New Insights Into the Geological Evolution of Eastern Indonesia From Recent Research Projects by the SE Asia Research Group

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Introduction

Eastern Indonesia has a prolonged, complex tectonic history. It is where the Eurasian, Indo-Australian, Caroline and Philippine Sea plates converge, and where processes such as subduction, obduction, slab rollback, rifting, supracrustal extension, lower crustal flow and exhumation are very young or still active (e.g. Hamilton, 1979; Silver et al., 1983; Hall, 1996; Bock et al., 2003; Spencer, 2011; Spakman & Hall, 2010; Hall, 2011).

For these reasons, the SE Asia Research Group (SEARG) at Royal Holloway, University of London, has made Eastern Indonesia one of its major research themes in recent years. The SEARG has been conducting geological research in SE Asia since 1982. Work has been undertaken in Indonesia, Malaysia, Thailand, the Philippines, Vietnam and the South China Sea. In 2012 the SEARG is directed by Professor Robert Hall, and involves 12 postgraduate students, 2 postdoctoral researchers, a large number of academic staff, research associates and collaborators in the UK and overseas. The group is funded by a consortium of oil companies.

Here we summarise recent and ongoing SEARG projects in Eastern Indonesia (Figure 1). Most of the projects are field-based, but they all also employ new data and techniques, such as 40Ar-39Ar, U-Pb dating (SHRIMP and LA-ICP-MS), Hf isotope dating (LA-MC-ICP-MS), U-Th/He dating, multibeam bathymetry, high quality seismic and remote sensing data.

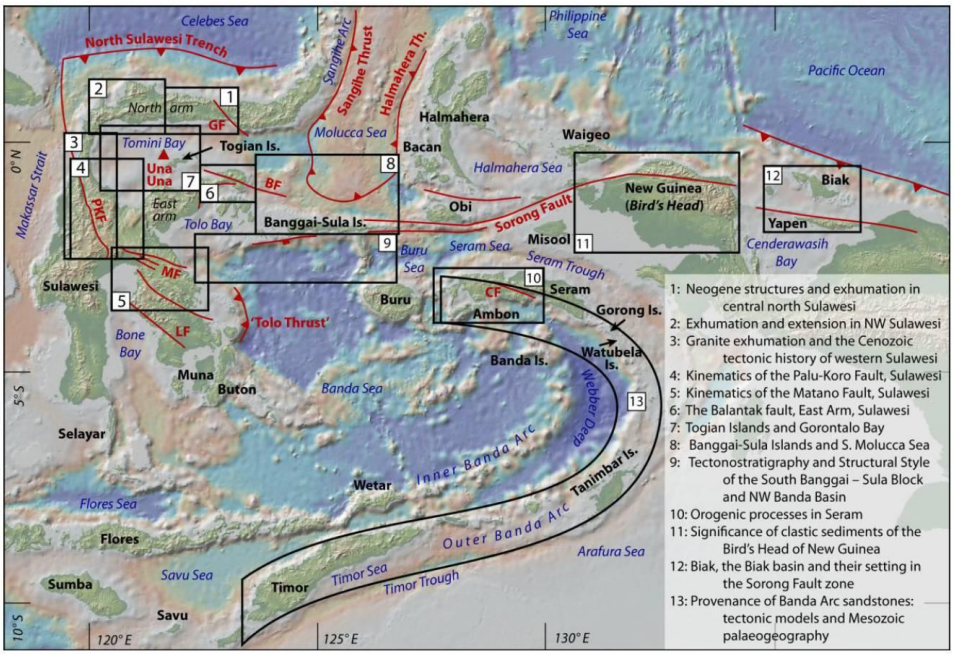


Figure 1. Overview map of Eastern Indonesia showing geographical features, structural elements and ongoing SEARG projects (numbered). PKF: Palu-Koro Fault; MF: Matano Fault; LF: Lawanopo Fault; GF: Gorontalo Fault; BF: Balantak Fault; CF: Central fault zone of Seram.

