Received: 25 January 2022 | Revised: 29 April 2022 | Accepted: 7 May 2022

DOI: 10.1111/bre.12682

RESEARCH ARTICLE

Basin Research IAS EAGE WILEY

Neogene sediment provenance and paleogeography of SE Sulawesi, Indonesia

Abang Mansyursyah Surya Nugraha[1,2] | **Robert Hall**[2]

[1]Earth Observatory of Singapore, Nanyang Technological University, Singapore, Singapore

[2]SE Asia Research Group, Department of Earth Sciences, Royal Holloway University of London, Egham, UK

Correspondence
Abang Mansyursyah Surya Nugraha, Earth Observatory of Singapore, Nanyang Technological University, 50 Nanyang Ave., 639798, Singapore, Singapore.
Email: abang.nugraha@ntu.edu.sg

Present address
Abang Mansyursyah Surya Nugraha, Earth Observatory of Singapore, Nanyang Technological University, Singapore, Singapore

Funding information
SE Asia Research Group of Royal Holloway University of London Earth Observatory of Singapore, Nanyang Technological University

Abstract

Neogene syn-and post-orogenic sedimentary rocks in Sulawesi are important to understand the history of collision of Australian continental crust with SE Asia. However, they have received relatively little attention, and have generally been considered to be molasse-type deposits of similar characteristics across Sulawesi—the Celebes Molasse. New field sedimentological observations, results from heavy mineral studies and detrital zircon U–Pb geochronology, together with conventional sandstone petrography identify three important provenance shifts, that can be correlated with significant tectonic events and enable the reconstruction of the Neogene palaeogeography of SE Sulawesi. The first provenance shift was related to the Early Miocene collision of Australian crust and the North Sulawesi volcanic arc, accompanied by ophiolite emplacement in East Sulawesi, marked by a change from pre-collision carbonates to ultramafic-rich clastics of the Bungku Formation. A second change in the Late Miocene was marked by input of abundant metamorphic detritus including blueschists into the Pandua Formation indicating exhumation of Oligo-Miocene subduction zone material. The third provenance change, of Mio-Pliocene age, was from the ophiolite- and blueschist-rich Pandua Formation to the quartz-rich Langkowala Formation, and records blocking of the ophiolite debris pathways by the rise and progressive unroofing of low- to high-grade metamorphic rocks. The Neogene sedimentary rocks of SE Sulawesi record Early Miocene collision and ophiolite emplacement, followed by extension which led to exhumation of Mesozoic and metamorphic rocks, driven by Banda subduction rollback.

KEYWORDS

light and heavy minerals, palaeogeography, provenance, SE Sulawesi, sediment, zircon geochronology

1 | INTRODUCTION

Sulawesi (formerly called "Celebes") is situated close to the triple junction of the Eurasian, Australian and Pacific plates (Figure 1). This large island (ca. 181,000 km^2) has a distinctive 'K' shape with four elevated arms (North, East, South and SE) separated by deep water bays: Gorontalo Bay, Tolo Bay and Bone Bay (Figure 1). Collision of

Australia and SE Asia probably began in Sulawesi, but despite decades of studies, the timing of the initial collision remains a subject of debate (e.g., Audley-Charles, 1974; Cottam et al., 2011; Davidson, 1991; Hall, 1996, 2002; Hamilton, 1979; Hall & Wilson, 2000; Parkinson, 1998). This collision caused the addition of microcontinental crust to the Sundaland margin, emplacement of ophiolite in eastern Sulawesi and significant localised uplift (Kündig, 1956; Silver et al., 1983). Sedimentological evidence provides an estimate of timing of initial uplift of the East Sulawesi Ophiolite (ESO) and Central Sulawesi metamorphic complexes. The first record of reworked ophiolitic material is from Lower Miocene carbonates and sandstones in SE Sulawesi (Nugraha & Hall, 2018; Nugraha, Hall, & BouDagher-Fadel, 2022; van der Vlerk & Dozy, 1934). Although early Neogene collision and uplift has been confirmed across eastern Sulawesi, the subsequent exhumation and sedimentation history of SE Sulawesi is still poorly understood. In this study we evaluate erosional exhumation of pre-collision rocks of the SE Arm using light and heavy mineral analyses including detrital zircon U–Pb geochronology to recognise provenance shifts, outline the provenance history of sedimentary basins and track exhumation of sediment source regions.

