencer, 2010, 2011; Hennig et al., 2016; van Leeuwen et al., 2016). These processes are recorded in different parts of the island and this resulted in a complex geology, as is shown in Figure 1. To provide further context, there was collision between different parts of Sulawesi causing ophiolite emplacement (e.g. Audley-Charles, 1974; Hamilton, 1979; Sukamto and Simandjuntak, 1983; Coffield et al., 1993; Bergman et al., 1996; Parkinson, 1998). This is interpreted to represent an arc-continent collision between the micro-continental Sula Spur and North Arm of Sulawesi in the Early Miocene (e.g. Audley-Charles, 1974; Hamilton, 1979; Sukamto and Simandjuntak, 1983; Coffield et al., 1993; Bergman et al., 1996; Hall, 1996; 2002, 2012; van Leeuwen and Muhardjo, 2005; van Leeuwen et al., 2007; Spakman and Hall 2010; Watkinson et al. 2011). This period of collision was followed or accompanied by Middle Miocene to Pliocene phases of magmatism and metamorphism in western and north Sulawesi (e.g. Bergman et al., 1996; Elburg and Foden, 1999a; 1999b; Elburg et al., 2003; van Leeuwen et al., 2007; 2016; Spencer, 2010; 2011; Hennig et al., 2016) and strike-slip faulting (Katili, 1970; 1978; Hamilton, 1979; van Leeuwen, 1981; Sukamto, 1982; Silver et al., 1983a; 1983b; Berry and Grady, 1987; Simandjuntak et al., 1994; Surono, 1994; Jaya and Nishikawa, 2013; White et al., 2014; Hennig et al., 2016; van Leeuwen et al., 2016). The uplift associated with collision, together with other episodes of deformation and uplift, led to the exhumation of several metamorphic basement inliers. This includes the Cretaceous Baru and Bantimala complexes in south-western Sulawesi, as well as similar rocks in the Latimojong Mountains, ~100-150 km to the NNE (e.g. Coffield et al., 1993; Bergman et al., 1996; Wakita et al., 1996; Parkinson et al., 1998). These basement rocks are unconformably overlain by Upper Cretaceous turbidite deposits (e.g. the Balangbaru and Marada formations) and have been cross-cut by numerous faults (e.g. Querubin and Walters, 2012).

3. The Geology of the Latimojong region

The Latimojong region is located to the west and southwest of Palopo, a town on the northwestern coast of Bone Bay (Fig. 2). It is quite rugged, mountainous and heavily forested terrane, and therefore the fieldwork that has been conducted in this region to date has largely been restricted to an E-W section across the western slope of the mountain range and along parts of the eastern margin of the mountain range. The geology of the area, very simply, consists of a mountainous inlier of metasediments as well as gabbro, basalt and serpentinite, as well as several carbonate sequences and various Mio-Pliocene intrusions and volcanics (Fig. 2).

The first reports on the study area were provided by Dutch geologists before World War II (e.g. Brouwer, 1934). Geologists from the Geological Research and Development Centre (GRDC) later mapped this region and other parts of Sulawesi at

1:250,000 scale during the 1970's and 1980's (e.g. Djuri and Sudjatmiko, 1974; Simandjuntak et al., 1991). Isotopic dating and geochemical studies have provided information on the age and nature of igneous rocks in the region (e.g. Priadi et al., 1994; Bergman et al., 1996; Polvé et al., 1997; Elburg et al., 2003; Elburg and Foden, 1998; 1999a; 1999b) and there have been continued efforts to document the stratigraphic and structural history (Coffield et al., 1993; Bergman et al., 1996; Baharuddin and Harahap, 2000; Endaharto, 2000). Several reports also discuss the local geology of the Awak Mas orogenic gold deposit that is found in the Latimojong Mountains (e.g. van Leeuwen and Pieters 2011; Querubin and Walters 2012).

Despite this earlier work, there is still considerable uncertainty about the region's stratigraphy, structural architecture and deformation history. Current understanding of the stratigraphy is based on 1:250,000 mapping and aerial photographic interpretation as well as sparse biostratigraphic data (e.g. Djuri and Sudjatmiko, 1974; Coffield et al., 1993; Bergman et al., 1996). Furthermore, conflicting radiometric age data have been reported based on different isotopic systems used to date the same rocks (e.g. low temperature thermochronology results are older than conventional ID-TIMS U-Pb crystallization ages of zircon reported by Bergman et al., 1996). Also, as relatively few studies have been conducted in the Latimojong region, much about its geology has been inferred from comparisons to similar sequences of rocks exposed in other parts of Sulawesi (e.g. Sukamto and Simandjuntak, 1983; van Leeuwen and Muhardjo, 2005; Calvert and Hall, 2007; Hennig et al., 2016). These comparisons with other areas have led to considerable confusion about the nomenclature that is used to define the stratigraphy of western Sulawesi. We therefore attempt to resolve these issues and report new biostratigraphic data from cherts and carbonate rocks as well as new U-Pb zircon ages for granitoids and volcanic rocks across the Latimojong region.

3.1 The Latimojong Complex and the Latimojong Formation

The oldest units exposed in the region are weakly to moderately metamorphosed rocks that include grey to black slates, phyllites, cherts, marbles, quartzites and silicified breccia that are intruded by intermediate to basic rocks (Djuri and Sudjatmiko, 1974; Coffield et al., 1993; Bergman et al., 1996; Djuri et al., 1998; Querubin and Walters 2012). Djuri and Sudjatmiko (1974) classified all of these rocks as part of the "Latimojong Formation". However, later workers subsequently used the same name to define a series of thinly bedded sandstone and laminated shale deposits or 'flysch' deposits found to the west, north-west and north of the Latimojong Mountains (Sukamto and Simandjuntak, 1983; Ratman and Atmawinata, 1993; Hadiwijoyo et al., 1993; Simandjuntak et al., 1991; van Leeuwen and Muhardjo, 2005; Calvert and Hall, 2007; van Leeuwen et al., 2016; Hennig et al., 2016). These sandstones and shales are not metamorphosed or have a low-grade metamorphic character.

The most detailed descriptions of the "Latimojong Formation" are therefore from other areas, most of which are many tens to hundreds of kilometers from the Latimojong region. This includes the distal turbidite sequences from the Lariang region as described by Calvert (2000) and van Leeuwen and Muhardjo (2005). Calvert (2000) reported dark grey shales with varying amounts of siltstones and occasionally fine sandstone, with rare medium sandstone, locally with flute casts, while van Leeuwen and Muhardjo (2005) described these as weakly metamorphosed pelitic and fine-grained psammitic rocks. These sequences and their equivalents in the Karama area yield Coniacian-Maastrichtian ages from nannofossil and foraminifera (Chamberlain and Seago, 1995), Cretaceous detrital zircons (van Leeuwen and Muhardjo, 2005) and Cretaceous ammonites (Reijzer 1920). Cretaceous (Campanian to early Maastrichtian) ages were also reported for similar rocks from the Mamuju map quadrangle to the west of Latimojong Mountains (Ratman and Atmawinata, 1993). Similar sequences of low-grade metasediments of Late Campanian-Late Maastrichtian age also occur in the South Arm of Sulawesi in the Bantimala and Barru areas (e.g. Balangbaru Formation; Sukamto, 1982; Hasan, 1991) and the Biru area (e.g. Marada Formation; van Leeuwen, 1981). They are considered to have formed in a fore-arc setting along the SE margin of Sundaland during NW-directed subduction in the Late Cretaceous (van Leeuwen and Muhardjo, 2005) and they overlie highly tectonized rocks of a Lower Cretaceous accretionary and ophiolite complex (van Leeuwen, 1981; Sukamto, 1982; Wakita et al., 1996; Maulana et al., 2010). These low-grade metasediments are clearly different to those originally described as the Latimojong Formation by Djuri and Sudjatmiko (1974) within the Latimojong region.

Other workers proposed the term "*Latimojong Complex*" for the rocks exposed in the Latimojong region (Coffield et al., 1993). This term was used to encompass two sequences: (1) unmetamorphosed sediments or very low grade metasediments, described as flysch or turbidites, which overlie: (2) strongly deformed low to high grade metamorphosed rocks, both of which were considered to exist in the Latimojong region. Based on our own observations in the Latimojong region, as well as other parts of western Sulawesi, we differentiate between these two sequences. We use the term '*Latimojong Metamorphic Complex*' for the older, strongly deformed/metamorphosed rocks and 'Latimojong Formation' for the younger, unmetamorphosed or very low-grade metamorphosed sedimentary rocks.

The Latimojong Metamorphic Complex is exposed throughout the Latimojong Mountains; it is unclear whether the Latimojong Formation exists in the Latimojong region. Both sequences are considered to be Cretaceous (in a stratigraphic sense), with the Latimojong Formation unconformably overlying the Latimojong Metamorphic Complex. However, readers should note that no contact between the two units has been observed, and that there is no reliable age data available for these sequences in the Latimojong region. For example, these were originally assigned a Late Cretaceous age on the basis of Globotruncana found within claystone (Djuri and Sudjatmiko 1974), but no localities for these fossils were reported. Later mapping reports by GRDC (Simandjuntak et al., 1991) refer back to Djuri and Sudjatmiko (1974), and also refer to Cretaceous aged fossils reported from grey limestones between Pasui and Rante Lemo by Brouwer (1934). These fossils include Orbitolina and Astrarea cf. Culumellata that were said to be potentially Cretaceous in age..

The Latimojong Metamorphic Complex includes multiply deformed quartz-muscovite-albite schist, glaucophane-lawsonite schist, graphitic schists and slate (Querubin and Walters 2011; this study). Meta-igneous rocks such as amphibolite, meta-gabbro and meta-granitoids are tectonically juxtaposed within parts of the Latimojong Metamorphic Complex. These could be mapped as part of the Latimojong Metamorphic Complex, but potentially represent younger rocks (e.g. the Lamasi Complex, Palopo Granite) that were tectonically juxtaposed with the older metamorphic sequences.

We assume that the Latimojong Metamorphic Complex is equivalent to the early Late Cretaceous medium-high grade metamorphic rocks exposed in South Sulawesi in the Bantimala and Barru areas (e.g. Wakita et al., 1996). We consider the Latimojong Formation was deposited unconformably on the Latimojong Metamorphic Complex and is equivalent in age to similar lithologies exposed in other parts of Western Sulawesi such as the Balangbaru and Marada formations (Sukamto and Simandjuntak, 1983; Hasan, 1991; van Leeuwen and Muhardjo, 2005; Calvert and Hall, 2007; van Leeuwen et al., 2016). We are just not certain whether the Latimojong Formation exists within the Latimojong region.

3.2 The Lamasi Complex

Mafic to intermediate igneous rocks are exposed in the eastern Latimojong Mountains and close to the northwest coast of Bone Bay (Fig. 2 and Fig. 3). These were originally named the Lamasi Volcanics, and described as an Oligocene sequence of lava flows, basalts, andesites, volcanic breccia and volcaniclastics (Djuri and Sudjatmiko, 1974). Subsequent work demonstrated that the area originally mapped as basalts and basaltic andesites (Djuri and Sudjatmiko, 1974), also includes serpentinite, layered gabbro, isotropic gabbro, microdiorite, basaltic sheeted dykes, pillow lavas (with altered interstitial chert), dolerite, hyaloclastite, tuffs and volcaniclastic breccia (Coffield et al., 1993; Bergman et al., 1996). This suite of more mafic rocks was later re-named the Lamasi Complex (Coffield et al., 1993; Bergman et al., 1996). The basaltic rocks were interpreted to represent obducted MORB or back-arc oceanic crust as they have ‘depleted’ or MORB-like Sr and Nd isotopic ratios and REE characteristics (Bergman et al., 1996). Various isotopic data (K-Ar, ^{40}Ar-^{39}Ar, Rb-Sr and Sm-Nd) suggest Cretaceous to Oligocene ages (Priadi et al., 1994; Bergman et al., 1996). These ages are supported by field observations that show that these volcanic rocks are overlain by Lower to Middle Miocene marls and limestones (Djuri and Sudjatmiko, 1974). Similar lithologies are exposed in the Bone Mountains region, south of the Latimojong Mountains, where basalts, andesites and subordinate rhyolites are interbedded within middle Eocene to early Miocene clastics and carbonates (e.g. van Leeuwen et al., 2010).

Other workers reported K-Ar ages (19 Ma to 15 Ma) for basalts and andesites that were said to be part of the Lamasi Volcanics (Priadi et al., 1994; Elberg and Foden, 1999b). The ~15 Ma sample reported by Priadi et al., (1994) was a basaltic pillow lava. However, the sample analysed by Elberg and Foden (1999b) was from andesite float assumed to represent the Lamasi Complex. These ages are considerably younger than the Cretaceous-Eocene ages presented by Priadi et al. (1994) and Bergman et al. (1996). We suggest that these Miocene ages reflect a different magmatic event to those we classify as the Lamasi Complex.

3.3 Toraja Group (Eocene-Oligocene)

The Toraja Group is a c.1000m thick succession of locally folded terrestrial/marginal marine to shallow marine deposits. It was initially named the Toraja Formation with a type location in the Latimojong region (Djuri and Sudjatmiko, 1974) and was subdivided informally into two members (Djuri and Sudjatmiko, 1974; Coffield et al., 1993; Endaharto, 2000). The lowest member includes reddish-brown and grey shales, claystone and limestone as well as quartz sandstone, conglomerate and coal. The upper member has layers of white to grey limestone (Djuri and Sudjatmiko, 1974; Coffield et al., 1993; Bergman et al., 1996; Endaharto, 2000). The same lithologies and stratigraphic relationships are also observed in other parts of west Sulawesi (Wilson and Bosence, 1996; van Leeuwen and Muhardjo, 2005; Calvert and Hall, 2007). They were later redefined as the Toraja Group, with the lower member named the Middle to Upper Eocene Kalumpang Formation and the inter-fingering/overlying carbonates assigned to the Middle Eocene to Upper Oligocene Budungbudung Formation (Calvert and Hall, 2007).

The Toraja Group has been interpreted as a terrestrial deltaic sequence in the Latimojong and Makale regions (Fig. 4), deposited unconformably above Mesozoic basement rocks (Coffield et al., 1993; Bergman et al., 1996; Calvert and Hall, 2007). The sediments have been interpreted as a syn-rift sequence deposited during rifting associated with extension in the Makassar Strait (Coffield et al., 1993; Bergman et al., 1996; Calvert and Hall, 2007). This model is supported by reports of quartz-dominated conglomerates at the base of the Toraja Group deposited during the early stages of graben development (van Leeuwen, 1981; Coffield et al., 1993; Calvert and Hall, 2007).

Foraminifera from the Toraja Group were initially assigned a Middle Eocene to Middle Miocene age (Djuri and Sudjatmiko, 1974) but the group is now considered to have been deposited between the Eocene and Oligocene (Coffield et al., 1993; Calvert and Hall, 2007). Thin nummulitic limestones deposited on tilted fault blocks in the region mark a marine transgression during the Middle Eocene, including at the base of the Budungbudung Formation (Coffield et al., 1993; Calvert and Hall, 2007).