Sulawesi

The SEARG is involved in several studies aimed at understanding the evolution of Sulawesi in the context of Eastern Indonesia.

West, central and SE Sulawesi

In west, central and SE Sulawesi, metamorphic rocks (e.g. Egeler, 1947), are partly overlain by volcanic-sedimentary rocks and intruded by granitoids as young as Pliocene (e.g. Sukamto, 1973; Sukido et al., 1993; Elburg et al., 2003; van Leeuwen & Muhardjo, 2005). Widespread uplift has formed >3km high mountains, associated with deep intermontaine basins.

The sinistral Palu-Koro Fault (PKF) (Figure 2) bisects central Sulawesi and links to the North Sulawesi Trench (e.g. Silver et al., 1983; Bellier et al., 2001). Many workers also link it via the Matano/Lawanopo faults to the Tolo thrust or 'East Sulawesi Trench' in the southeast, forming a continuous structure that bounds a rotating Sula Block (e.g. Hamilton 1979; Silver et al., 1983; Bellier et al., 2006). Others link the Matano Fault (MF) to a Sorong fault strand that passes south of the Banggai-Sula Islands (e.g. Katili, 1975; Socquet et al., 2006).

SEARG studies of the PKF show that strike-slip diminishes to the south, and the fault terminates at the northern end of Bone Bay. Similarly, the MF terminates in the west where it is