Highlights

- Three major provenance changes in Neogene Celebes Molasse linked to tectonic events and source changes.
- Early Miocene change from carbonates to ultrabasic-rich clastics marks Australia collision and ophiolite uplift.
- Late Miocene sediment input included blueschists as Oligo-Miocene subduction zone rocks were exhumed.
- Mio-Pliocene change to quartz-rich clastics records metamorphic/Mesozoic rocks unroofing and drainage changes.

2 | REGIONAL GEOLOGY

The SE Arm is underlain by metamorphic rocks and Mesozoic sedimentary rocks of Australian origin (Figure 2a, Decker et al., 2017; Ferdian et al., 2012; Nugraha & Hall, 2018; Sukamto, 1975a, 1975b; Surono & Bachri, 2002; Sukamto & Simandjuntak, 1983). The Mesozoic sedimentary rocks include the siliciclastic Meluhu and carbonate Tokala Formations. The Meluhu Formation consists of fluvial conglomeratic sandstones, mudstones and shales which deepen-up into deltaic mudstones, sandstones, conglomerates and shallow marginal marine deposits of marl and limestone (Rusmana & Sukarna, 1985; Surono, 1994, 1997, 1998; Surono & Bachri, 2002). The formation was interpreted to have been deposited in the Late Triassic based on bivalve (*Halobia* sp. and *Daonella* sp.) and ammonite (*Preflorianites* sp. and *Tropites* sp.) fossils (Rusmana et al., 1993; Surono, 1994). Detrital U–Pb zircon dating indicates a maximum depositional age of Late Triassic (Decker et al., 2017; Ferdian et al., 2012) for some sandstones of the Meluhu Formation. The Tokala Formation consists of conodont-bearing limestones, reefal deposits and intertidal/supratidal algal laminites that show a general regressive trend from a marginal to an inner platform environment. It yields Late Triassic (*Rhynchonella*, *Misolia* and *Misikella posthensteini*) fossils (Cornée et al., 1994, 1999; Kündig, 1956; Martini et al., 1997; Simandjuntak, 1986) and palynological assemblages of Upper Triassic-Lower Jurassic palynomorphs (Martini et al., 1997).

These Mesozoic rocks are unconformably overlain by Cretaceous and Paleogene carbonates. The Cretaceous Matano Formation in the SE Arm consists of well-bedded limestones (mudstone/wackestone and packstone), oolitic and oncolitic limestones and calcilutites with shale and red cherts that are often metamorphosed (Cornée et al., 1995; Rusmana et al., 1993). It yields planktonic foraminifera and calcareous nannoplankton assemblages of Albian and Campanian-Maastrichtian age. The Palaeogene Tampakura Formation unconformably overlies the Meluhu Formation. It includes oolites, lime mudstones, wackestones, packstones, grainstones and framestones. Foraminifera and nannoflora analyses of the Tampakura Formation suggest an Upper Eocene to Lower Oligocene carbonate rimmed shelf (Surono, 1994, 1995, 1996, 1998).