3.4 Makale Formation (Lower to Middle Miocene)

The Makale Formation is a 500m to 1000m-thick sequence of interbedded reef limestone and marl that conformably overlies the Toraja Group (Djuri and Sudkatmiko, 1974; Sukamto and Simandjuntak, 1983). It is considered to be the regional stratigraphic equivalent of the Middle Miocene to Lower Pliocene Tacipi Limestone (found to the east of the Walanae Fault), with the underlying Toraja Group being equivalent to the Tonasa Limestone (Wilson and Bosence, 1996). The Makale Formation probably developed as a series of pinnacle/patch reefs, similar to that proposed for the Tacipi Limestone (e.g. Grainge and Davies 1985; Coffield et al., 1993; Wilson and Bosence, 1996; Ascaria, 1997).

Reef limestones of the Makale Formation cap many of the summits in the Latimojong and Makale regions with recognizable steep cliffs and karst topography (Fig. 5). This formation is thought to represent a widespread fully marine carbonate platform. Its age is somewhat debated, with Early to Middle Miocene (Djuri and Sudkatmiko, 1974), Late Oligocene to Middle Miocene (Baharduddin and Harahap, 2000) and Eocene to Middle Miocene (Coffield et al., 1993; Endaharto, 2000) ages proposed on the basis of different fossil assemblages. The base of the formation has been described as concealed or faulted (Djuri and Sudkatmiko, 1974), and as conformable on the Toraja Group (Endaharto, 2000). The top of the formation has been eroded and overlying units have been removed (Djuri and Sudkatmiko, 1974). The basal part is overlain by deeper marine, outer shelf platform limestone (dominantly mudstones and wackestones) (Coffield et al., 1993).

3.5 Igneous Rocks

3.5.1 Oligocene Intrusives

Granites and granodiorite named the Kambuno Granite cross-cut Cenozoic volcanic breccias near Rantepao. These granites yielded a K-Ar age of 29.9 Ma (Priadi et al., 1994). Little information exists about location and extent of these granitoids, except that they are found ~5 km north of Sadang Village along the Sadang River.

3.5.2 Mio-Pliocene Extrusives (Enrekang Volcanic Series)

The Enrekang Volcanic Series is found to the west of the Latimojong Mountains and covers large parts of central-West Sulawesi (Coffield et al., 1993). It consists of volcaniclastic sandstones and conglomerates interbedded with tuffs and lava flows (e.g. Fig. 6). These sequences are ~500m to ~1000m thick and were deposited during the Middle Miocene to Pliocene, based on foraminifera and nannofossils in sedimentary rocks (Djuri and Sudkatmiko, 1974; Maryanto, 2002) and ca. 13 Ma to 2.4 Ma ages determined from K-Ar dating of biotite (Bergman et al., 1996; Polvé et al., 1997; Elburg and Foden, 1999b). The volcanic rocks are exclusively potassic to ultra-potassic in composition (e.g. Polvé et al., 1997) and have been considered equivalent to the Camba Volcanics in the South Arm of Sulawesi (e.g. Sukamto, 1982; Sukamto and Simandjuntak, 1983; Yuwono et al., 1988; Wilson and Bosence, 1996).

3.5.3 Mio-Pliocene Intrusives

Mio-Pliocene intrusive rocks are found in the Latimojong region (Djuri and Sudkatmiko, 1974; Coffield et al., 1993; Priadi et al., 1994; Bergman et al., 1996; Polvé et al., 1997). These are considered to be the plutonic equivalents of the Middle Miocene to Pliocene Enrekang Volcanic Series (Coffield et al., 1993; Bergman et al., 1996). Rb-Sr, Nd-Sm and U-Pb isotopic data were used to infer that these magmatic rocks melted a Late Proterozoic to Early Paleozoic crustal source during continent-continent collision (Bergman et al., 1996).

The granitoids exposed in the Latimojong region are known as the Palopo Granite (Simandjuntak et al., 1991; Priadi et al., 1994) or Palopo Pluton (Bergman et al., 1996). These granitoids intrude, or are in fault contact, with the Latimojong Metamorphic Complex, the Lamasi Complex and the Toraja Group (Djuri and Sudjatmiko, 1974; Simandjuntak et al., 1991; Priadi et al., 1994; Bergman et al., 1996). The Palopo Granite consists of medium- to coarse-grained granite and granodiorite (Simandjuntak et al., 1991) (Fig. 7). The granite is composed of quartz, orthoclase and minor hornblende, while the granodiorite consists of larger phenocrysts of plagioclase and K-feldspar within a quartz, feldspar, hornblende and biotite groundmass (Simandjuntak et al., 1991). The mafic minerals in both granitoids are commonly chloritized (Simandjuntak et al., 1991).

K-Ar dates of the Palopo Granite were obtained from tonalite, granodiorite and a granite dyke in the Palopo region and yielded ages of 5.0 Ma, 5.5 Ma and 8.1 Ma respectively (Sukamto, 1975). These ages were reproduced in later K-Ar analyses of the Palopo Granite (e.g. Priadi et al., 1994; Bergman et al., 1996; Polvé et al., 1997). Bergman et al. (1996) also obtained Rb-Sr and Sm-Nd whole rock analyses, as well as a U-Pb ID-TIMS date of zircon, together with fission track analyses of apatite, zircon and titanite for several Palopo Granite samples. The ages that were obtained from these various analyses range between ~11 Ma and ~2 Ma. The one U-Pb zircon age from the Palopo Granite (5.4 Ma) was the same as K-Ar age (5.4 ± 0.4 Ma) from the same sample (Bergman et al., 1996). This is highly unusual, and indicates either that there was a problem with one (or both) of these analyses, or that the granite must have cooled rapidly on emplacement.

3.6 Upper Miocene to Recent clastic deposits

The sedimentary rocks described above are overlain by Upper Miocene to Pliocene mudstones, siltstones, sandstones and conglomerates of the Walanae Formation (Grainge and Davies, 1985) (Fig. 8), as well up to c.100 m of recent alluvium, clay, silt, sand, gravel and limestone (Djuri and Sudjatmiko, 1974).

4. Mapping and sample details

The work we present is largely a summary of several field campaigns conducted during 1995-1997 (AJB/JS) and in 2012 (LTW/RH). The majority of the results that are presented here are from fieldwork conducted in September 2012, however, we relied on the Southeast Asia Research Group's sample catalogue as well as existing maps and thin sections to develop a revised map of the Latimojong region (Fig. 2). Further details on the field observations and lithologies observed are included in Supplementary File 1. This map was developed using a GIS using high-resolution, remotely sensed data and aerial imagery to develop a better understanding of the regional structural grain and potential contacts between units (Fig. 2). These data were highly valuable as we did not locate many contacts between geological units in the field. The majority of the contacts that we did observe were sub-vertical and these are likely to be associated with phases of strike-slip faulting during the Late Miocene to Recent.

Several spot samples of chert, carbonate and volcaniclastic rocks were sampled from the Latimojong Metamorphic Complex, Lamasi Complex, Toraja Formation, Enrekang Volcanic Series and Makale Formation for radiolarian and foraminiferal biostratigraphy (Fig. 2). The results for each sequence/formation are discussed below (Section 5). Various granitic and volcanic rocks were also sampled in the area (Fig. 2, Fig. 6, Fig. 7, Fig. 9). Eleven representative samples were selected for geochemical analyses. Eight of these samples were then selected for zircon U-Pb dating. The primary aim of the geochemical and isotopic analyses was to determine if certain compositions were generated at specific times. In several cases, we were able to obtain samples of dykes that cross-cut older sedimentary and igneous rocks that have allowed us to limit the timing of deposition/emplacement of particular units.

5. Biostratigraphic results

5.1 Chert from the Latimojong Metamorphic Complex or Lamasi Complex

Several samples of chert intercalated with pillow basalts from the Lamasi Complex (e.g. Fig. 3) were sampled, but no radiolarians could be identified due to extensive veining and recrystallization. Identifiable radiolarians were extracted from a 0.5m boulder of red chert found in a river to the west of the Latimojong Mountains (Fig. 2 and Fig. 10). This sample contained several poorly preserved radiolarian tests, including *Stichomitra* cf. *japonica, Xitus* cf. *clava, Thanarla* cf. *pulchra, Distylocapsa* sp., *Hiscocapsa* sp. and *Dictyomitra* spp. (Fig. 10), indicating an Early Cretaceous (possibly Albian) age (O'Dogherty, 2009). The chert sample was found alongside other river float, including pieces of schist, quartzite, sandstone, diorite and deformed igneous breccia. We suspect this most likely represents material from the Latimojong Metamorphic Complex.

5.2 Foraminifera from the Toraja Group, Makale Formation and Enrekang Volcanics

Benthic and planktonic foraminifera from eighteen samples of packstone and wackestones from the Latimojong region (Fig. 2) were dated based on BouDagher-Fadel (2008, 2013), and assigned ages using the time scale of Gradstein et al. (2012). The age range of each of these samples and the stratigraphic unit they are assigned to (Toraja Group, Makale Formation and Enrekang Volcanic Series; Djuri and Sadjatmiko, 1974; Calvert and Hall, 2007) are summarised in Fig. 11. The location of each of these samples is shown on the geological map in Fig. 2. Details of the sample location and foraminifera identified in each sample are presented in Supp. File 1 and the interactive map file.

5.2.1 The Toraja Group

Foraminifera analyses indicate that the Toraja Group is Eocene to Oligocene (Ypresian to Chattian; 56–23 Ma) and was deposited in a reef and inner neritic setting in the Latimojong region (Fig. 11 and Supp. File 1 and 2). Many of the samples record age ranges that do not overlap (e.g. K12-10, K12-13, K12-17, PA178, PA277), while the timing of deposition of other samples were poorly constrained (e.g. K12-22A, PA58, PA59) (Fig 10 and Supp. File 1).

5.2.2 The Makale Formation

Five samples of foraminifera-bearing packstones and wackestones (PA56, PA63, PA184, K12-20A, K12-20B) from the Makale Formation (Fig. 2) have Miocene ages of Burdigalian and Serravallian (20.5–11.5 Ma) (Fig. 11). These assemblages, along with those obtained from the Toraja Group, indicate that there was potentially a minimum of ~2.5 Myr. to a maximum of 15 Myr. without significant carbonate deposition (Fig. 11), assuming no sampling bias.

5.2.3 Enrekang Volcanic Series

Two samples of indurated foraminifera-bearing wackestone (K12-20A and -20B) were collected from the Enrekang Volcanic Series. Sample K12-20A provided only a wide Cenozoic age as the foraminifera could be identified only to genus level (e.g. *Operculina sp., Amphistegina sp., Globigerina sp.*), but sample K12-20B yielded a Late Miocene–Early Pliocene age. The age of this sample is interpreted to indicate that the Enrekang Volcanic Series was deposited at some time between the Tortonian and Zanclean (11.5 Ma to 3.5 Ma) (Fig. 11) in the Latimojong region.

6. Geochemistry and isotopic dating of igneous rocks

6.1 Methodology: Geochemistry and Isotopic Dating

6.1.1 Sample Processing

Samples were crushed into 2-5 cm^3 pieces using a jaw crusher. The crushed aggregate was rinsed to remove any potential contaminants and left to dry before being pulverised to a fine-powder using a tungsten carbide swing mill. The aggregate was sieved using a disposable nylon mesh to capture material that was <250 µm. This was 'deslimed' to remove the finest grain size fraction. A zircon concentrate was obtained by processing this material through high-density liquids and magnetic separation. Zircons were hand picked and set in 25 mm epoxy disks along with the Temora-2 U-Pb zircon standard (Black et al., 2004). The mount was polished to expose the mid-sections of the grains and was examined with an optical microscope and photographed under transmitted and reflected light. All zircons were then imaged with a Robinson Cathodoluminescence (CL) detector fitted to a JEOL JSM 6610-A scanning electron microscope (SEM) at the Research School of Earth Sciences, The Australian National University (ANU).

6.1.2 Zircon Geochronology

U-Pb isotopic measurements were collected from zircons from eight samples using a sensitive high resolution ion microprobe (SHRIMP-RG) at the Research School of Earth Sciences, ANU. The CL imagery as well as reflected and transmitted light microscopy were used to identify zircon cores and growth rims that were suitable for dating. Standard zircon SL13 (U = 238 ppm; Th = 21 ppm; Claoué-Long et al., 1995) was used to calibrate the U and Th concentrations and Pb/U ratios were corrected for instrumental inter-element fractionation using the ratios measured on the standard zircon Temora 2 (416.8 ± 1.3 Ma; Black et al., 2004). One analysis of a Temora zircon was made for every four analyses of unknowns. The data were reduced in a manner similar to that described by Williams (1998, and references therein), using the SQUID 2 Excel macro (Ludwig, 2009) and these were interrogated further using Isoplot (Ludwig, 2003). The decay constants recommended by the IUGS Subcommission on Geochronology (as given in Steiger and Jäger, 1977) were used in age calculations. Uncertainties given for individual U-Pb analyses (ratios and ages) are at the 1-sigma level. All age results less than 800 Ma are reported using ^{207}Pb corrected $^{206}Pb/^{238}U$ system because of the uncertainties associated with low ^{204}Pb,

^{207}Pb and ^{208}Pb yields from zircons of this age. Ages >800 Ma are reported using ^{204}Pb corrected ^{207}Pb/^{206}Pb system. We assessed the common Pb concentrations recorded for each of the analyses for each sample. We found that rejecting analyses with >2% common Pb made no appreciable difference to the weighted mean age calculated for each sample, but it did influence the MSWD associated with this age. The uranium concentrations and age obtained for each zircon were examined to assess for potential matrix effects associated with high-U zircon sample (e.g. White and Ireland, 2012). This issue was only observed in one sample (K12-6B), and in this case analyses that recorded U concentrations >5000 ppm were rejected from the calculation of the weighted mean age.

6.1.3 Geochemistry

An aliquot of each milled rock sample (described above in 4.1.1) was collected prior to being sieved. The aliquot was milled further and made into glass disks and pellets for whole rock major and trace element geochemical analyses. The major and trace element data were collected using a Panalytical Axios WDS XRF spectrometer at Royal Holloway, University of London.

7. Zircon Geochronology Results

The eight variably deformed granitoids and volcanic to hypabyssal rocks were dated from the Latimojong region. The geochronology results are discussed below according to lithology and age, ordered youngest to oldest. These results are summarised in Table 1. Tera Wasserburg concordia diagrams and relative probability age plots for the samples are shown in Fig. 12 and Fig. 13 respectively.

7.1 Enrekang Volcanic Series

Three dacitic samples yielded latest Miocene to Pliocene zircon U-Pb ages and are classified as the Enrekang Volcanic Series. The youngest sample is a fine-grained felsic dyke (K12-33B) that cross-cuts a schist of the Latimojong Complex (Fig. 6a). SHRIMP U-Pb analyses of five individual zircon crystals were appreciably older (1432 Ma, 235 Ma, 213 Ma, 38 Ma, 35.8 Ma) compared to the dominant 3.9 Ma age population. These older analyses are interpreted to be inherited ages from the partially melted country rocks. The other fifteen zircon analyses are interpreted as magmatic ages. Four of these analyses yielded >2% common Pb and were thus rejected from further consideration. The remaining 11 analyses yielded a weighted mean age of 3.9 ± 0.1 Ma (MSWD = 1.0) and is interpreted as the age of crystallization of this sample.