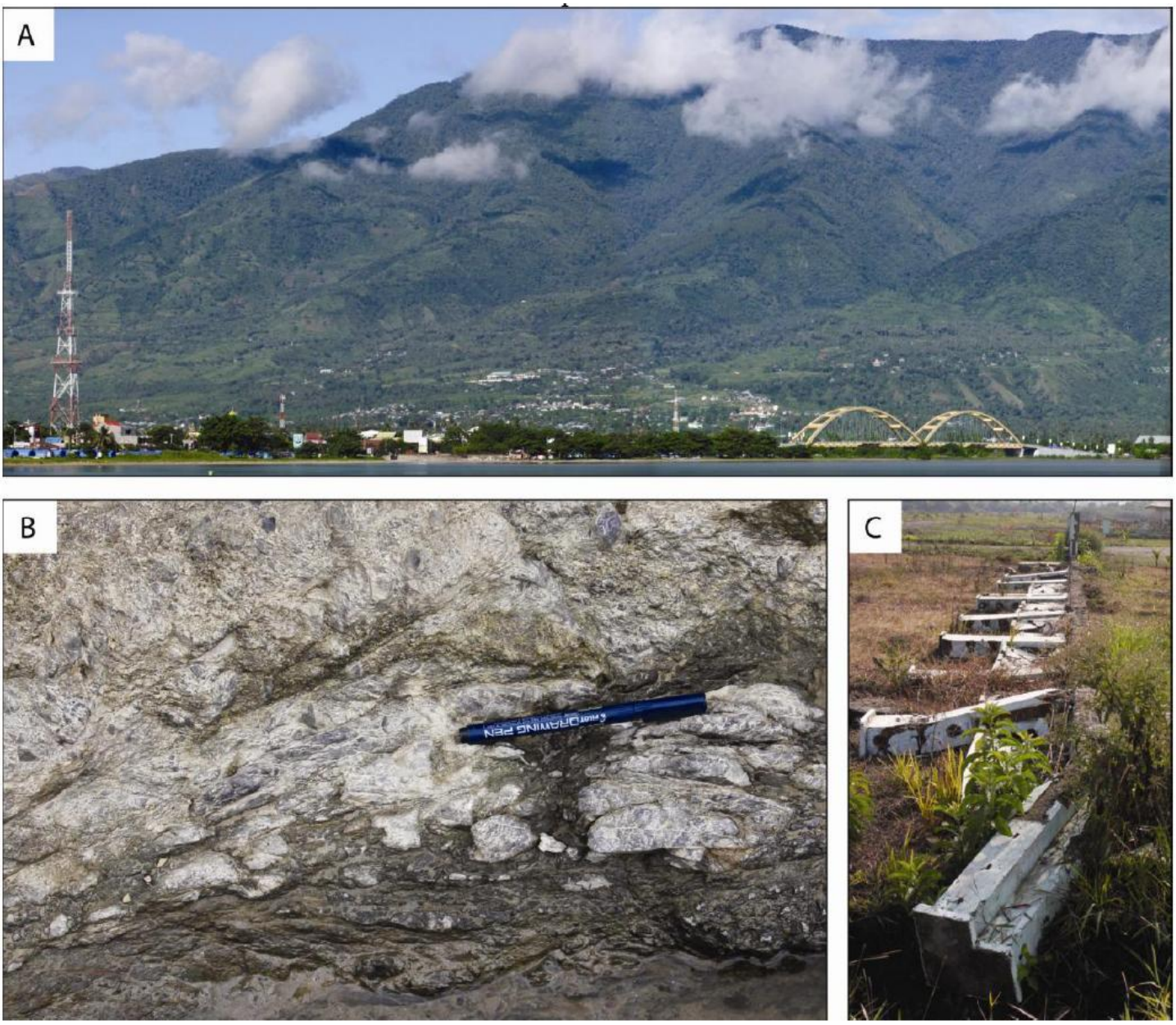


Figure 2. **(A) View west across Palu Bay to mountains adjacent to the Palu-Koro Fault. (B) Sinistral Reidel shears in fault breccia of a major Palu-Koro Fault strand south of Gimpu. (C) Damage caused by the 15-02-11 Mw 6.1 Matano Fault earthquake at Mahalona.**

propagating towards, but does not yet connect to the PKF (Watkinson, in prep.). Such a strain distribution is inconsistent with the fault bounding a rotating block. Instead, we suggest that the PKF forms the western transform boundary of a zone of lithospheric extension, and the MF is a transtensional structure at the southern margin of extension.

At the eastern end of the MF, recent work by the SEARG, utilising high resolution multibeam and seismic data, suggests that the Tolo thrust is a gravity-driven feature (Rudyawan, 2011), and not a tectonic structure that could terminate a strike-slip fault. These data also show that strands of the Sorong fault barely reach the Banggai-Sula Islands from the east (Ferdian et al., 2010; Rudyawan, 2011), and certainly do not link to strike-slip faults onshore Sulawesi (Rudyawan, 2011).

Metamorphic massifs in central Sulawesi characterised by NNW-trending corrugations may have been formed during exhumation of a metamorphic core complex (MCC) (Spencer, 2011). Recent SEARG fieldwork in central Sulawesi tentatively supports an interpretation of MCC exhumation during top-to-the-north shear, representing considerable lithospheric extension (Watkinson et al., in prep.).

In west and central Sulawesi, Cenozoic magmatic rocks include older calc-alkaline/tholeiitic intrusions and younger (including Pliocene) mafic-felsic magmas (Elburg et al., 2003). A current SEARG project aims to determine when and how granitoids in west and central Sulawesi were exhumed, by using low-temperature U-Th/He and 40Ar-39Ar thermochronology on apatites and micas. Of particular interest are the relationships between granitoid emplacement, cooling and uplift, to extension and exhumation of the metamorphics and strike-slip along the PKF.