Ultramafic and mafic rocks in the East Arm are part of the Eastern Sulawesi Ophiolite Belt (Simandjuntak, 1986), or East Sulawesi Ophiolite (Bergman et al., 1996; Kadarusman et al., 2004; Monnier et al., 1995; Parkinson, 1998; Villeneuve et al., 2001), that was emplaced in the Neogene. East Sulawesi is dominated by ultramafic rocks with subordinate gabbros, sheeted dolerites and scarce pillow basalts. A complete ophiolite sequence was reported to be exposed in Poh Head at the eastern end of the East Arm (Silver et al., 1983; Simandjuntak, 1986). K-Ar and Ar-Ar dating on basalts and gabbros of the ESO suggested Cretaceous (79–137 Ma), Palaeogene (64–28 Ma) and Neogene (16–23 Ma) ages (Bergman et al., 1996; Monnier et al., 1995; Mubroto et al., 1994; Parkinson, 1998; Simandjuntak, 1986, 1992). The ESO is tectonically intercalated with metamorphic rocks and Mesozoic-Paleogene sedimentary rocks (Brouwer, 1934;

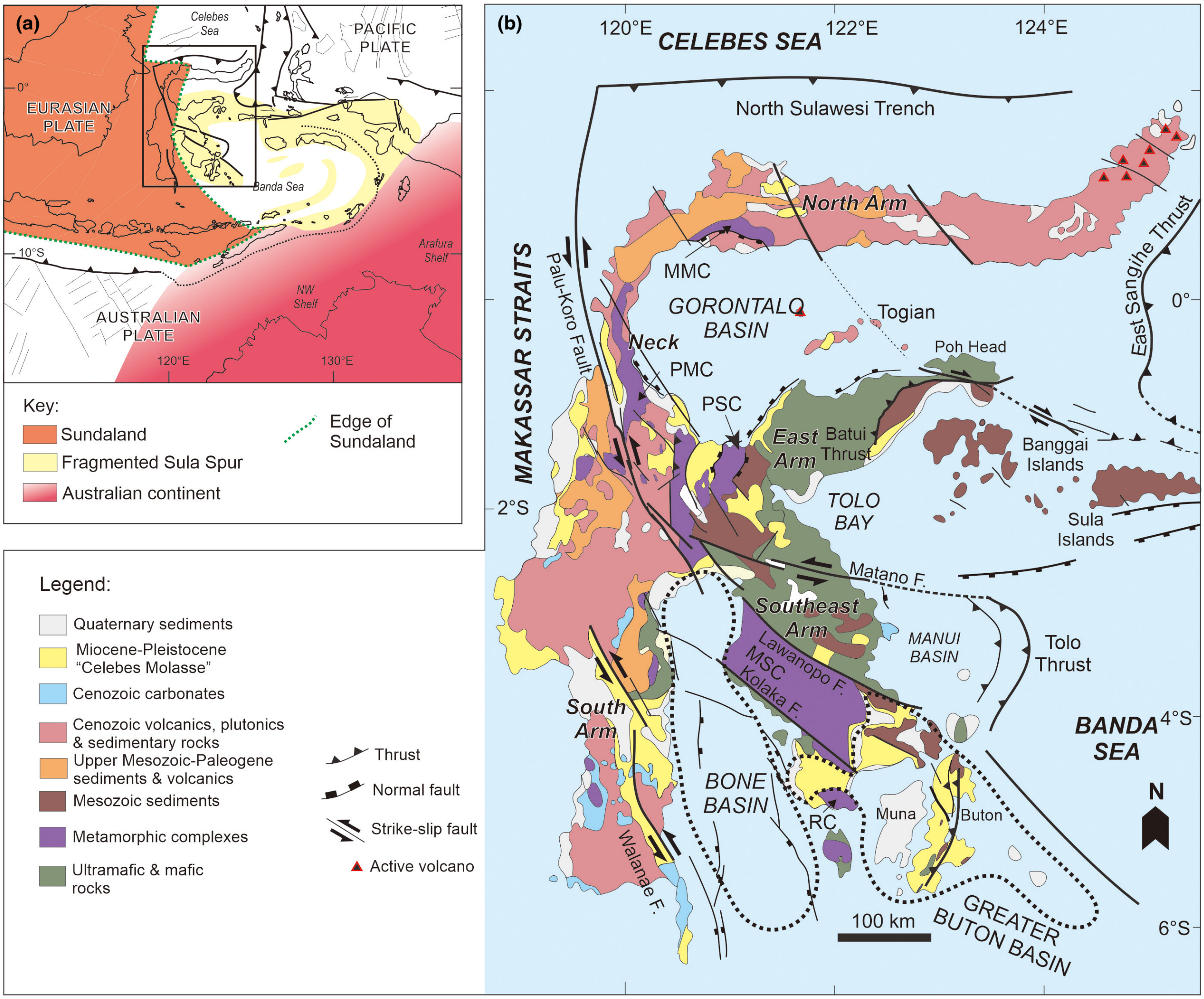

FIGURE 1 (a) The principal tectonic blocks of eastern Indonesia on present day map (modified after Hall, 2012; Watkinson, 2011). Location of Sulawesi Island is in black box. Note that Sulawesi is at the junctions of three major plates and records continent-continent collision between Sundaland and fragments of Australian continental margin. (b) Simplified geological map of Sulawesi. Modified after Hall and Wilson (2000), Watkinson (2011), Pholbud et al. (2012), Camplin and Hall (2014). MMC, Malino metamorphic complex; MSC, Mekonga metamorphic complex; PMC, Palu metamorphic complex; PSC, Pompangeo schist complex, RC, Rumbia complex.