The second dacite sample (K12-21A) from the Enrekang Volcanic Series has a weighted mean age of 6.8 ± 0.1 Ma (MSWD = 2.7) (n = 24 analyses). This sample also contained two inherited zircon cores (136 Ma and 9.1 Ma).

The third sample of dacite (K12-27) from the Enrekang Volcanic Series yielded a weighted mean age of 7.5 ± 0.1 Ma (MSWD = 1.5) (n = 15). There were several inherited ages (193 Ma, 38.3 Ma, 37.7 Ma, 35.7 Ma, 36.3 Ma, 36.5 Ma and 34.5 Ma). The inherited analyses between 38–34 Ma clearly define one age population and yield a weighted mean age of 36.5 ± 0.7 Ma (MSWD = 1.2) (n = 6). All of these 38-34 Ma analyses were obtained from zircon cores, or zircon grains that showed no evidence of overgrowths. This age was also recorded by the Enrekang Volcanic Series dyke (sample K12-33B) discussed above and a sample that we propose is part of the Lamasi Volcanics (K12-11B) (Fig. 13a, 13d, 13h) discussed below. We therefore interpret this 36.5 Ma age to record Eocene magmatism in Western Sulawesi, preserved in zircon xenocrysts sampled by the Pliocene dacitic magma.

7.2 Palopo Granite

Zircons were extracted from one undeformed sample (K12-4B) and two deformed samples (K12-35B and K12-6B) of granodiorite from the Palopo Granite. These samples yielded weighted mean ages of:

- 5.0 ± 0.1 Ma (MSWD = 2.1) (n = 16) [K12-4B].
- 6.3 ± 0.1 Ma (MSWD = 1.0) (n = 14) [K12-35B].
- 6.4 ± 0.2 Ma (MSWD = 4.8) (n = 9) [K12-6B].

Each of these granodiorite samples recorded inherited ages. Only one inherited age (1728 Ma) was obtained from sample K12-4B. Multiple inherited ages [309 Ma, 265 Ma, 219 Ma, 195 Ma and 102 Ma] and [1460 Ma, 373 Ma, 260 Ma, 131 Ma, 102 Ma, 9.8 Ma and 8.3 Ma] were obtained from samples K12-35B and K12-6B respectively.

7.3 Bua Rhyolite Dyke [Lamasi Complex?] (Sample: K12-7-31)

Zircons were extracted from a rhyolite dyke that cross-cuts basalts from the Lamasi Volcanics (Fig. 9). We refer to this rhyolitic dyke as the 'Bua Rhyolite' as it outcrops near Bua Village (e.g. Fig. 2 and Fig. 9). The magmatic zircons in this sample exhibit very low uranium and thorium concentrations ([U]: 15–108 ppm and [Th]: 2–47 ppm) and most grains recorded common Pb concentrations >2% (Supp. Data File 3). If these are excluded, the remaining analyses yield a weighted mean age of 25.0 Ma ± 0.7 Ma (MSWD = 0.5) (n = 4). This age is effectively the same as a weighted mean age that includes all of the high common Pb analyses [25.0 Ma ± 0.3 Ma (MSWD = 1.1) (n = 23 analyses)]. The Bua Rhyolite is therefore interpreted to have crystallized at 25.0 Ma ± 0.7 Ma and this provides a minimum age for the Lamasi Complex. The Bua Rhyolite Dyke also contains inherited Paleoproterozoic (2474 Ma) and Archean (2680 Ma) zircon cores.

<u>7.4 Andesite [Lamasi Complex] (Sample: K12-11B)</u>

Several zircons were extracted from one sample of andesite (K12-11B) and we were able to date twelve grains from this sample. Four of the analyses were between 37 Ma and 40 Ma. These yielded a weighted mean age of 38.2 ± 1.3 Ma (MSWD = 2.2) and we interpret this as the age of crystallization of this sample. The remaining analyses are interpreted as inherited ages (1717 Ma, 102 Ma, 101 Ma, 99.6 Ma, 99.2 Ma, 94.2 Ma, 89.6 Ma, 51 Ma and 44 Ma). We interpret this sample to be part of the Lamasi Complex.

8. Geochemistry results for the igneous rocks

The geochemical data obtained from the igneous rocks indicate that there are several distinct populations with different whole rock chemistries. While many of the volcanic samples show evidence of moderate to substantial alteration, three broad compositional groups can be identified (Fig. 14a). Samples from the Enrekang Volcanic Series and the Palopo Granite plot within the dacite/granodiorite field (Fig. 14a). Two analyses plot outside this dominant group represented by the Enrekang Volcanic Series and Palopo Granite. These 'outliers' represent an altered andesite (K12-11B) found within a strike-slip fault zone and the Bua Rhyolite Dyke (K12-31) that cross-cuts basalts of the Lamasi Volcanics.

The broad differences in geochemistry are also reflected in other geochemical indices (e.g. Frost et al., 2001; Frost and Frost 2008) and discrimination plots (e.g. Modified Alkali Lime vs. SiO_2; FeO/(FeO+MgO) vs. SiO_2 and Aluminium Saturation Index (ASI) vs. SiO_2) (Fig. 14b-d) (Supp. Data File 4). The geochemical groupings also correspond to different crystallization ages (cf. Fig. 14 and the geochronology results presented in Section 7).

9. Discussion

9.1 Revised Geological Map and Stratigraphy

Our field investigations have shown considerable differences from earlier geological maps of the Latimojong region (e.g. Djuri and Sudjatmiko, 1974; Simandjuntak et al., 1991; Bergman et al. 1996) (Fig. 2). Some of these discrepancies reflect the location of our traverses that sampled new exposures (e.g. new road cuttings) provided as the region has been developed. Our fieldwork and access to high-resolution remotely sensed data enabled a revised geological map to be produced (Fig. 2). The new biostratigraphic and isotopic dating provide some limitations on the age of deposition, igneous activity and deformation in the region. From what we observed, we consider that many of the thrust contacts proposed by Bergman et al. (1996) could equally be normal faults, strike-slip faults or stratigraphic (conformable or unconformable) contacts. Because of the terrain and vegetation almost all contacts are interpreted.

9.1.1 The Latimojong Metamorphic Complex

There are no precise age controls on the age of the Latimojong Metamorphic Complex. Our mapping of the region has reduced its area compared to earlier geological maps (Fig. 2) (e.g. Djuri and Sudjatmiko, 1974). The metamorphic rocks are assumed to be Cretaceous as they are similar to lithologies that have been dated in Barru and Bantimala (e.g. Wakita et al., 1996; Parkinson et al., 1998). The Aptian-Albian age radiolaria that we identified in a piece of chert float, found to the west of the Latimojong Mountains, provides some support for this assumption. More support for this is provided by 128-123 Ma zircon fission track ages obtained from two metasediment samples collected from the western edge of the Latimojong Mountains as well as a Cretaceous (114 ± 2 Ma) K/Ar age obtained from white mica in an Oligocene sandstone from the Latimojong region (Bergman et al., 1996). When considered together, these Cretaceous ages may indicate that the Latimojong Metamorphic Complex formed in the Early Cretaceous. Future isotopic age data (e.g.

^{40}Ar-^{39}Ar analyses of mica and U-Pb dating of zircon) from Latimojong Metamorphic Complex schists should provide more clarity as to the age of metamorphism and the age spectra of the protolith.

9.1.2 The Lamasi Complex

The rocks of the Lamasi Complex are predominantly found to the east of the Latimojong Mountains (Fig. 2). We assigned the majority of mafic volcanic (e.g. basalt) and intrusive rocks (gabbros) that occur east of the Latimojong Mountains to the Lamasi Complex. We interpret that the 25.0 ± 0.7 Ma date obtained from a rhyolite dyke (the Bua Rhyolite) that cross-cuts basalt (Fig. 9) provides a minimum limit on the age of the Lamasi Complex. A similar age (29.9 Ma) was obtained from a K-Ar age for granite that cross-cut Cenozoic volcanic breccias near Rantepao (Priadi et al., 1994). Together, these two ages from felsic rocks that crosscut mafic rocks provide a minimum time estimate for the emplacement of the Lamasi Complex volcanics. We therefore suspect that the ~38.2 ± 1.3 Ma age obtained from a highly altered andesite (Sample: K12-11B) reflects a phase of volcanism associated with the Lamasi Complex. The evidence for this Eocene-Oligocene phase of magmatism is also supported by ages obtained from inherited zircons from dacites of the Enrekang Volcanic Series (e.g. K12-27: Fig. 13f). Similar ages have also been reported from earlier K-Ar dating (e.g. Priadi et al., 1994) and from igneous rocks further north in Central Sulawesi and Sulawesi's "Neck" (Hennig et al., 2016).

We speculate that the gabbros and ultramafic rocks found in this area are part of the Latimojong Metamorphic Complex and are of Cretaceous age (although this is not reflected in the geological map shown in Fig. 2). Similar ultramafic rocks are found associated with Cretaceous medium- to high-grade metamorphic rocks in the Barru and Bantimala regions in southern Sulawesi (e.g. Wakita at al., 1996; Parkinson et al., 1998).

The isotopic and biostratigraphic ages obtained from the Lamasi Complex and the Toraja Group indicate that the lowermost sediments of the Toraja Group were deposited at the same time as the igneous rocks of the Lamasi Complex were crystallizing during the Eocene (Fig. 15). Continued deposition of the Toraja Group likely means that these sediments stratigraphically overlie the Lamasi Complex in places. We could not verify this stratigraphic relationship in the Latimojong region (partly due to the terrain, vegetation cover as well as the numerous strike-slip faults). However, this stratigraphic relationship is observed in the Lariang and Karama regions (Calvert and Hall, 2007). Eocene volcanics are also considered to represent the acoustic basement in the East Sengkang Basin (Grainge and Davies, 1985), which is directly to the south of the Latimojong region. The Lamasi Complex may also correspond with the similar volcanics found within the mid- to late Eocene Matajang Formation (Group B) in the Bone Mountains region. Considering this widespread basaltic-andesitic volcanism, the Lamasi Complex may represent Eocene-Oligocene arc/back-arc volcanic rocks obducted during the Early to Middle Miocene and/or translated by movement along regional faults (e.g. Bergman et al., 1996; van Leeuwen et al., 2010).

9.1.3 Toraja Group

The biostratigraphic data obtained in this study indicate that the sedimentary rocks of the Toraja Group were deposited during the Eocene (from the Ypresian) and Oligocene (to the Chattian). This is largely in agreement with other work conducted in the region and further afield (e.g. Coffield et al., 1993; Calvert and Hall, 2007). However, all previous work indicates the Toraja Group was deposited between the Middle Eocene and Oligocene, while one of our samples extends this range to the Ypresian (Sample: K12-18). To our knowledge, there are no earlier reports of early Eocene fossils for the Toraja Group, so this age is potentially quite important. While this age was obtained from an isolated spot sample, we are confident of the age assigned to this particular sample on the basis of the foraminifera present. This new piece of information indicates evidence of shallow marine/reef conditions at c. 54–52 Ma. This may represent a marine incursion during the Early Eocene (e.g. Fig. 11 and Fig. 15), similar to the thin layer of nummulitic carbonates deposited during the Middle Eocene at the base of the Budungbudung Formation found northwest of the Latimojong region (e.g. Calvert and Hall, 2007). The Toraja Group and associated sequences from other parts of western Sulawesi indicate that shallow marine carbonate deposition became more widespread during later parts of the Eocene and Oligocene (Sukamto and Simandjuntak, 1983; Coffield et al., 1993; Wilson and Bosence, 1996; Bergman et al., 1996; Calvert and Hall, 2007).

9.1.4 Makale Formation

Our results from several spot samples indicate that the carbonates of the Makale Formation were deposited during the Early to Middle Miocene (Burdigalian to Serravallian) (Fig. 11 and Fig. 15). These ages are in agreement with the work of Djuri and Sudkatmiko (1974). We consider the Eocene and Oligocene ages reported by other workers (see Section 3.4) were obtained from the Toraja Group, rather than the Makale Formation (e.g. Fig. 15). Our primary justification for dating the Makale Formation as Early to Middle Miocene in age, and the Toraja Group as Eocene to Oligocene in age is based on the pattern of outcrops that emerged through mapping (Fig. 2) and because the ages obtained from foraminifera show that there could have been a ~2.5 Ma break in deposition during the earliest Miocene (Aquitanian) (Fig. 11 and Fig. 15). The ages we propose for the Makale Formation support it being the stratigraphic equivalent of the Tacipi Limestone located further to the south (e.g. see Section 3.4 for further details)..

9.1.5 Enrekang Volcanic Series and the Palopo Granite

The Enrekang Volcanic Series was used by Coffield et al., (1993) to group several formations of high-K volcanics together (the Sekata Formation and the Adang, Sesean and Talaya volcanics). None of these formations have been studied in detail, but some geochemical, isotopic and radiometric age data exist (Priadi et al., 1994; Bergman et al., 1996; Elburg and Foden 1999). These data indicate that the Enrekang Volcanic Series consists of stratovolcano and volcanic apron successions with various pyroclastic and volcaniclastic deposits that were deposited between 13.1 Ma and 2.4 Ma (e.g. Priadi et al., 1994; Bergman et al., 1996). In the Latimojong region, we dated two dacites that were emplaced between 6-8 Ma as well as a 3.9 Ma felsic dyke that cross-cut part of the Latimojong Metamorphic Complex. On the basis of their age, geochemistry and petrology, we classified these dacites as being part of the Enrekang Volcanic Series. These results were compared alongside the biostratigraphic ages obtained from foraminifera in two samples from the Enrekang Volcanic Series (K12-22B) (Fig. 11). The overlap between the ages from foraminifera and those obtained from U-Pb isotopic analyses of zircons define an age range of 8.0 Ma to 3.6 Ma for the magmatism and volcaniclastic sedimentation of the Enrekang Volcanic Series (i.e. mid-Tortonian to Zanclean) (Fig. 15). Readers should note however, that all of these ages represent “spot samples”, so the true age range for this sequence may be broader.

Interestingly, the dacites and felsic dyke yield similar ages and compositions to the Palopo Granite (Fig. 12–14) and it is possible that these are the plutonic and volcanic equivalents of one another. Geochemically, the Enrekang Volcanic Series are similar to the Palopo Granite, apart from two dacite samples (K12-21A/21B: taken from the same outcrop) that are metaluminous and have higher K contents than the granitoids. The geochemical data obtained from the Palopo Granite indicate these are high-K, magnesian, peraluminous and calc-alkaline to alkali-calcic granitoids. These results largely replicate the earlier work of Priadi et al., (1994) and indicate the granitoids fit within Sulawesi's Mio-Pliocene high-K calc-alkaline ("CAK") granitoid belt (e.g. Polvé et al. (1997); Hennig et al., 2016)).