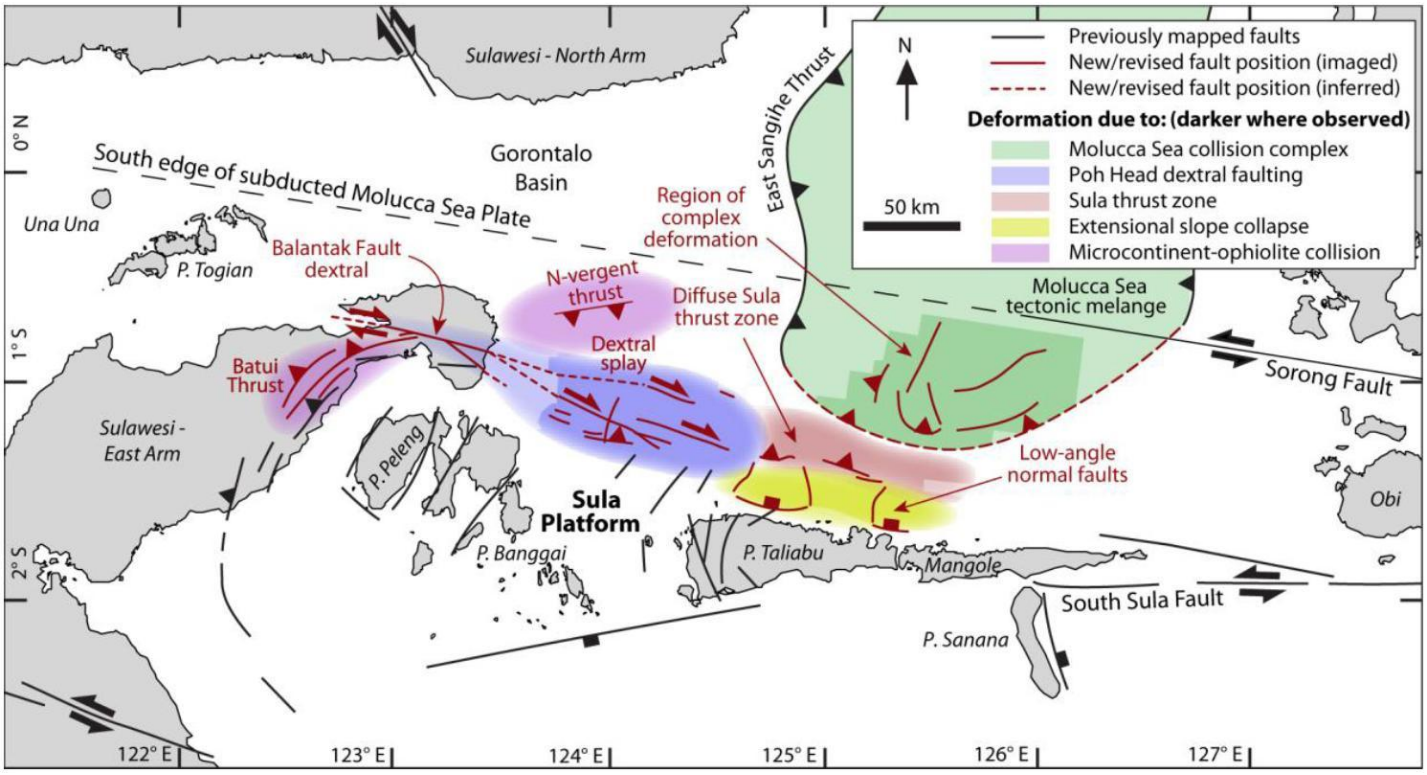


Figure 3. Map showing newly imaged faults and their deformation mechanisms. Note the absence of a through-going Sula Thrust, the Sorong Fault as a plate boundary which does not reach the surface, and the Balantak Fault and region of dextral transpression west of the east arm. Sources of deformation in the region are indicated by regions of colour. From Watkinson et al. (2011).

Tomini Bay

The Gorontalo Basin of Tomini Bay is a deep, enigmatic basin, containing up to 5 km of sediment (Hamilton, 1979). New field, geochemical and geophysical studies by the SEARG are revealing more about the basin. Cottam et al. (2011) presented a new stratigraphy for the Togian Islands, in the centre of Tomini Bay, and interpreted the age, character and evolution of the basin. The western end is underlain by continental crust, the central part by Eocene to Miocene oceanic and arc rocks, with the possibility of Banggai-Sula microcontinental crust south of the Togian Islands. Field relationships indicate a latest Miocene to Pliocene age for inception of the basin. Volcanism in the Togian Islands is not a result of Celebes Sea subduction. Instead, it is the result of extension in the Pliocene and Pleistocene. Modern volcanism at Una Una may be the result of the same process (Cottam et al., 2011).