Brouwer et al., 1947; Koolhoven, 1930; Kündig, 1956; Silver et al., 1983; Simandjuntak, 1986; Simandjuntak et al., 1993; Sukamto & Simandjuntak, 1983). Although a full ophiolite suite is found only at the eastern end of the East Arm, ultramafic and mafic rocks in SE Sulawesi, Kabaena, Buton and the Wowoni islands are often considered to be parts of the dismembered ESO (Kündig, 1956; Silver et al., 1983). Hamilton (1979) observed that "gabbro, diabase, basalt, spilite, amphibolite and greenschist" are of minor volume in the SE Arm and "the relative scarcity of mafic rocks in the SE Arm pose problems," although ultramafic rocks are abundant. Isotopic dating of the Eastern Sulawesi metamorphic rocks (ESMC), which include blueschists, in the SE Arm suggest Oligo-Miocene subduction-related metamorphism (Helmers et al., 1989; Mawaleda et al., 2018; Parkinson, 1996; Wijbrans et al., 1994).

The ophiolitic, metamorphic and Mesozoic rocks are all overlain unconformably by Neogene syn- to post-orogenic deposits previously assigned to the Celebes Molasse. In the SE Arm, Surono (1994) divided the Sulawesi Molasse into the Pandua, Langkowala, Boepinang, Eemoiko, Buara and Alangga Formations that were deposited during the Neogene. Recent work (Nugraha & Hall, 2018; Nugraha, Hall, & BouDagher-Fadel, 2022), has simplified the Neogene stratigraphy into carbonates and fluvio-deltaic clastics of the Lower Miocene Bungku Formation, shallow to marginal marine deposits of the Upper Miocene