9.2 Post-crystallisation deformation

Several samples of the Palopo Granite exhibit mylonitic fabrics that developed after the crystallization of the granite. This is confirmed from the microstructures, for example brittle-fracturing and mechanically induced grain-size reduction of feldspars and recrystallized quartz. The U-Pb SHRIMP zircon ages of c. 6.3 Ma obtained from deformed granodiorite (e.g. K12-6B and K12-35B) compared to 5.0 Ma from undeformed granodiorite (K12-4B) brackets the timing of mylonitization to between 6.3 Ma and 5.0 Ma. These mylonites are steeply dipping and record strike-slip deformation, and we consider that these may reflect the westerly continuation of the Kolaka Fault Zone (Fig. 2). An age of 4.4 ± 0.2 Ma from an undeformed dacite within the Kolaka Fault Zone, was interpreted as being injected at the same time as fault movement or after faulting had ceased (White et al., 2014). If the Kolaka Fault Zone does extend from Kolaka, across Bone Bay, and into the Latimojong region (e.g. Fig. 1 and 2: Camplin and Hall, 2014; White et al., 2014), then the age of the deformed (~6.3 Ma) vs. undeformed (~5.0 Ma) granodiorites from the Palopo Granite provides a tighter limit on the timing of movement along the Kolaka Fault (at least on the western side of Bone Bay) than that proposed by White et al., (2014). Additional thermochronological analyses and petrographic investigations are underway to constrain the timing of this fault movement.

9.3 Basement Age

Rb-Sr, Nd-Sm and U-Pb isotopic data were used to infer that the Palopo Granite melted a Late Proterozoic to Early Paleozoic crustal source during continent-continent collision (Bergman et al., 1996). The source interpretation is supported by the inherited ages obtained from zircon cores within granitic and volcanic rocks in this study, and in other parts of Central Sulawesi, Southeast Arm and the Neck (White et al., 2014; Hennig et al., 2016; van Leeuwen et al., 2016). The inherited ages most likely represent the remains of igneous and sedimentary rocks that were partially melted to produce the Palopo Granite and Enrekang Volcanic Series. These do not necessarily require a basement age of Late Proterozoic to Early Paleozoic, but indicate that there are Proterozoic and Paleozoic zircons within the basement rocks of central–west Sulawesi.

9.4 Tectonic Evolution

Western Sulawesi (including the Latimojong region) has been interpreted to have developed in a foreland setting within a westward-verging orogenic wedge at the eastern margin of Sundaland between the Eocene to Pliocene (Coffield et al., 1993; Bergman et al., 1996). This model proposed that the Mio-Pliocene magmatic rocks formed due to melting driven by crustal thickening after continent-continent collision (Coffield et al., 1993; Bergman et al., 1996). This idea was largely influenced by the interpretation of: (1) widespread thrusting during the Oligocene and Mio-Pliocene; and (2) isotopic measurements from the Mio-Pliocene granitoids recording inherited Paleozoic ages (Bergman et al., 1996).

Our work has raised several questions about these earlier interpretations. For instance there is little evidence for widespread thrusting in the Oligocene and Mio-Pliocene in the Latimojong region. Most of the contacts that we observed were sub-vertical strike-slip fault zones (as well as mylonites in granite), no definite thrusts were found.

The same can be said about the inference of post-collision melting based on Paleozoic age data obtained from various isotopic measurements of the granitoids (e.g. Bergman et al., 1996). These simply show that the granites partially melted sedimentary rocks composed of Paleozoic detritus. These data alone do not indicate an episode of collision or thrusting occurred.

We interpret the medium- to high-grade metamorphic rocks exposed in the

Latimojong Mountains (the Latimojong Metamorphic Complex) to be equivalent to similar lithologies observed in Barru and Bantimala (e.g. Wakita et al., 1996; Parkinson et al., 1998). These rocks represent the basement, and younger sequences were deposited above an unconformity that developed during the Cretaceous.

It seems that Upper Cretaceous and Paleocene rocks have been removed from the stratigraphic record in the Latimojong region, with widespread development of a regional angular unconformity that is found at the top of Upper Cretaceous units (van Leeuwen and Muhardjo, 2005), possibly due to uplift associated with a short lived phase of subduction during the Paleocene (Hall, 2012). Continental and shallow water sedimentation commenced again during the Eocene and continued into the Oligocene (e.g. Toraja Group). This was associated with rifting and was interspersed with periods of arc and backarc volcanism (e.g. Lamasi Complex). However, the collision of the Sula Spur with Sulawesi's North Arm in the Early Miocene caused uplift and the development of another unconformity. Later there was a period of relative quiescence and growth of pinnacle and patch reefs (Makale Formation) during the Early to Middle Miocene. This was followed by a renewed phase of magmatism, related to crustal extension (Maulana et al., 2016) and/or flux-melting of the mantle wedge driven by subduction (i.e. the crustal extension could be driven by slab rollback and hinge migration). This produced the high K granitoids and volcanics during the Late Miocene to Pliocene (Palopo Granite / Enrekang Volcanic Series). Further uplift, alluvial fan deposition and strike slip faulting occurred later during the Pliocene to Pleistocene (e.g. Walanae Formation).

10. Conclusion

New biostratigraphic, geochronological and geochemical analyses have provided information about the tectonic history of the Latimojong region of South Sulawesi. This began with the development of an accretionary complex (the Latimojong Metamorphic Complex) that was assembled during the Cretaceous. These rocks were subsequently deformed and uplifted above sea level at some point before the Eocene. This may have been associated with the obduction of Eocene-Oligocene back-arc rocks (the Lamasi Complex). Deposition of clastic material recommenced during the Eocene, first in a terrestrial setting, which later evolved to reefs and near shore marine deposits (Toraja Formation). Subsequence phases of volcanism occurred during the

Miocene to Pliocene (Enrekang Volcanic Series/Palopo Pluton) and were contemporaneous with patch reef development (Makale Formation). Most of these sequences were then tectonically juxtaposed along strike-slip fault zones that developed due to transpressional forces associated opening of Bone Bay. This period of deformation probably also drove the uplift of the Latimojong region, which in turn led to alluvial deposits during the mid-Pliocene to present.

Our mapping of the region indicates substantial differences from earlier work. For instance, we found no clear evidence of thrusts between geological units. However, we did find evidence of brittle to ductile strike slip faults that were active between 6.3 Ma and 5.0 Ma according to our geochronological work. We also found that the Latimojong Formation does not occur anywhere near the Latimojong region. Both of these points will help to resolve issues associated with correlating lithostratigraphic units across different parts of Sulawesi and in developing more accurate tectonic models of the region.

Acknowledgements

This work was sponsored by a consortium of energy companies who fund the Southeast Asia Research Group (SEARG) and we are grateful for this support. We thank Kevin D’Souza for photographing the macroscopic detail of hand-specimens, Ega Nugraha and Karen Oud for assistance collecting and preparing samples, as well as Shane Paxton and Bin Fu for mineral separation and geochronology sample preparation. We would also like to thank Theo van Leeuwen for his thorough review of this manuscript.

References

Ascaria, N.A., 1997. Carbonate facies development and sedimentary evolution of the Miocene Tacipi Formation, South Sulawesi, Indonesia. PhD Thesis. University of London, 397 p.

Audley-Charles, M.G., 1974. Sulawesi. In: Spencer, A.M. (Ed.), Mesozoic-Cenozoic Orogenic Belts, Geological Society of London Special Publication, 4, 365–378.

Baharuddin, Harahap, B.H., 2000. Tinjauan kembali kerangka stratigrafi dan tektonik daerah Palopo, Sulawesi Selatan. J. Geol. Sumberdaya Min. 10, 24–38.

Bergman, S.C., Coffield, D.Q., Talbot, J.P., Garrard, R.J., 1996. Tertiary tectonic and magmatic evolution of Western Sulawesi and the Makassar Strait, Indonesia: Evidence for a Miocene continent-continent collision. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia, Geological Society of London Special Publication, 106, 391–430.

Berry, R.F., Grady, A.E., 1987. Mesoscopic structures produced by Plio-Pleistocene wrench faulting in South Sulawesi, Indonesia. Journal of Structural Geology 9, 563–571.

Black, L., Kamo, S., Allen, C., Davis, D., Aleinikoff, J., Valley, J., Mundil, R., Campbell, I., Korsch, R., Williams, I.S., 2004. Improved $^{206}Pb/^{238}U$ microprobe geochronology by the monitoring of a trace-element-related matrix effect; SHRIMP, ID–TIMS, ELA–ICP–MS and oxygen isotope documentation for a series of zircon standards. Chemical Geology 205, 115–140.

BouDagher-Fadel, M.K., 2008. Evolution and Geological Significance of Larger Benthic Foraminifera. Developments in Palaeontology and Stratigraphy. Elsevier, Amsterdam.

Boudagher-Fadel, M.K., 2013. Biostratigraphic and geological significance of planktonic foraminifera, 2nd ed. University College London, London, United Kingdom.

Brouwer, H.A., 1934. Geologische onderzoekingen op het eiland Celebes. Kolinien Geologische-Mijnbouw Genootschap, Verhandelingen. Geologische Series 10, 39–218.

Calvert, S.J., 2000. The Cenozoic evolution of the Lariang and Karama basins, Sulawesi. Indonesian Petroleum Association Proceedings 27th Annual Convention, 505–511.

Calvert, S.J., Hall, R., 2007. Cenozoic evolution of the Lariang and Karama regions, North Makassar Basin, western Sulawesi, Indonesia. Petroleum Geoscience 13, 353–368.

Camplin, D. J., Hall, R., 2014. Neogene history of Bone Gulf, Sulawesi, Indonesia. Marine and Petroleum Geology 57, 88–108.

Chamberlain, M., Seago, R., 1995. Geological Evaluation of the Lariang PSC area, South Sulawesi., Unpublished Report. Amoseas International.

Claoué-Long, J.C., Compston, W., Roberts, J., Fanning, C.M., 1995. Two Carboniferous Ages: a Comparison of SHRIMP Zircon Dating with Conventional Zircon Ages and ^{40}Ar/^{39}Ar Analysis, in: Berggen, W.A., Kent, D.V., Aubry, M.P., Hardenbol, J. (Eds.), Geochronology Time Scales and Global Stratigraphic Correlation, SEPM Special Publication, pp. 3–21.

Coffield, D.Q., Bergman, S.C., Garrard, R.A., Guritno, N., Robinson, N.M., Talbot, J., 1993. Tectonic and Stratigraphic Evolution of the Kalosi PSC Area and Associated Development of a Tertiary Petroleum System, South Sulawesi, Indonesia. Proceedings of the Indonesian Petroleum Association 22nd Annual Convention, 679–706.

Djuri and Sudjatmiko. 1974. Geologic map of the Majene and western part of the Palopo quadrangles, South Sulawesi (1:250,000). Geological Survey of Indonesia, Ministry of Mines, Bandung, Indonesia.

Djuri, Sudjatmiko, Bachri, S., Sukido. 1998. Geological map of the Majene and western part of the Palopo sheets, Sulawesi (1:250,000), 2nd Edition. Geological Research and Development Centre, Bandung, Indonesia.

Elburg, M., Foden, J., 1998. Temporal changes in arc magma geochemistry, northern Sulawesi, Indonesia. Earth and Planetary Science Letters 163, 381–398.

Elburg, M., Foden, J., 1999a. Sources for magmatism in Central Sulawesi: geochemical and Sr–Nd–Pb isotopic constraints. Chemical Geology 156, 67–93.

Elburg, M.A., Foden, J., 1999b. Geochemical response to varying tectonic settings: An example from southern Sulawesi (Indonesia). Geochimica Cosmochimica Acta 63, 1155–1172.

Elburg, M., van Leeuwen, T., Foden, J., Muhardjo, 2003. Spatial and temporal isotopic domains of contrasting igneous suites in Western and Northern Sulawesi, Indonesia. Chemical Geology 199, 243–276.

Endaharto, M., 2000. Studi stratigrafi kaitannya dengan perkembangan struktur geologi di Kawasan Latimojong, lengan Barat Sulawesi. Jurnal Geologi dan Sumberdaya Mineral 10, 107 p.

Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., Frost, C.D., 2001. A geochemical classification for granitic rocks. Journal of Petrology 42, 2033–2048.

Frost, B.R., Frost, C.D., 2008. A geochemical classification for feldspathic igneous rocks. Journal of Petrology 49, 1955–1969.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., 2012. The Geological Time Scale 2012, 1st ed. Elsevier.

Grainge, A.M., Davies, K.G., 1985. Reef exploration in the east Sengkang Basin, Sulawesi, Indonesia. Marine and Petroleum Geology 2, 142–155.

Hadiwijoyo, S., Sukarna, D. & Sutisna, K. 1993. *Geology of the Pasangkayu Quadrangle, Sulawesi. (Quadrangle 2014) Scale 1:250,000.* Geological Research and Development Centre, Bandung, Indonesia.

Hall, R., 1996. Reconstructing Cenozoic SE Asia. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia, Geological Society London Special Publication 106, 153–184.

Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. Journal of Asian Earth Sciences 20, 353–431.

Hall, R., 2012. Late Jurassic–Cenozoic reconstructions of the Indonesian region and the Indian Ocean. Tectonophysics 570-571, 1–41.

Hamilton, W.B., 1979. Tectonics of the Indonesian region. USGS Professional Paper 1078, 345 pp.

Hasan, K., 1991. The Upper Cretaceous Flysch Succession of the Balangbaru Formation, Southwest-Sulawesi. Proceedings of the Indonesian Petroleum Association 20th Annual Convention, 183–208.

Hennig, J., Hall, R., Armstrong, R.A. 2016. U-Pb zircon geochronology of rocks from west Central Sulawesi, Indonesia: Extension-related metamorphism and magmatism during the early stages of mountain building. Gondwana Research 32, 41–63. doi:10.1016/j.gr.2014.12.012

Jaya, A., Nishikawa, O., 2013. Paleostress reconstruction from calcite twin and fault-slip data using the multiple inverse method in the East Walanae fault zone:

Implications for the Neogene contraction in South Sulawesi, Indonesia. Journal of Structural Geology 55, 34–49.

Katili, J.A., 1970. Large transcurrent faults in Southeast Asia with special reference to Indonesia. Geologische Rundschau 59, 581–600.

Katili, J.A., 1978. Past and present geotectonic position of Sulawesi, Indonesia. Tectonophysics 45, 289–322.

Ludwig, K.R., 2003. Isoplot 3.00: A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronological Centre Special Publication 4, 70 pp.

Ludwig, K.R., 2009. SQUID 2, A User's Manual. Berkeley Geochronological Centre Special Publication 5, 110 pp.

Maryanto, S. 2002. Stratigrafi tersier daerah Toraja, 31st Annual Convention of Indonesian Association of Geologists, 734-768.

Maulana, A., Ellis, D.J., Christy, A.G., 2010. Petrology, geochemistry and tectonic evolution of the South Sulawesi basement rocks. Proceedings of the Indonesian Petroleum Association 34th Annual Convention, IPA10-G-192 1–26.

Maulana, A., Imai, A., van Leeuwen, T., Watanabe, K., Yonezu, K., Nakano, T., Boyce, A., Page, L., Schersten, A. 2016. Origin and geodynamic setting of Late Cenozoic granitoids in Sulawesi, Indonesia. Journal of Asian Earth Sciences 124, 102-125.

O'Dogherty, L., 2009. Inventory of Mesozoic radiolarian species (1867-2008). Geodiversitas 31, 371–503. doi:http://dx.doi.org/10.5252/g2009n2a6

Parkinson, C., 1998. Emplacement of the East Sulawesi Ophiolite: evidence from subophiolite metamorphic rocks Journal of Asian Earth Sciences 16, 13–28.