Sulawesi's North Arm

In the western north arm, the Malino Metamorphic Complex (MMC) contains gneisses and schists with a greenschist carapace, and may be a MCC (Kavalieris et al., 1992; van Leeuwen et al., 2007). The SEARG is undertaking detailed field and thermochronological investigations to determine whether the MMC is indeed a MCC similar to those of central Sulawesi, and whether it formed/is forming during the same phase of extension. A related project on the Neogene tectonics of the central north arm aims to understand relationships between the Gorontalo Fault, intermontaine basins and uplift east of the MMC. Igneous rocks, including an unexpectedly large quantity of felsic material, will be used to determine emplacement ages and uplift rates.

Banggai-Sula Islands

The Banggai-Sula microcontinent has long been considered to have been sliced from New Guinea and travelled west along strands of the Sorong Fault (e.g. Visser & Hermes, 1962; Hamilton, 1979; Silver & Smith, 1983). Collision of the microcontinent with the east arm of Sulawesi has been thought to have caused deformation throughout Sulawesi (e.g. Bergman et al., 1996; Simandjuntak & Barber, 1996; Calvert, 2000; McClay et al., 2000).

Recent SEARG projects utilising new seismic and multibeam data from north and south of the islands show that major continuous faults previously interpreted to bound the microcontinent, including strands of the Sorong Fault, do not exist (Ferdian et al., 2010; Rudyawan, 2011; Watkinson et al., 2011) (Figure 3). Gently dipping strata of the Banggai-Sula microcontinent margin can be traced north beneath younger rocks, and are not truncated by a major fault. The strike-slip Balantak Fault passes from the east arm of Sulawesi and terminates in a zone of dextral transpression close to the Banggai-Sula Islands. There is no evidence that the Banggai-Sula microcontinent was translated along through-going structures, or that compressional deformation related to its suturing to Sulawesi was widespread (Cottam et al., 2011; Watkinson et al., 2011).

Seram

Controversies surround the geological evolution of Seram. These include the possibility of subduction at the Seram