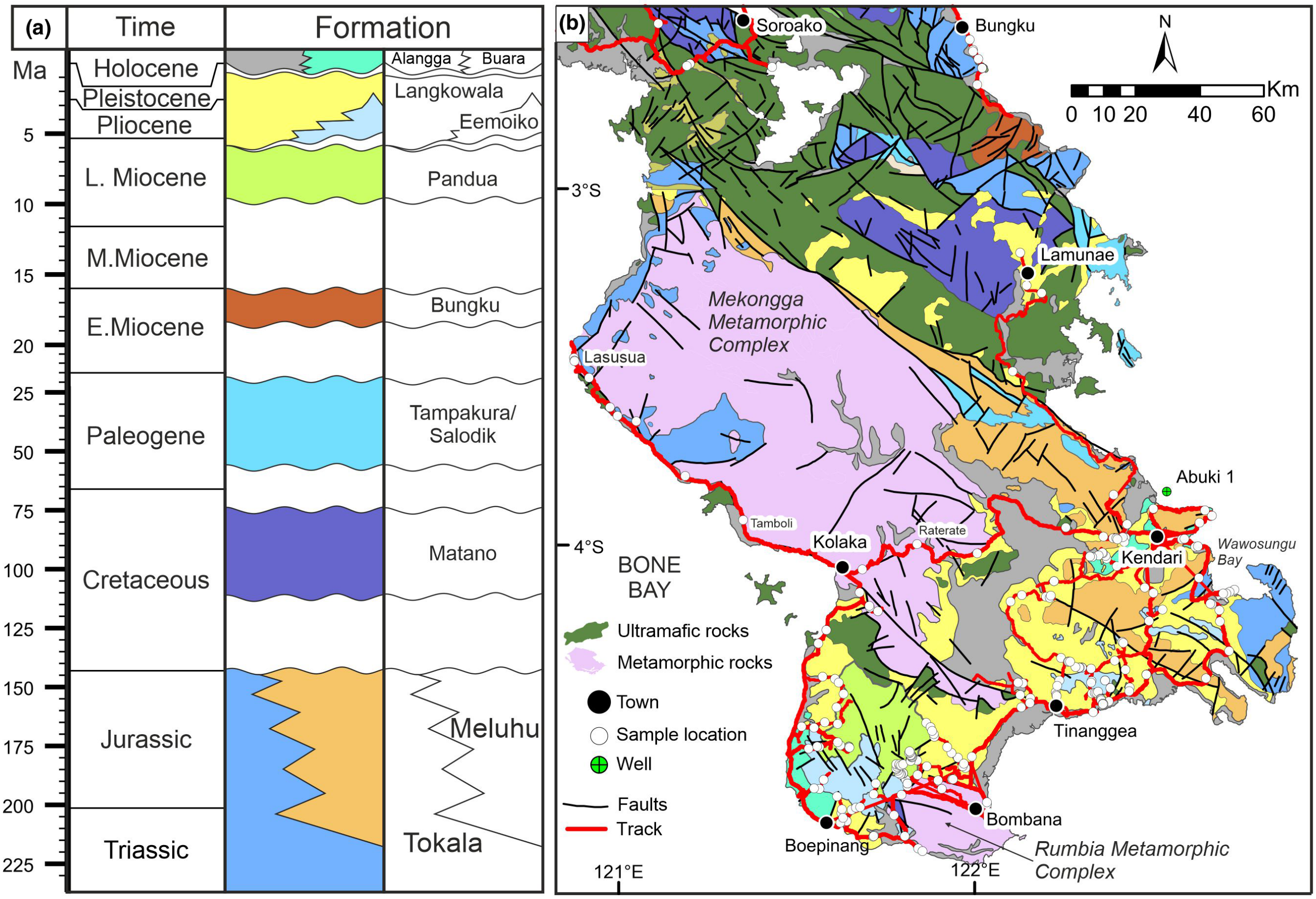

FIGURE 2 (a) Revised stratigraphy (general rock types: *siliciclastics and ^carbonates) and (b) geological map of SE Sulawesi (modified from Rusmana et al., 1993; Simandjuntak et al., 1993).

Pandua Formation, fluvial to marine deposits of the uppermost Miocene–lowermost Pleistocene Langkowala Formation, and carbonates of the Pliocene Eemoiko Formation (Figure 2). These formations are overlain unconformably by Quaternary carbonates and siliciclastics of the Buara and Allangga Formations, respectively.

3 | DATA AND METHODOLOGY

3.1 | Data

A total of 44 samples were collected from the Bungku, Pandua, Langkowala and Eemoiko Formations for petrographic analysis using thin sections. Seven samples from the Pandua and Langkowala Formations were processed for heavy mineral analysis. Six samples were prepared for detrital zircon U–Pb geochronology, including two samples from the Meluhu Formation.