Parkinson, C.D., Miyazaki, K., Wakita, K., Barber, A.J., Carswell, D.A., 1998. An overview and tectonic synthesis of the pre-Tertiary very- high-pressure metamorphic and associated rocks of Java, Sulawesi and Kalimantan, Indonesia. Island Arc 7, 184–200.

Polvé, M., Maury, R.C., Bellon, H., Rangin, C., Priadi, B., Yuwono, S., Joron, J.L., Atmadja, R.S., 1997. Magmatic evolution of Sulawesi (Indonesia): constraints on the Cenozoic geodynamic history of the Sundaland active margin. Tectonophysics 272, 69–92.

Priadi, B., Polvé, M., Maury, R.C., Bellon, H., Soeria-Atmadja, R., Joron, J.L., Cotten, J., 1994. Tertiary and Quaternary magmatism in Central Sulawesi:

chronological and petrological constraints. Journal of Southeast Asian Earth Sciences 9, 81–93.

Querubin, C. D., Walters, S. 2012. Geology and mineralization of Awak Mas: A sedimentary hosted gold deposit, South Sulawesi, Indonesia. Majalah Geologi Indonesia 27(2), 69-85.

Ratman, N., Atmawinata, S., 1993. Geology of the Mamuju Quadrangle, Sulawesi. Scale 1:250,000. Geological Survey of Indonesia, Directorate of Mineral Resources, Geological Research and Development Centre, Bandung.

Reijzer, J., 1920, Geologische aanteekeningen betreffende de Zuidelijke Toraja-landen, verzameld uit de verslagen der mijnbouwkundige onderzoekingen in Midden-Celebes. Jaarboek van het Mijnwezen in Nederlandsch Oost-Indië 47 (1918), deel 1 Verhandelingen, p. 154–209.

Silver, E.A., McCaffrey, R., Joyodiwiryo, Y., Stevens, S., 1983a. Ophiolite emplacement by collision between the Sula Platform and the Sulawesi island arc, Indonesia. Journal of Geophysical Research 88, 9419–9435.

Silver, E.A., McCaffrey, R., Smith, R.B., 1983b. Collision, rotation, and the initiation of subduction in the evolution of Sulawesi, Indonesia. Journal of Geophysical Research. 88, 9407–9418.

Simandjuntak, T.O., Rusmana, E., Surono, Supandjono, J.B., 1991. Geology of the Malili Quandrangle, Sulawesi. Scale 1:250,000. Geological Research and Development Centre, Department of Mines and Energy, Bandung, Indonesia.

Simandjuntak, T.O., Surono, Sukido, 1994. Geology of the Kolaka Sheet, Sulawesi (Quadrangles 2111, 2210, 2211), Scale 1:250,000, Geological Research and Development Centre, Bandung.

Spakman, W., Hall, R. 2010. Surface deformation and slab-mantle interaction during Banda arc subduction rollback. Nature Geoscience 3, 562-566.

Spencer, J. E., 2010. Structural analysis of three extensional detachment faults with data from the 2000 Space-Shuttle Radar Topography Mission. GSA Today 20, 4–10.

Spencer, J.E., 2011. Gently dipping normal faults identified with Space Shuttle radar topography data in central Sulawesi, Indonesia, and some implications for fault mechanics. Earth and Planetary Science Letters 308, 267–276.

Steiger, R.H., Jäger, E., 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters 36, 359–362.

Sukamto, R., 1975. Geological map of the Ujung Pandang Sheet, Scale 1:1,000,000. Geological Survey of Indonesia, Bandung.

Sukamto, R., 1982. Geological map of Pangkajene and Watampone Quadrangles, Scale 1:250,000. Indonesian Geological Research and Development Centre, Bandung.

Sukamto, R., Simandjuntak, T.O., 1983. Tectonic relationship between geologic provinces of Western Sulawesi, Eastern Sulawesi and Banggai-Sula in the light of sedimentological aspects. Bulletin of the Geological Research and Development Centre 7, 1–12.

Surono, 1994. Stratigraphy of the southeast Sulawesi continental terrane, Eastern Indonesia. Journal of Geology and Mineral Resources 4, 4–11.

van Leeuwen, T.M., 1981. The geology of southwest Sulawesi with special reference to the Biru area. In: Barber, A.J., Wiryosujono, S. (Eds.), The Geology and Tectonics of Eastern Indonesia, Geological Research and Development Centre, Bandung, Special Publication, 2, 277–304.

van Leeuwen, T.M., Muhardjo, 2005. Stratigraphy and tectonic setting of the Cretaceous and Paleogene volcanic-sedimentary successions in northwest Sulawesi, Indonesia: implications for the Cenozoic evolution of Western and Northern Sulawesi. Journal of Asian Earth Sciences 25, 481–511.

van Leeuwen, T.M., Pieters, P. E., 2011. Mineral Deposits of Sulawesi. Proceedings of the Sulawesi Mineral Resources 2011 Seminar, MGEI-IAGI, 28-29 November, 2011, Manado, North Sulawesi, Indonesia, pp. 130, doi:10.13140/2.1.3843.2322

van Leeuwen, T., Allen, C.M., Kadarusman, A., Elburg, M., Michael Palin, J., Muhardjo, Suwijanto, 2007. Petrologic, isotopic, and radiometric age constraints on the origin and tectonic history of the Malino Metamorphic Complex, NW Sulawesi, Indonesia. Journal of Asian Earth Sciences 29, 751–777.

van Leeuwen, T.M., Susanto, E.S., Maryanto, S., Hadiwisastra, S., Sudijono, Muhardjo, Prihardjo, 2010. Tectonostratigraphic evolution of Cenozoic marginal basin and continental margin successions in the Bone Mountains, Southwest Sulawesi, Indonesia. Journal of Asian Earth Sciences 38, 233-254.

van Leeuwen, T., Allen, C.M., Elburg, M., Massonne, H.-J., Palin, J.M., Hennig, J., 2016. The Palu Metamorphic Complex, NW Sulawesi, Indonesia: Origin and evolution of a young metamorphic terrane with links to Gondwana and Sundaland. Journal of Asian Earth Sciences 115, 133–152.

Wakita, K., Sopaheluwakan, J., Miyazaki, K., Zulkarnain, I., Munasri, 1996. Tectonic evolution of the Bantimala Complex, South Sulawesi, Indonesia. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia, Geological Society of London Special Publication, 106, 353–364.

Watkinson, I.M., Hall, R., Ferdian, F., 2011. Tectonic re-interpretation of the Banggai-Sula–Molucca Sea margin, Indonesia. In: Hall, R., Cottam, M.A., Wilson, M.E.J. (Eds.), The SE Asian Gateway: History and Tectonics of the Australia-Asia collision, Geological Society of London Special Publication, 355, 203–224.

White, L.T., Ireland, T.R., 2012. High-uranium matrix effect in zircon and its implications for SHRIMP U–Pb age determinations. Chemical Geology 306-307, 78–91.

White, L.T., Hall, R., Armstrong, R.A., 2014. The age of undeformed dacite intrusions within the Kolaka Fault Zone, SE Sulawesi, Indonesia. Journal of Asian Earth Sciences 94, 105–112.

Williams, I.S., 1998. U-Th-Pb Geochronology by Ion Microprobe, in: McKibben, M.A., Shanks, W.C., III, Ridley, W.I. (Eds.), Applications of microanalytical techniques to understanding mineralizing processes. Reviews in Economic Geology 7, 1–35.

Wilson, M.E.J., Bosence, D.W.J., 1996. The Tertiary Evolution of South Sulawesi: A Record in Redeposited Carbonates of the Tonasa Limestone Formation. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia, Geological Society of London Special Publication, 106, 365–389.

Yuwono, Y.S., Maury, R.C., Soeria-Atmadja, R., Bellon, H. 1988. Tertiary and Quaternary geodynamic evolution of South Sulawesi: constraints from the study of volcanic units. Geologi Indonesia, Jakarta 13(1), 32–48.

Table Captions

Table 1. Summary of the sample locations, lithologies and which samples were selected for geochemical and U-Pb dating. The samples have been grouped according to their petrology, proposed geological unit and their age (from youngest to oldest).

Figure Captions

Figure 1. Map showing the location of the geological terranes and major faults of Sulawesi. The location of the Latimojong region and the focus of this study is shown with a black box (adapted from White et al., 2014).

Figure 2. Geological map of the study area showing the location of major geological units, interpreted structures as well as the location of samples and geographic locations discussed in the text. All of the geological boundaries represent interpretated, as contacts were not observed in the field. The ages reported on the map, represent those obtained in this study.

Figure 3. Field photos of different units of the Lamasi Volcanics. These include (a-b) pillow basalts, often with altered glass and interstitial chert; (c) vesicular and non-vesicular basalt dykes, (d) gabbro, occasionally cross-cut by 1-10cm pegmatite veins and dykes, and: (e) serpentinite or altered basalt.

Figure 4. Field photographs of the (a) 'red-bed' shales of the Toraja Formation and the well-bedded deposits of fluvial sandstones.

Figure 5. Field photograph of the karst landscape on the western side of the Latimojong Mountains. These carbonates are part of the Makale Formation, which is the stratigraphic equivalent of the Tonasa Limestone.

Figure 6. Field photographs of the Enrekang Volcanic Series at the outcrop scale as well as in hand specimen. Ages each of these outcrops/samples were acquired using SHRIMP U-Pb dating of zircon. (a-b) Shows a felsic dyke (sample K12-33B) cross-cutting basement schists of the Latimojong Complex; (c-d) shows a boulder of porphyritic dacite (K12-27) within the inferred north-western continuation of the

Kolaka Fault Zone; (e-f) shows quarry workers extracting this dacite as well as the grain-scale detail of dacite sample K12-21A/B.

Figure 7. Field photographs of the granodiorites of the Palopo Granite. These granodiorites are (a-c) undeformed in parts, but are (d-e) mylonitised in other outcrops. The granites also contain xenoliths and enclaves, some of which show evidence of (b) mingling between the granite and restite. (d) These enclaves have also been flattened/stretched parallel to the mylonitic fabric in places and were later cross-cut by aplitic dykes. Sample K12-4B represents an undeformed granodiorite collected from the same location as is shown in (b) and (c). Sample K12-6A/6B were deformed samples collected from the sample location as is shown in (d). Sample K12-35B is a deformed granodiorite collected from the same location as is shown in (e).

Figure 8. An example of (a) the well-bedded sandstones and conglomerate continental deposits of the Walanae Formation, as well as (b) some of the leaf fossils found within finer-grained units of this formation.

Figure 9. Field photographs of the "Bua Rhyolite" which cross-cuts basalts of the Lamasi Volcanics.

Figure 10. Scanning electron microscopy of radiolarians that were extracted from a sample of chert float collected west of the Latimojong Mountains. These were identified as follows: 1. Stichomitra cf. *japonica* (Nakaseko & Nishimura); 2 *Xitus* cf. *clava* (Parona); 3. Gen. sp. indet.; 4. Gen. sp. indet.; 5. *Dictyomitra* sp.; 6. *Dictyomitra* sp.; 7. *Thanarla* cf. *pulchra* (Squinabol); 8. *Dictyomitra* sp.; 9. *Distylocapsa* sp.; 10. Gen. sp. indet.; 11. *Hiscocapsa* sp.; 12. Gen. sp. Indet.; 13. Gen. sp. indet.

Figure 11. Chronostratigraphic chart and corresponding biostratigraphic ages obtained from the identification of foraminifera in the Toraja Formation, Makale Formation and the Enrekang Volcanic Series.

Figure 12. Tera-Wasserburg Concordia diagrams of the U-Pb SHRIMP results for each of the igneous samples that were dated in this study.

Figure 13. Relative frequency apparent age plots of U-Pb SHRIMP results for each of the igneous samples that were dated in this study.

Figure 14. Various plots showing the geochemical data collected from the igneous rock samples that were collected as part of this study. The distinctive chemical groups correspond with different petrological characteristics as well as the crystallization ages of these rocks.

Figure 15. Revised chronostratigraphic chart for the Latimojong Mountains region that takes the results of this and previous studies into account.

Supplementary Files

Interactive Map File: A KMZ file containing location data of observed lithologies at various field sites across the Latimojong region.

Supp. Data File 1. Details of foraminifera identified for various samples from the Latimojong region of Sulawesi.

Supp. Data File 2. Representative and age determining foraminifera from the (a-h) Toraja Formation, (i) Makale Formation and (j) Enrekang Volcanic Series: (a) Cycloclypeus eidae [Sample: K12-10]; (b) Lepidocyclina isolepidinoides [Sample: K12-10]; (c) Globoquadrina sp. [Sample: K12-14]; (d) Asterocyclina sp., [Sample: K12-17]; (e) Discocyclina dispansa [Sample: K12-17]; (f) Nummulites sp. [K12-17]; (g) Pellatispira sp. [Sample: K12-17]; (h) Dentoglobigerina altispira [Sample: K12-15]; (i) Globoquadrina dehiscens [Sample: K12-20B]; (j) Globorotalia miocenica [Sample K12-22B].

Supp. Data File 3. Results of SHRIMP U-Pb analyses of zircons for the various igneous rocks that were dated as part of this study.

Supp. Data File 4. Major and trace element data collected from whole-rock XRF analyses of the igneous samples that were investigated as part of this study.