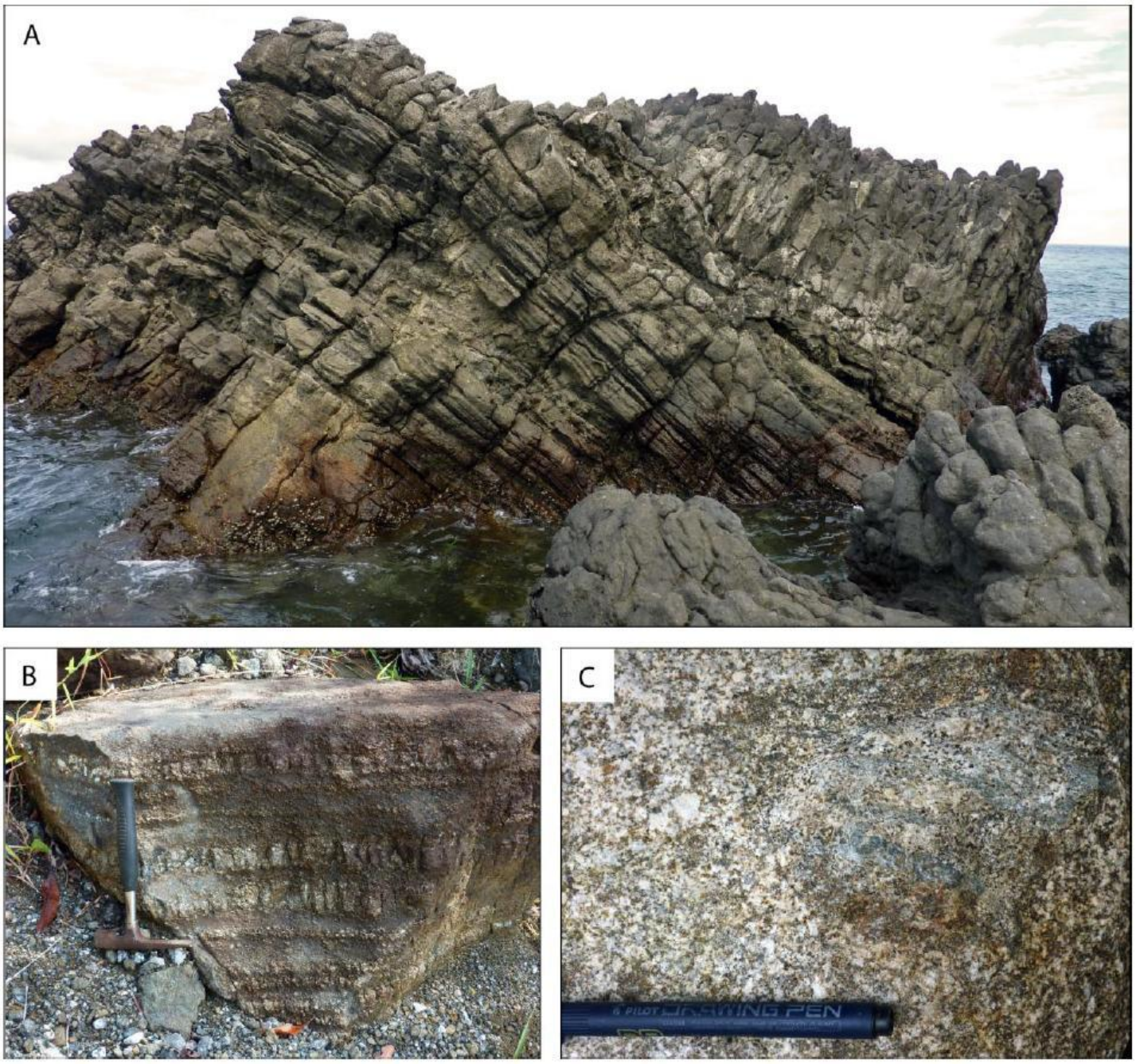


Figure 4. (A) Bedded cordierite-bearing dacites (ambonites), Ambon Island. (B) Layered peridotite, closely associated with cordierite-bearing granite. (C) Large cordierite + spinel + sillimanite restite in granite, Ambon.

trough (e.g. Hamilton, 1979; Karig et al., 1987); thrust sheet emplacement and ophiolite obduction (e.g. Audley-Charles et al., 1979; Linthout & Helmers, 1994); and the causes of anatexis and cordierite-rich volcanism (Linthout & Helmers, 1994; Honthaas et al., 1999).

Recent SEARG studies in Seram are aimed at resolving these uncertainties. Peridotites crop out throughout Seram, particularly in the west, in the SE, and in the Gorong and Watubela islands to the east. Peridotites are not associated with other typical ophiolitic components. Granites (SHRIMP U-Pb zircon age: 3 Ma, J. Decker, pers. comm., 2011) characterised by abundant cordierite and garnet, and numerous cordierite + spinel + sillimanite restites, are in contact with the peridotites. Eruptive cordierite + garnet dacites ('ambonites') are widespread on nearby Ambon (Figure 4) and have a similar ~3 Ma age (J. Decker, pers. comm., 2011).

There are many examples where peridotite appears to intrude the granites. Peridotites and granites seem to comprise a single tectonic unit exhumed along low-angle NNE-dipping detachments, not obducted by SSW-dipping thrusts as previously thought. Seram's central fault zone incorporates thin slivers of peridotite and may have been active at a similar time. North of the central fault zone in the Kobipoto Complex, cordierite-granites as well as (ultra-) high temperature granulites, with identical mineralogy to the granite-hosted restites, are found with peridotites and were probably exhumed in a similar manner to those of west Seram (Pownall et al., 2012).