This study also incorporated a 2D seismic line from western Bone Gulf (to the southwest of the SE Arm) and stratigraphic age ranges and paleocurrent data from Nugraha, Hall, and BouDagher-Fadel (2022), Nugraha, Hall, BouDagher-Fadel, Todd, and Switzer (2022)). The seismic line is part of a 2D seismic dataset which was acquired by TGS in 2007 and shows well-preserved shelf margin clinoforms that can be correlated with the formations on land in the SE Arm (Figure 3; Camplin & Hall, 2014).

3.2 | Laboratory methods

3.2.1 | Petrology

Medium- to coarse-grained sandstones and carbonates were collected for petrological analysis (Supporting Information S1). Line point-counting (Galehouse, 1971) was performed using the Gazzi-Dickinson method and at least 500 grains were identified for each sample. Sandstone compositions were plotted on QFL (quartz-feldspars-lithic fragments) and QmFLt (monocrystalline quartz-feldspars-total lithic fragments) diagrams following the conventions of Dickinson (1970, 1985), Dickinson and Suczek (1979), Dickinson et al. (1983), Ingersoll (1983) and Dorsey (1988) (Figure 4). However, light mineral analysis alone cannot

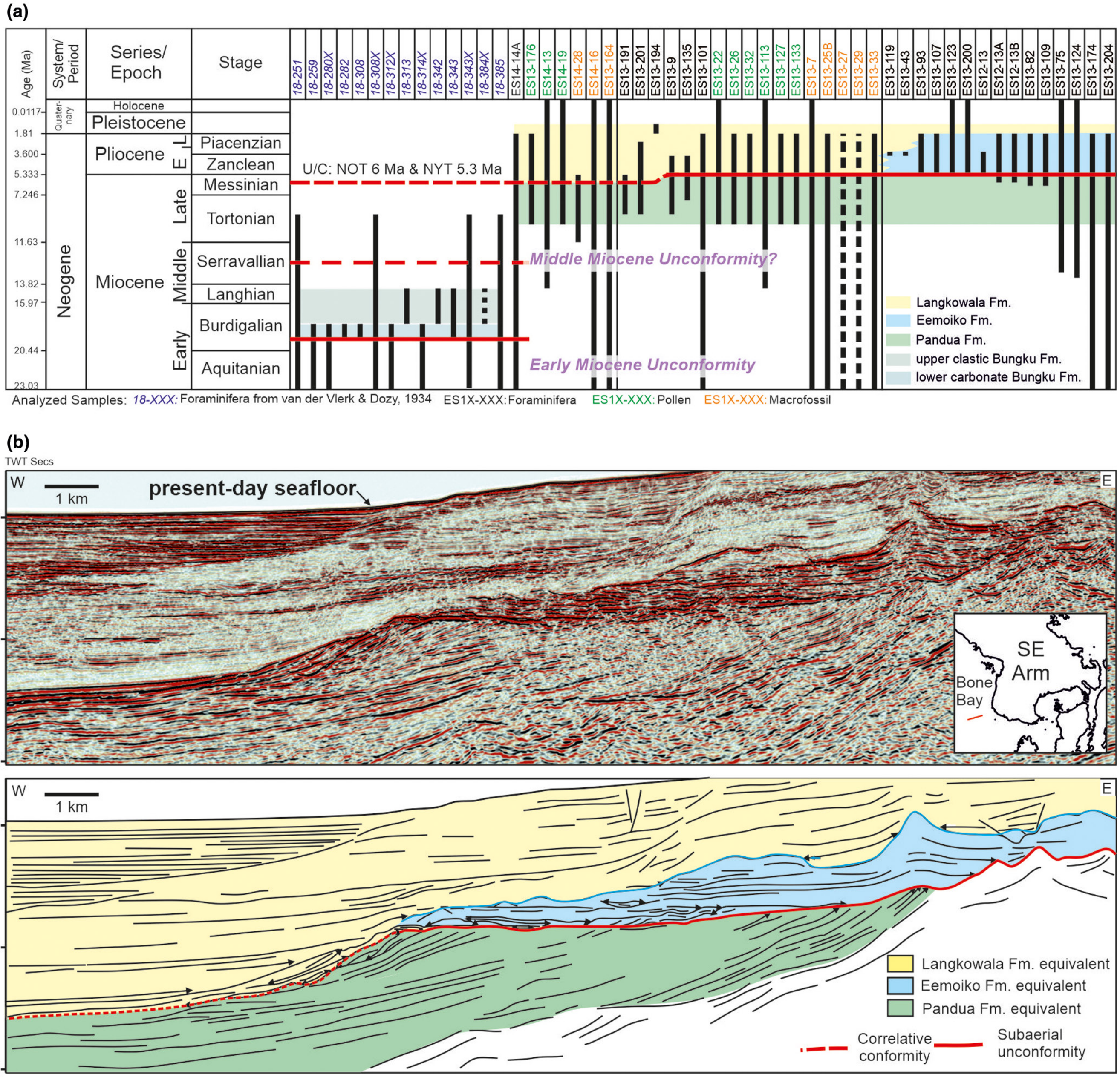