Figure 1

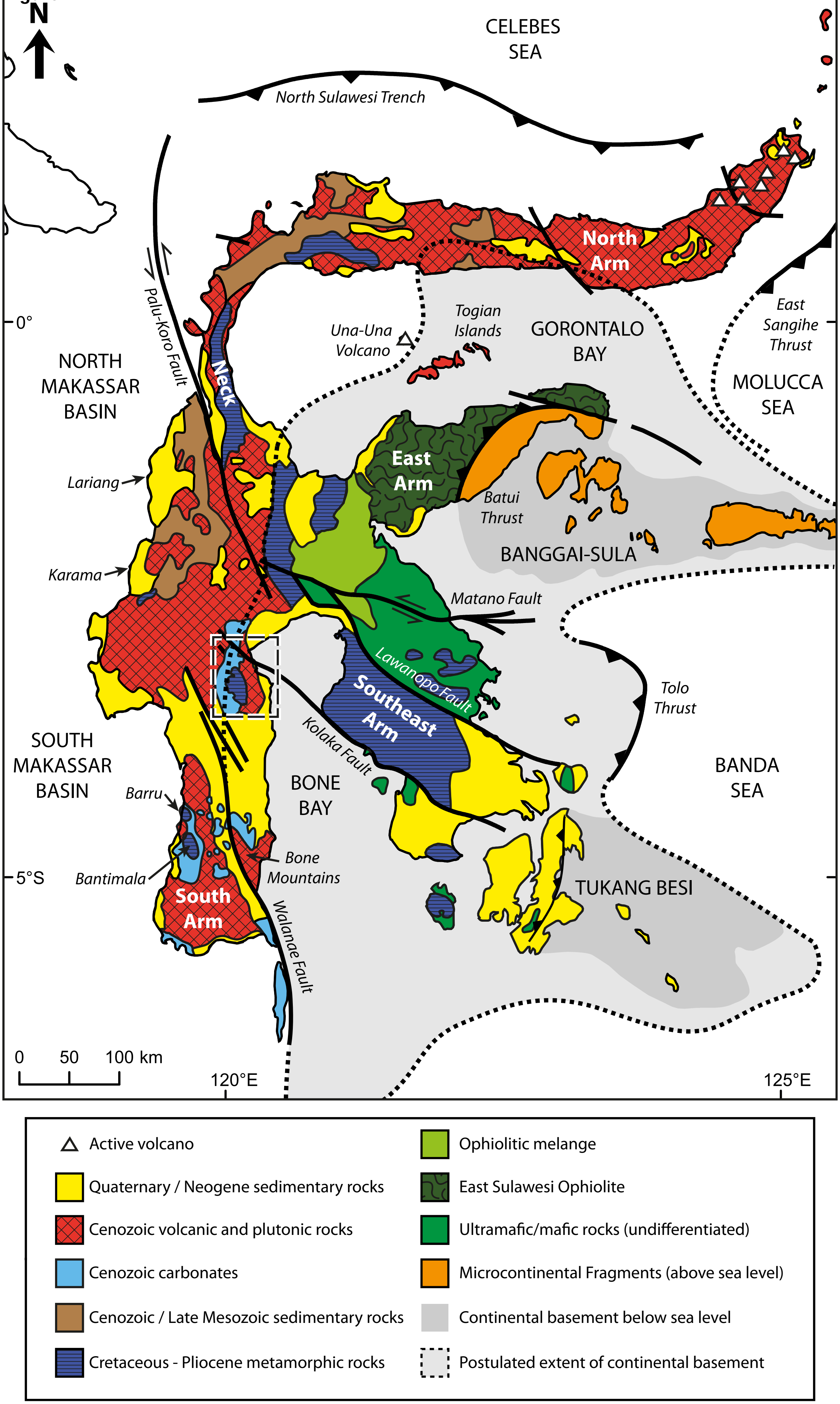
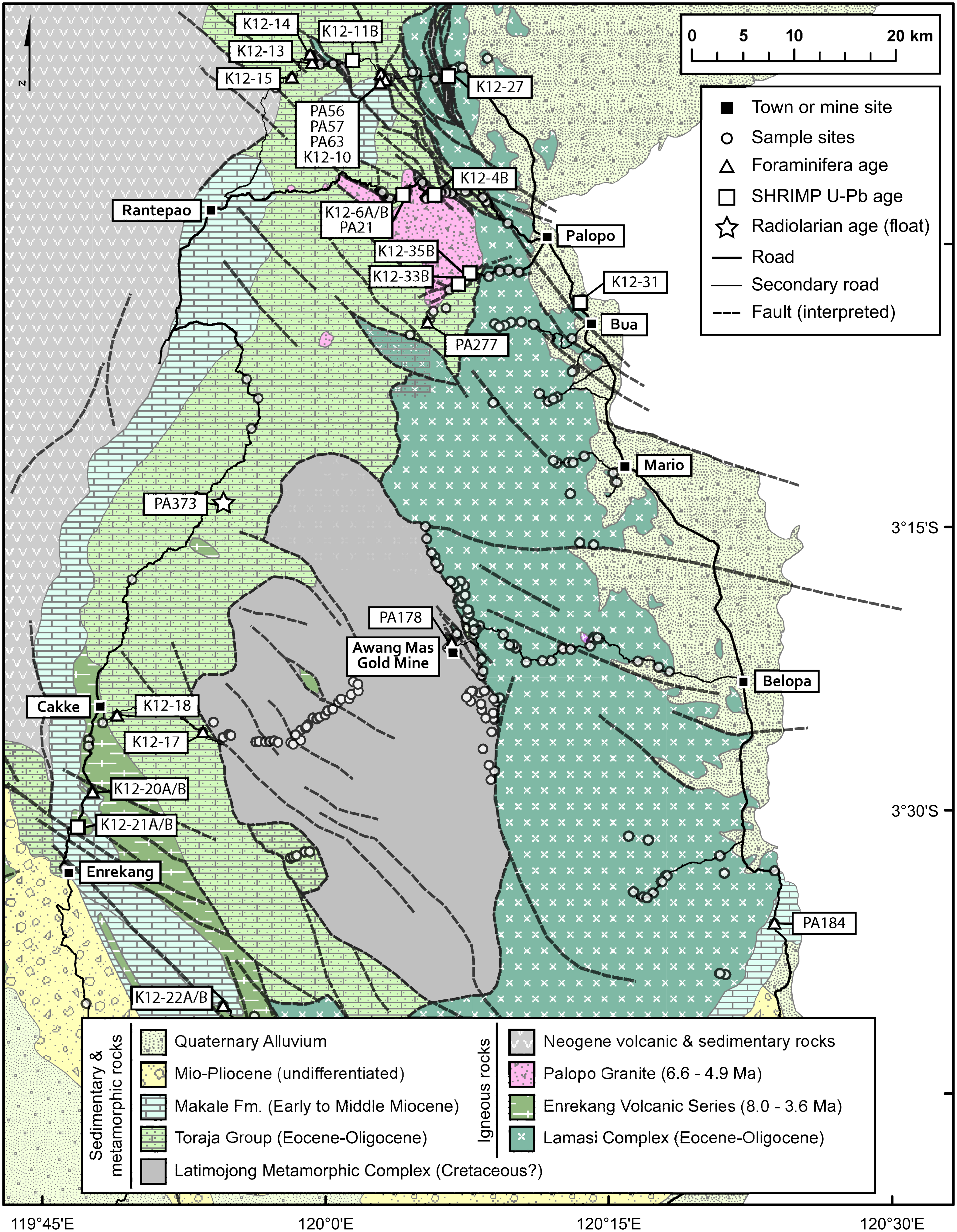

N
CELEBES SEA
North Sulawesi Trench
North Arm
East Sangihe Thrust
MOLUCCA SEA
GORONTALO BAY
Togian Islands
Una-Una Volcano
Palu-Koro Fault
0°
NORTH MAKASSAR BASIN
Neck
Lariang
Karama
East Arm
Batui Thrust
BANGGAI-SULA
Matano Fault
Lawanopo Fault
Southeast Arm
Kolaka Fault
Tolo Thrust
BANDA SEA
SOUTH MAKASSAR BASIN
BONE BAY
Barru
Bantimala
Bone Mountains
5°S
South Arm
Walanae Fault
TUKANG BESI
0 50 100 km
120°E
125°E
Active volcano
Quaternary / Neogene sedimentary rocks
Cenozoic volcanic and plutonic rocks
Cenozoic carbonates
Cenozoic / Late Mesozoic sedimentary rocks
Cretaceous - Pliocene metamorphic rocks
Ophiolitic melange
East Sulawesi Ophiolite
Ultramafic/mafic rocks (undifferentiated)
Microcontinental Fragments (above sea level)
Continental basement below sea level
Postulated extent of continental basement

Figure 2



0 5 10 20 km
Town or mine site
Sample sites
Foraminifera age
SHRIMP U-Pb age
Radiolarian age (float)
Road
Secondary road
Fault (interpreted)
K12-14
K12-11B
K12-13
K12-15
K12-27
PA56
PA57
PA63
K12-10
K12-4B
K12-6A/B
PA21
Rantepao
Palopo
K12-35B
K12-33B
K12-31
Bua
PA277
Mario
PA373
3°15'S
PA178
Awang Mas Gold Mine
Belopa
Cakke
K12-18
K12-17
K12-20A/B
3°30'S
K12-21A/B
Enrekang
PA184
K12-22A/B
Sedimentary & metamorphic rocks
Quaternary Alluvium
Mio-Pliocene (undifferentiated)
Makale Fm. (Early to Middle Miocene)
Toraja Group (Eocene-Oligocene)
Latimojong Metamorphic Complex (Cretaceous?)
Igneous rocks
Neogene volcanic & sedimentary rocks
Palopo Granite (6.6 - 4.9 Ma)
Enrekang Volcanic Series (8.0 - 3.6 Ma)
Lamasi Complex (Eocene-Oligocene)
119°45'E
120°0'E
120°15'E
120°30'E