West Papua

The Bird's Head of New Guinea is underlain by Australian continental crust and is considered to represent a coherent and little deformed domain of

Australian affinity with a relatively complete Palaeozoic to Recent stratigraphy (e.g. Dow et al., 1988; Audley–Charles, 1991).

An ongoing SEARG study is focused on the clastic sedimentation of the Bird's Head. Heavy mineral analysis and zircon dating is revealing the composition and provenance of these sediments. The Mesozoic Tipuma Formation includes material from local source rocks north of the formation and material from the North Australian craton (Gunawan et al., In Press) (Figure 5). Sediments from the Tipuma Formation indicate that this region experienced volcanic activity during the Triassic (Gunawan et al., In Press). This project has also shown that the Bird's Head has a more complicated tectonic history than previous models suggest.

The Biak basin, between Biak and Yapen islands, is a frontier region whose structural and sedimentary evolution and hydrocarbon potential is poorly known. The relationship between the Sorong Fault, subsidence of the Biak basin and uplift of the islands is the focus of a new SEARG project that will integrate detailed field studies, offshore seismic and multibeam data.

Banda Arc

The geodynamic evolution of the Banda Arc is a subject of great interest (e.g. Cardwell et al., 1978; McCaffrey et al., 1989; Hall, 2002). Recent work combining seismic tomography and plate tectonic reconstructions (Spakman & Hall, 2010) has shown that Jurassic oceanic crust of the Banda embayment was subducted from 15 Ma. Eastwards slab rollback continued up to 2 Ma, and was associated with extensional break-up of the Sula Spur – an arm of Australian crust extending around the north of the Banda Arc. Slab rollback and associated delamination of the continental crust explains many of the enigmatic features of the Banda Arc, such as the synformal geometry of the subducted plate in the mantle, deep marine troughs, and the distribution of fragments of Australian crust in

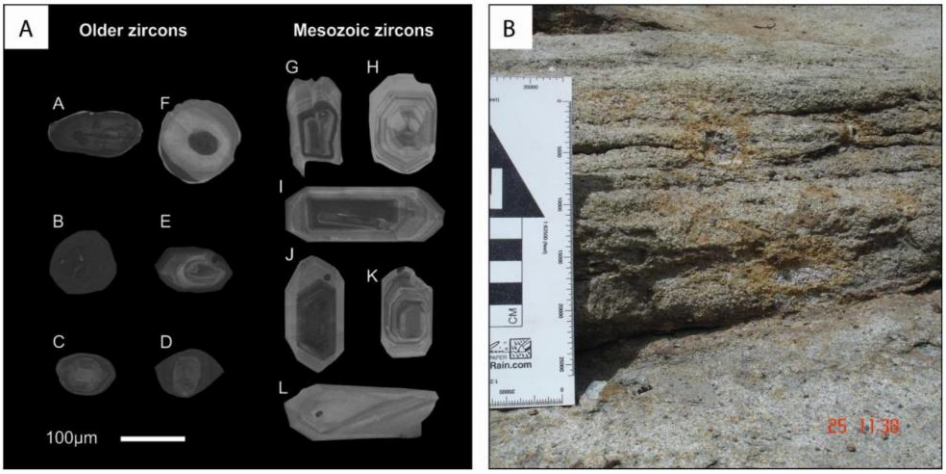


Figure 5. (A) CL image showing older (Precambrian ages) and Mesozoic zircons from the Tipuma Formation in the Bird's Head. (B) Bedded sandstones of the Tipuma Formation, Bird's Head. After Gunawan et al., In Press. Watkinson et al. SEARG research in Eastern Indonesia 7.