FIGURE 3 (a) Integrated stratigraphic ranges from the Neogene sediment samples on based on the biostratigraphic range of the foraminifera, nannofossil, macrofossil and pollen taxa. (b) Uninterpreted (above) and interpreted (below) offshore seismic line (Camplin & Hall, 2014) in eastern Bone Bay showing seismic units that are interpreted equivalents to the onshore SE Sulawesi stratigraphic units. Note the red line marking the interpreted Mio-Pliocene unconformity surface.

provide a complete insight into provenance and needs to be integrated with other analyses such as heavy mineral modes and detrital U–Pb zircon dating.

3.2.2 | Heavy minerals

Selected samples were processed using standard heavy mineral separation methods (Mange & Maurer, 1992) to get about 300 g of 63–250 μm dry and clean fractions (Supporting Information S2). Selected samples were crushed, decarbonated in 10% acetic acid, wet and dry sieved (63–250 μm meshes sieving stack) and separated in a funnel using Lithium polytungstate (LST, at a density of 2.89 g/cm^3). Identification was performed using an optical polarising microscope (NIKON Eclipse Lv 100) with a ribbon counting method (Galehouse, 1971). Additional Scanning Electron Microscope (Hitachi S3000 SEM) and Energy Dispersive Spectroscopy (EDS, X-MaxN 50-silicon drift) analyses were performed to