Figure 3
Click here to download high resolution image

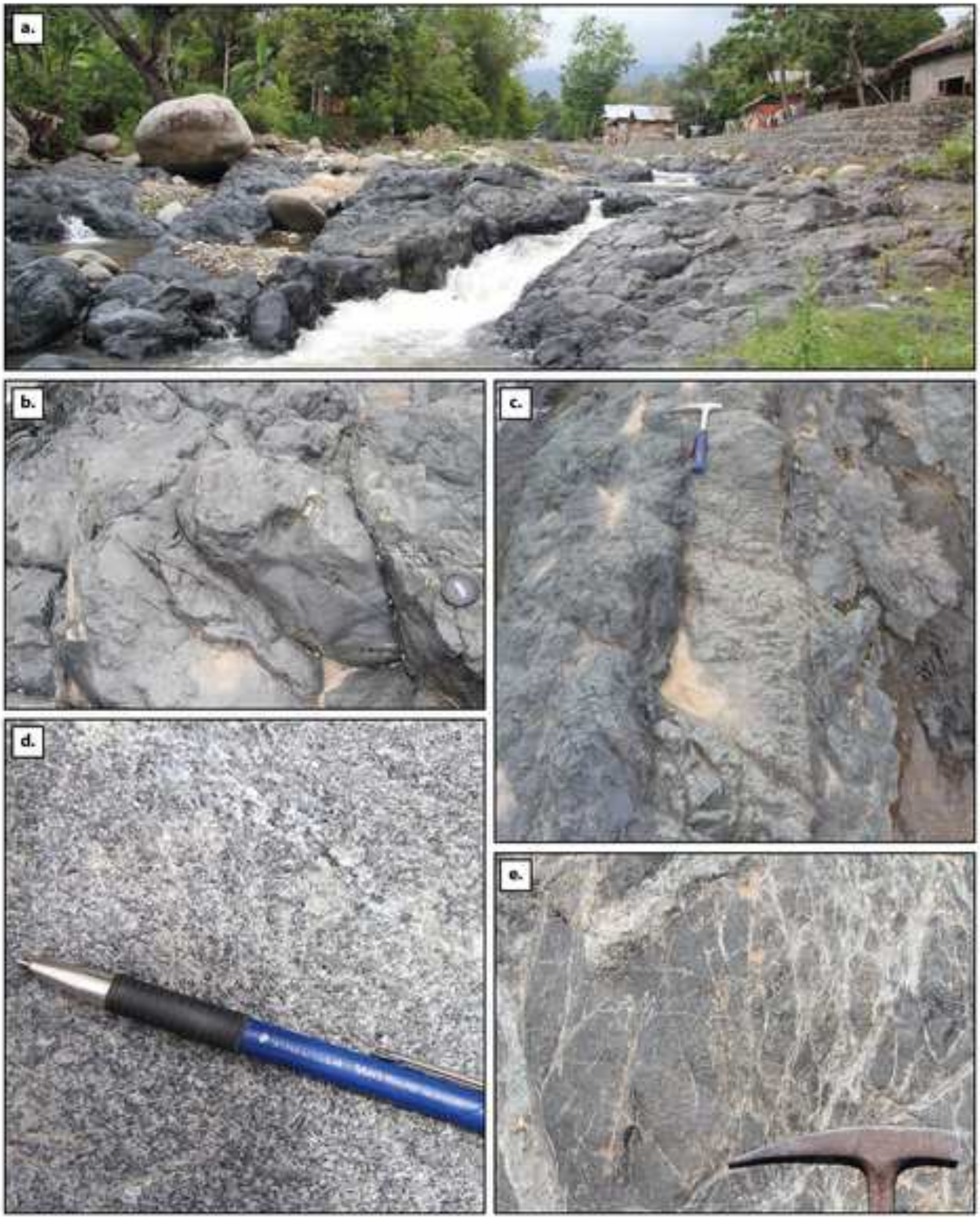


Figure 4
Click here to download high resolution image

Figure 5
Click here to download high resolution image

Figure 6
Click here to download high resolution image

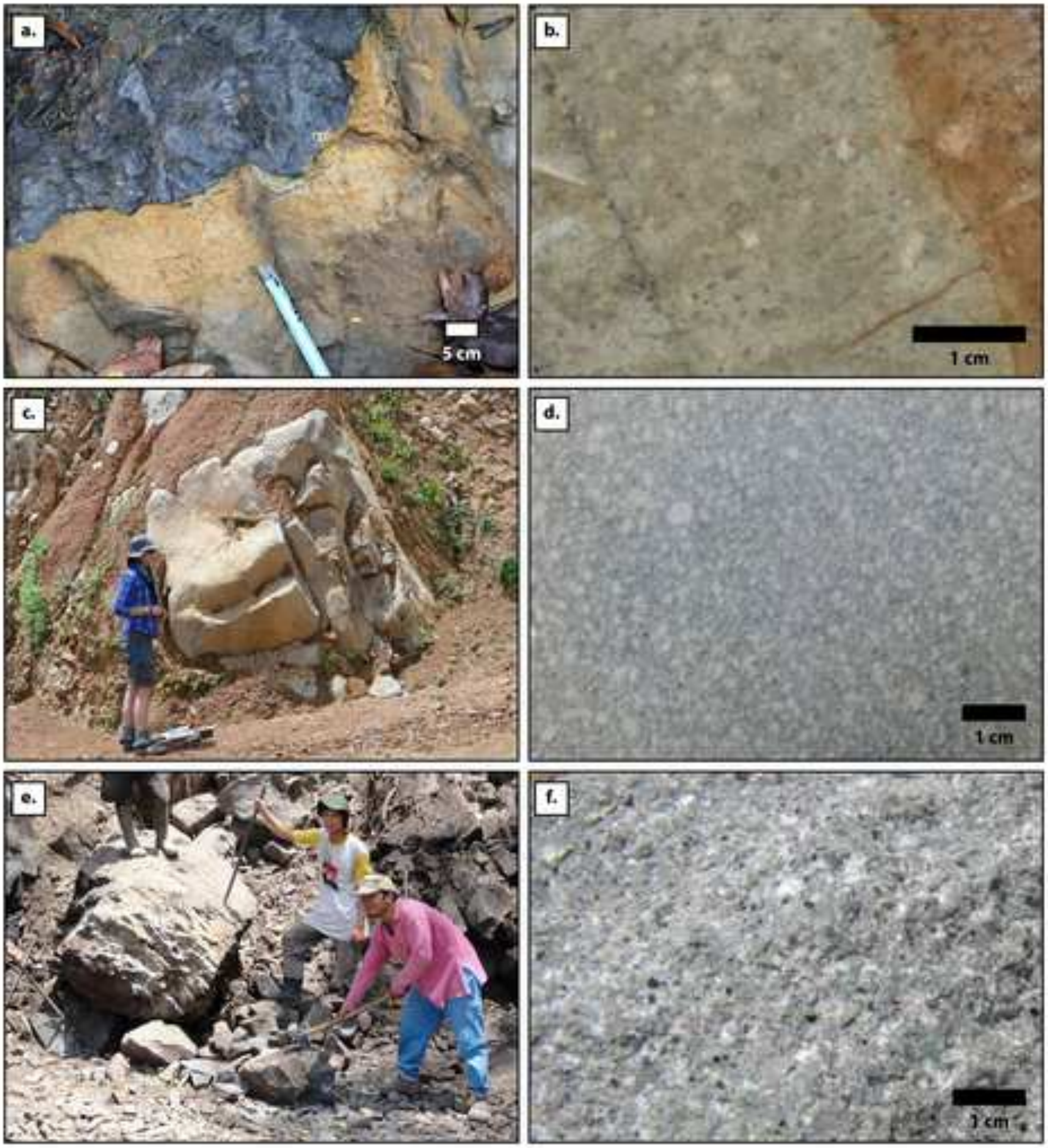


Figure 7
Click here to download high resolution image

Figure 8
Click here to download high resolution image

Figure 9
Click here to download high resolution image

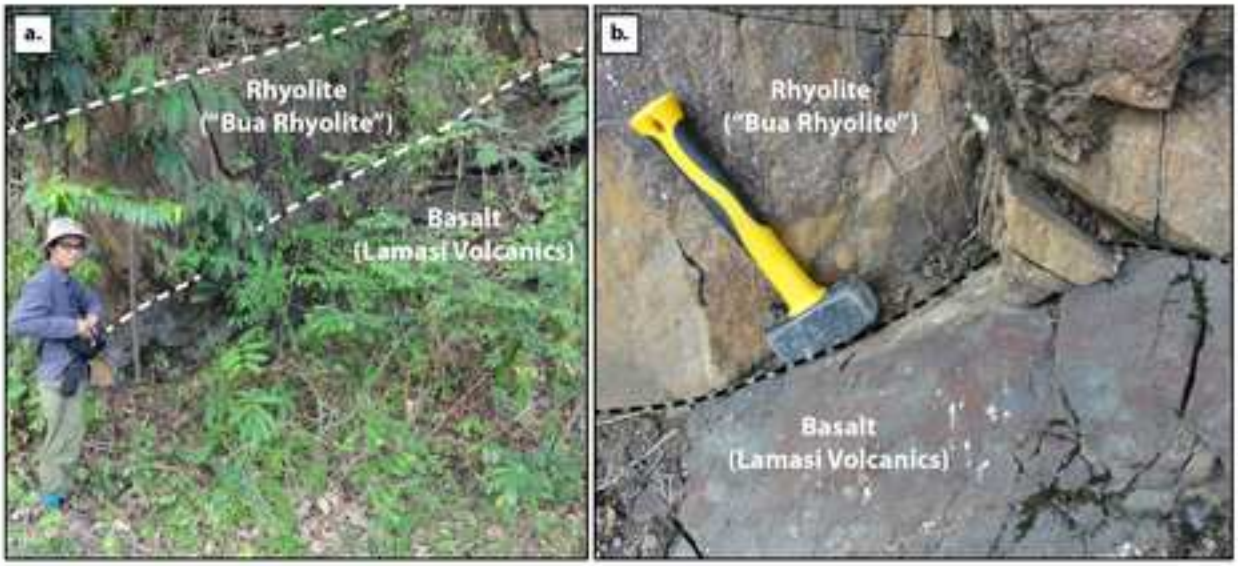


Figure 10
Click here to download high resolution image

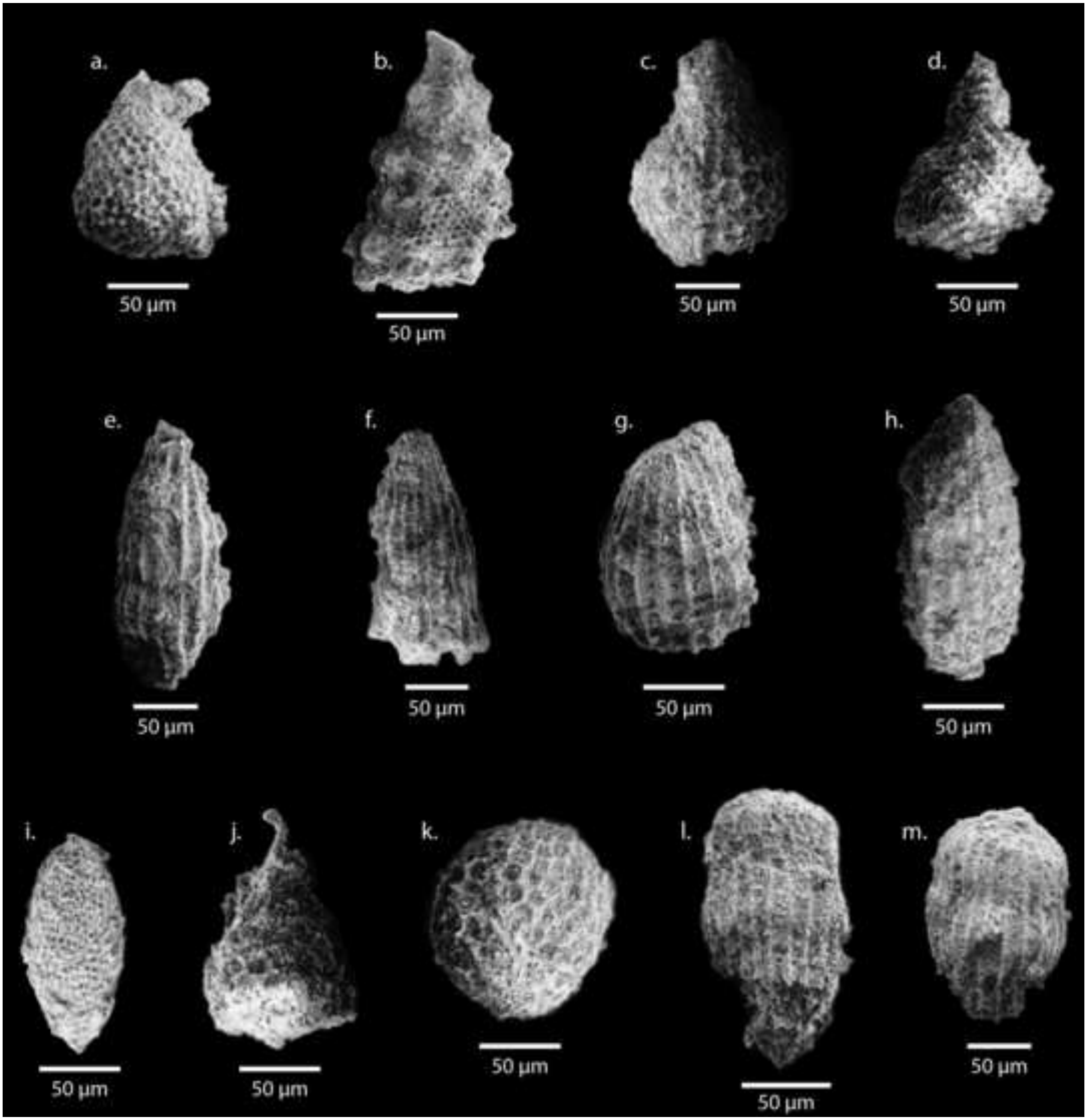
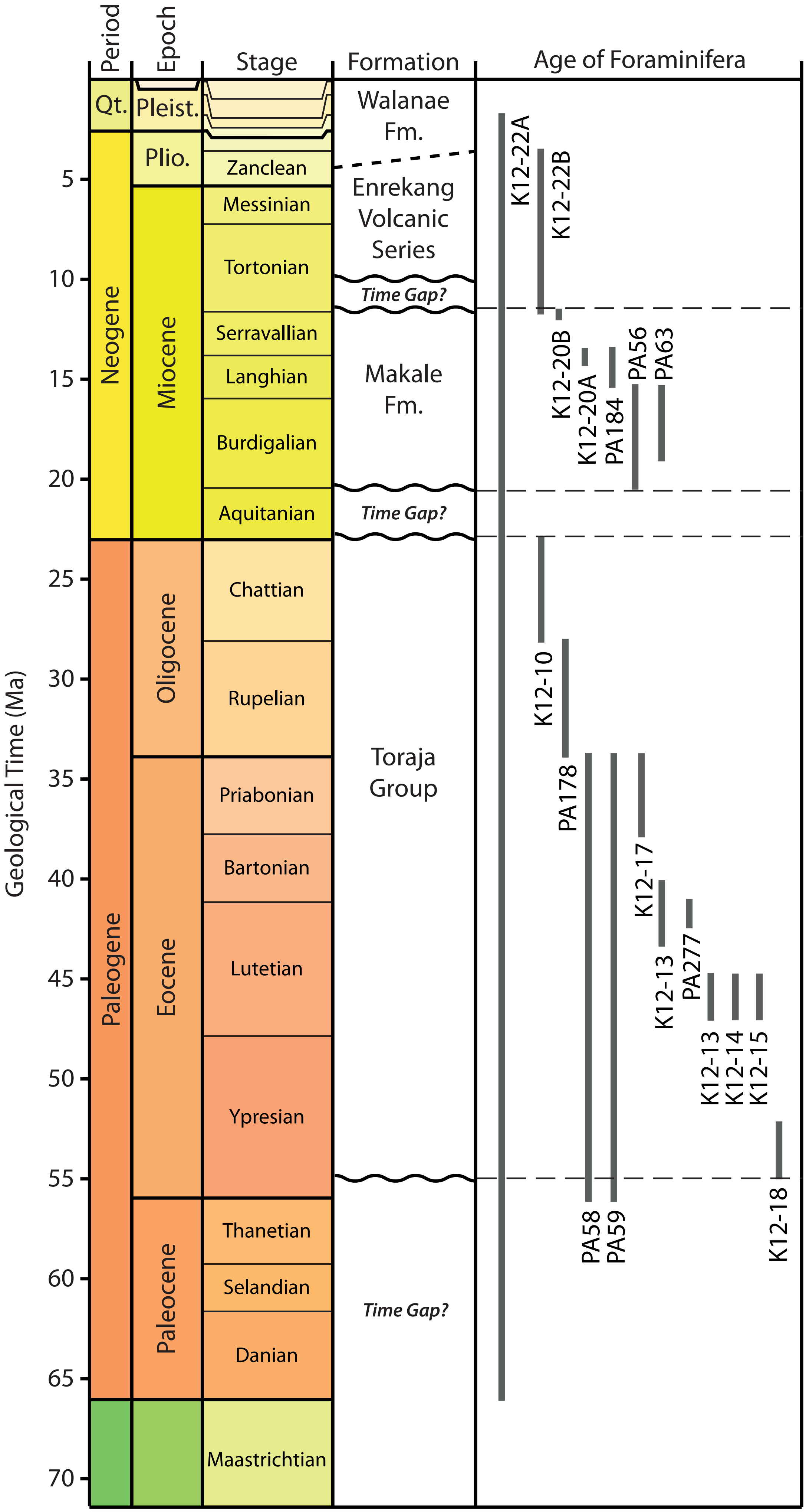
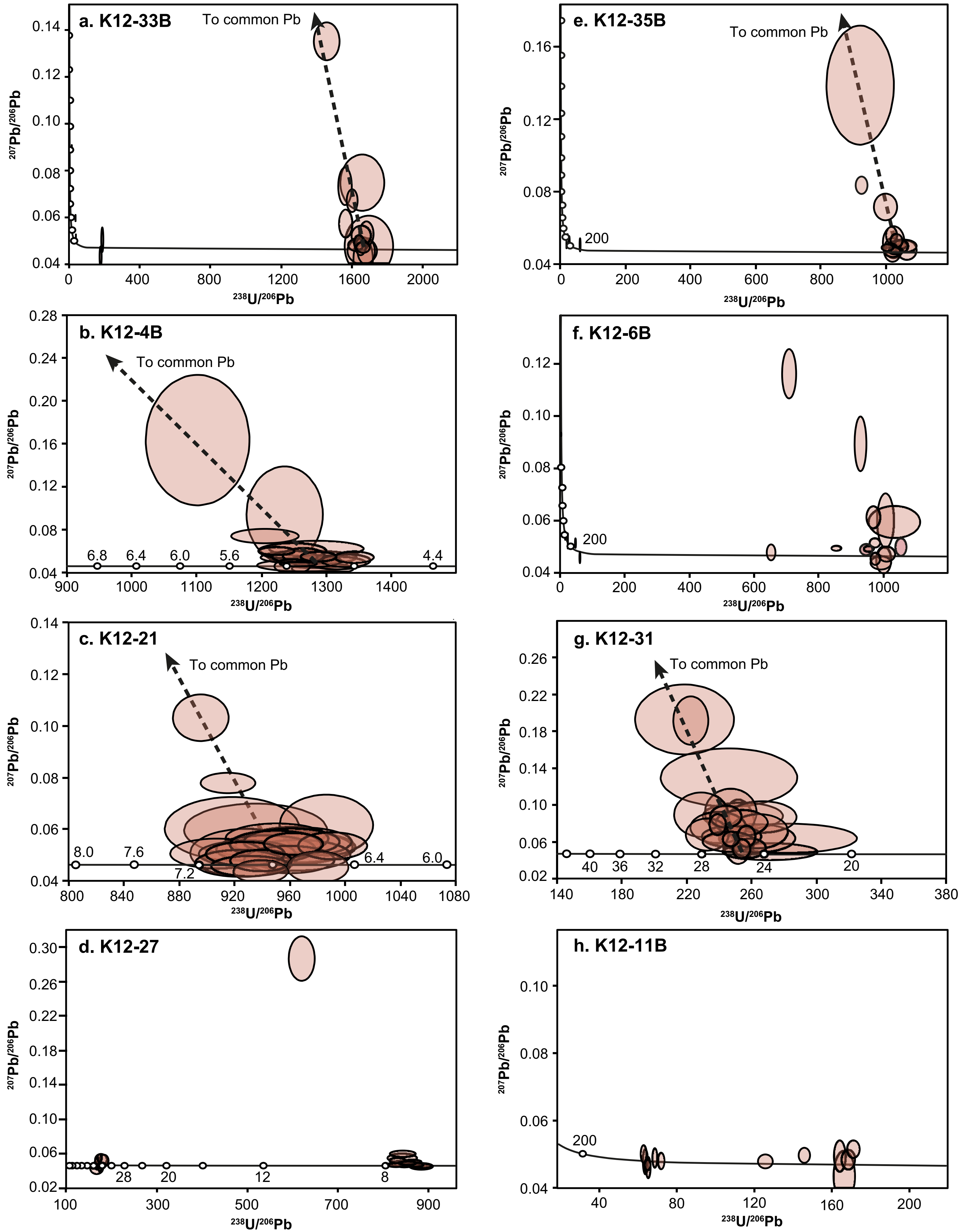


Figure 11



Period
Epoch
Stage
Formation
Age of Foraminifera
Qt.
Pleist.
Plio.
Zanclean
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Neogene
Miocene
Paleogene
Oligocene
Eocene
Paleocene
Walanae Fm.
Enrekang Volcanic Series
Time Gap?
Makale Fm.
Time Gap?
Toraja Group
Time Gap?
Geological Time (Ma)
5
10
15
20
25
30
35
40
45
50
55
60
65
70
K12-22A
K12-22B
K12-20B
K12-20A
PA184
PA56
PA63
K12-10
PA178
K12-17
K12-13
PA277
K12-13
K12-14
K12-15
PA58
PA59
K12-18

Figure 12



a. K12-33B
To common Pb
b. K12-4B
To common Pb
c. K12-21
To common Pb
d. K12-27
e. K12-35B
To common Pb
f. K12-6B
g. K12-31
To common Pb
h. K12-11B
$^{207}Pb/^{206}Pb$
$^{238}U/^{206}Pb$