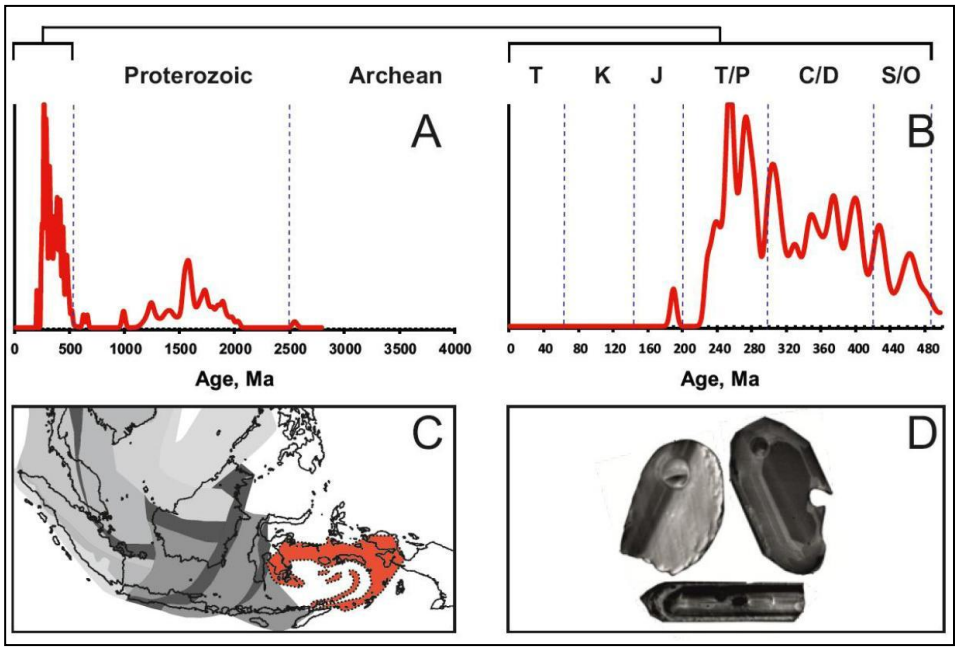


Figure 6. (A&B) Schematic probability density plot of detrital zircon U-Pb ages from the Banda Arc. (C) Cartoon showing location of Australian basement fragments (After Hall et al., in prep.) from which these zircons were analysed. (D) Examples of zircon CL-images. Watkinson et al. SEARG research in Eastern Indonesia 8.

Eastern Indonesia (Spakman & Hall, 2010).

An ongoing SEARG study aims to provide a detailed regional provenance fingerprint of zircons in SE Asia by compiling a database of existing U-Pb and Hf isotope analyses and acquiring new data (e.g. samples recently collected from Timor). Preliminary results suggest that detrital zircons in the Banda Arc (Seram), including recently discovered Permian-Triassic population (Figure 6), were derived from the Sula Spur. This confirms the existence of an acid volcanic Permian-Triassic source in or near the Sula Spur, similar to that recognised for the Bird's Head area (Sevastjanova et al., 2012).

Conclusions

Recent research by the SEARG and its collaborators shows that many long-held assumptions about the structural, magmatic, metamorphic and sedimentary evolution of Eastern Indonesia require revision. Previously it was assumed that continuous lithospheric faults bounded continental fragments, and deformation was predominantly related to collision and

extrusion tectonics. Models for the development of sedimentary basins built around these ideas have been proven to be incorrect, and blocks are generally not bounded by continuous faults. The SEARG's research shows that collision (e.g. India – Asia collision, Banggai-Sula – Sulawesi collision) is not as important in controlling intraplate deformation as subduction initiation, slab rollback, lithospheric delamination and lower crustal flow.

Acknowledgements

The SE Asia Research group is funded by a consortium of oil companies. Too many individuals and organisations have contributed to our research to list here, but a few include: Marnie Forster, Gordon Lister, Benyamin Sapiie and students at Institut Teknologi Bandung, Wim Spakman, Theo van Leeuwen, TGS-NOPEC, Fugro (FMCS) and Searcher Seismic.

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