Figure 13

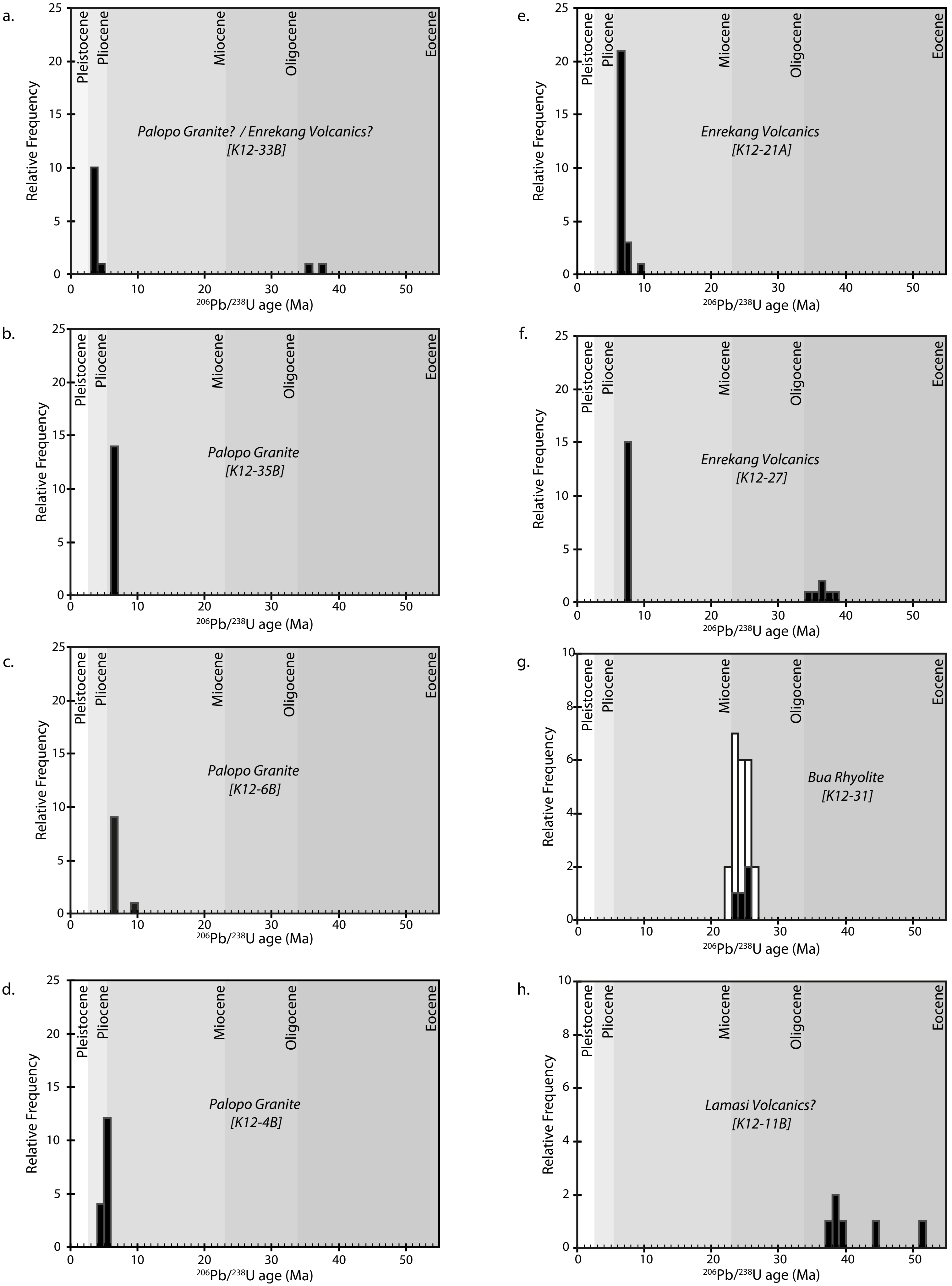
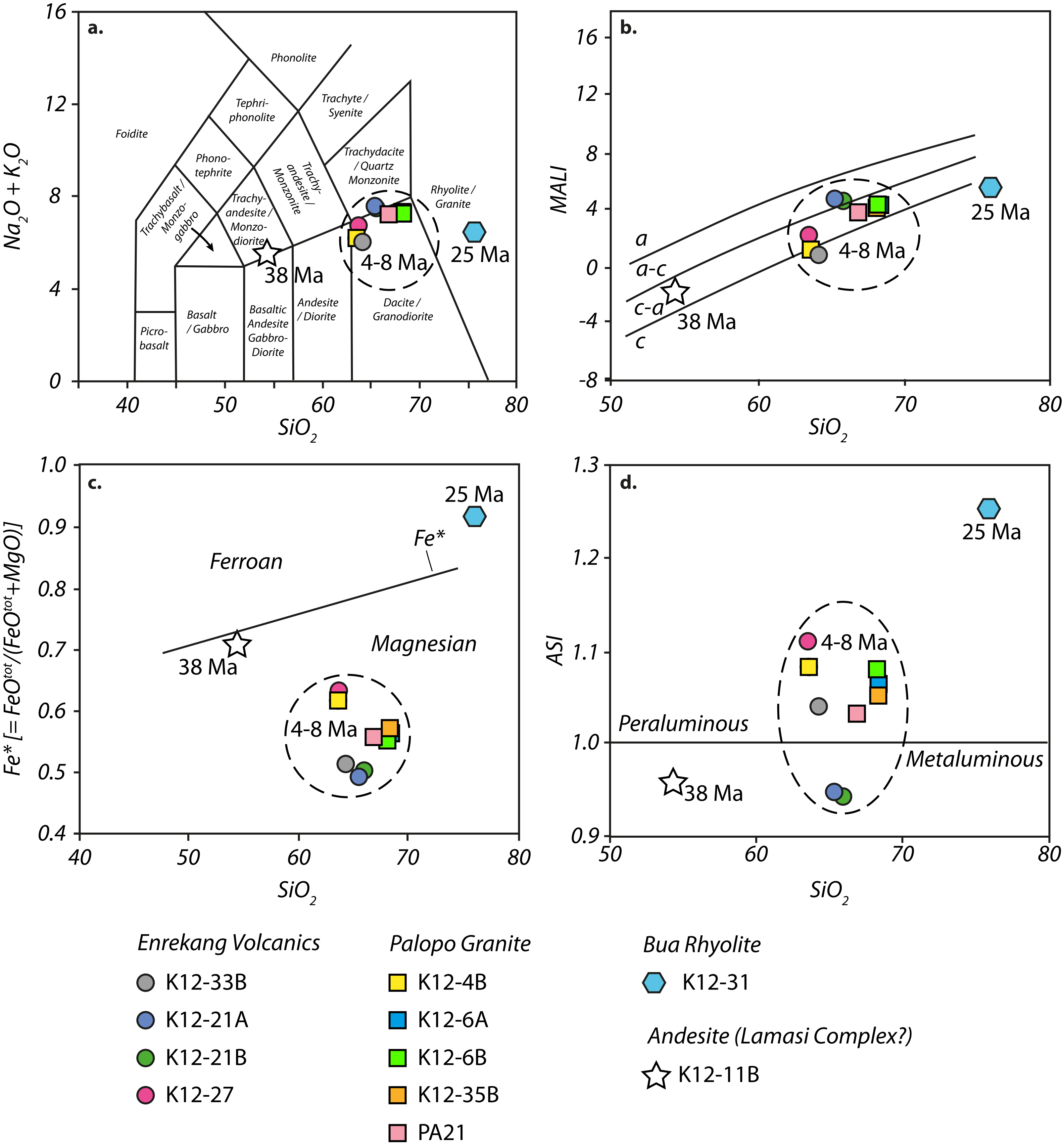
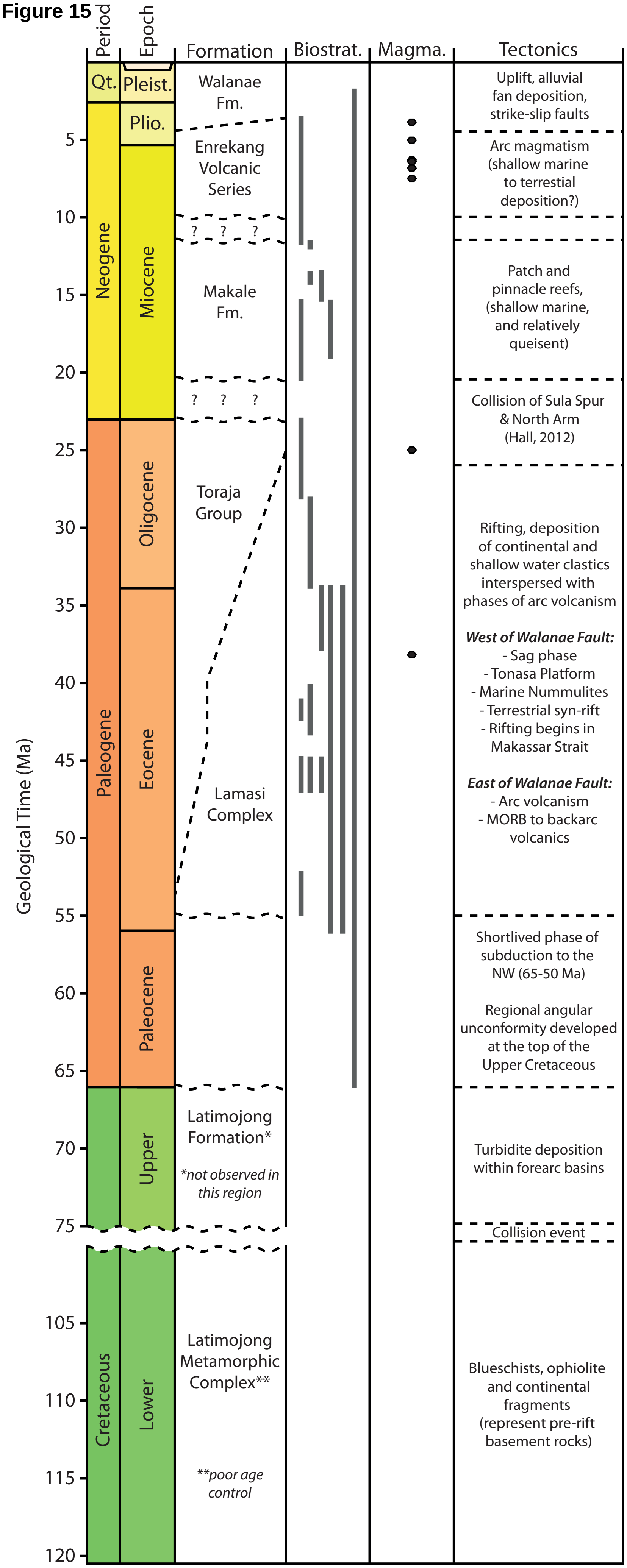

a.
Pleistocene
Pliocene
Miocene
Oligocene
Eocene
Palopo Granite? / Enrekang Volcanics?
[K12-33B]
Relative Frequency
$^{206}Pb/^{238}U$ age (Ma)
b.
Palopo Granite
[K12-35B]
c.
Palopo Granite
[K12-6B]
d.
Palopo Granite
[K12-4B]
e.
Enrekang Volcanics
[K12-21A]
f.
Enrekang Volcanics
[K12-27]
g.
Bua Rhyolite
[K12-31]
h.
Lamasi Volcanics?
[K12-11B]

Figure 14



a.
b.
c.
d.
Phonolite
Tephri-phonolite
Trachyte / Syenite
Foidite
Phono-tephrite
Trachy-andesite / Monzonite
Trachydacite / Quartz Monzonite
Trachybasalt / Monzo-gabbro
Trachy-andesite / Monzo-diorite
Rhyolite / Granite
Basalt / Gabbro
Basaltic Andesite Gabbro-Diorite
Andesite / Diorite
Dacite / Granodiorite
Picro-basalt
$Na_2O + K_2O$
SiO_2
MALI
a
a-c
c-a
c
38 Ma
4-8 Ma
25 Ma
$Fe^* [= FeO^{tot}/(FeO^{tot}+MgO)]$
Ferroan
Magnesian
Fe*
ASI
Peraluminous
Metaluminous
Enrekang Volcanics
K12-33B
K12-21A
K12-21B
K12-27
Palopo Granite
K12-4B
K12-6A
K12-6B
K12-35B
PA21
Bua Rhyolite
K12-31
Andesite (Lamasi Complex?)
K12-11B

Figure 15



Period
Epoch
Formation
Biostrat.
Magma.
Tectonics
Qt.
Pleist.
Plio.
Neogene
Miocene
Paleogene
Oligocene
Eocene
Paleocene
Cretaceous
Upper
Lower
Geological Time (Ma)
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
105
110
115
120
Walanae Fm.
Enrekang Volcanic Series
? ? ?
Makale Fm.
? ? ?
Toraja Group
Lamasi Complex
Latimojong Formation*
*not observed in this region
Latimojong Metamorphic Complex**
**poor age control
Uplift, alluvial fan deposition, strike-slip faults
Arc magmatism (shallow marine to terrestial deposition?)
Patch and pinnacle reefs, (shallow marine, and relatively queisent)
Collision of Sula Spur & North Arm (Hall, 2012)
Rifting, deposition of continental and shallow water clastics interspersed with phases of arc volcanism
West of Walanae Fault:
- Sag phase
- Tonasa Platform
- Marine Nummulites
- Terrestrial syn-rift
- Rifting begins in Makassar Strait
East of Walanae Fault:
- Arc volcanism
- MORB to backarc volcanics
Shortlived phase of subduction to the NW (65-50 Ma)
Regional angular unconformity developed at the top of the Upper Cretaceous
Turbidite deposition within forearc basins
Collision event
Blueschists, ophiolite and continental fragments (represent pre-rift basement rocks)

Table 1

Sample	Lat.	Long.	Lithology	Geochem.	U-Pb age (± 1σ)
Enrekang Volcanics					
K12-33B	-3.03571	120.11734	Felsic Dyke	x	3.9 Ma ± 0.1 Ma
K12-21A	-3.51503	119.78141	Dacite (porphyritic)	x	6.8 Ma ± 0.1 Ma
K12-21B	-3.51503	119.78141	Dacite (porphyritic)	x	-
K12-27	-2.85184	120.10847	Dacite (porphyritic, altered)	x	7.5 Ma ± 0.1 Ma
Palopo Granite					
K12-4B	-2.95663	120.09621	Granodiorite (undeformed)	x	5.0 Ma ± 0.1 Ma
K12-35B	-3.02595	120.12712	Granodiorite (deformed)	x	6.3 Ma ± 0.1 Ma
K12-6A	-2.95646	120.06854	Granodiorite (deformed)	x	-
K12-6B	-2.95646	120.06854	Granodiorite (deformed)	x	6.4 Ma ± 0.2 Ma
PA21	-2.95253	120.07236	Granodiorite (deformed)	x	-
"Bua Rhyolite"					
K12-31	-3.05184	120.22453	Rhyolite (altered)	x	25.0 Ma ± 0.7 Ma
Altered Andesite (Lamasi Volcanics?)					
K12-11B	-2.83792	120.02377	Andesite (highly altered)	x	38.2 Ma ± 1.3 Ma

Graphical Abstract (for review)