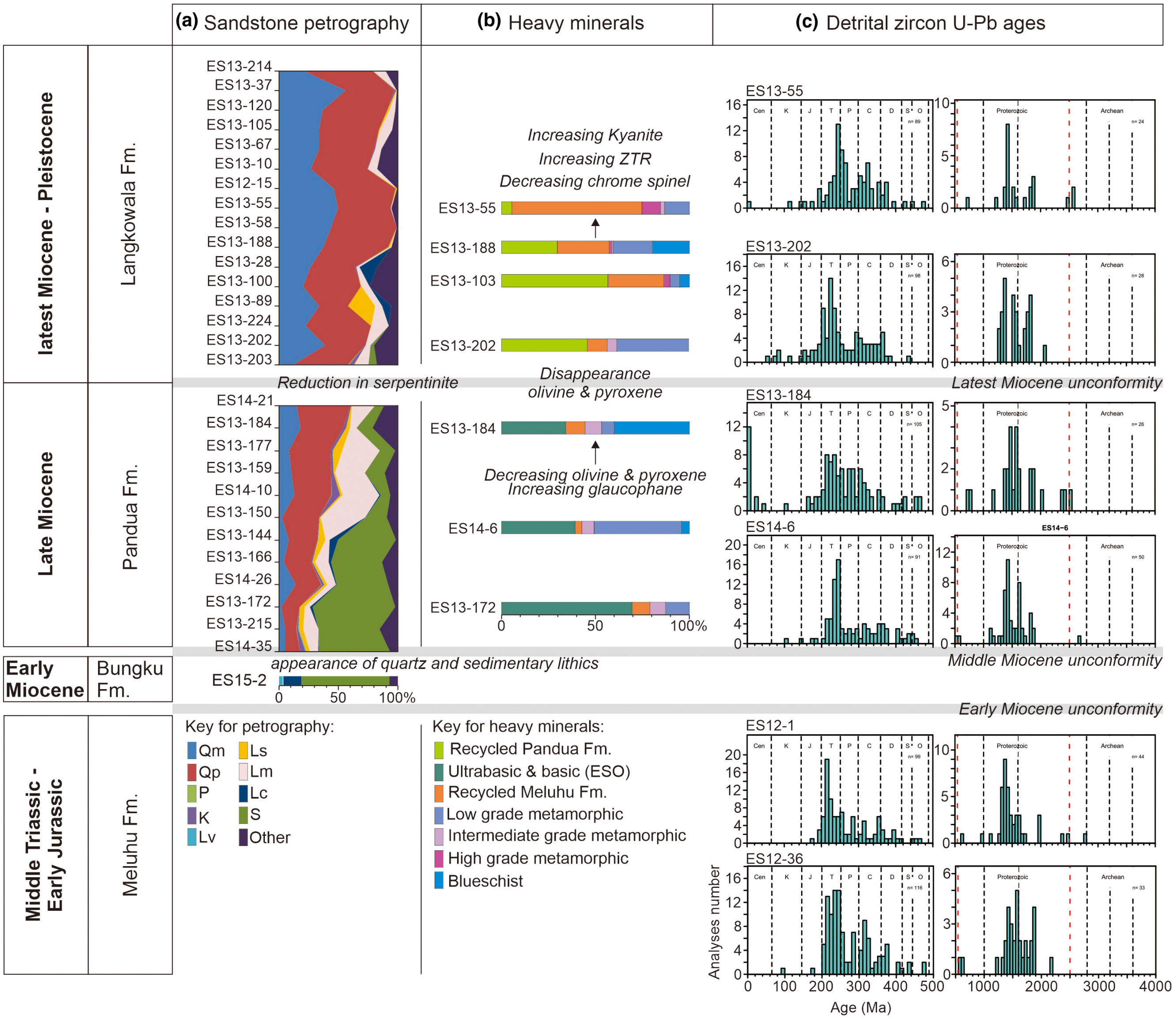

FIGURE 4 Composite plot of provenance data for this study, including (a) sandstone petrography compositions (Qm: Monocrystalline quartz; Qp: Polycrystalline quartz; P: Plagioclase; K: Potassium feldspar; lv: Volcanic lithic; ls: Sedimentary lithic; Lm: Metamorphic lithic; Lc: Carbonate lithic; S: Serpentinite), (b) heavy mineral assemblages (ZTR: Zircon, tourmaline and rutile) and (c) detrital zircon U–pb ages depicted as age histograms.

establish or confirm the identity of some heavy minerals. Indicative minerals such as chrome spinel and kyanite were confirmed by scanning electron microscopy and energy-dispersive X-ray spectroscopy (SEM-EDS) analyses. A Cr-rich composition, octahedral or irregular shape and conchoidal breakage pattern are the main characteristics of chrome spinel. Kyanite has a bladed or prismatic shape, perfect cleavage and parting.

3.2.3 | Zircon geochronology

Selected samples were processed using heavy mineral separation as described above, followed by Frantz magnetic separation (15° forward slope angle, 25° side tilt and ampere settings of 1.7 mA), diiodomethane (DIM, at a density of density 3.3 g/cm^3) heavy liquid separation and zircon picking (using an Olympus SZx12 binocular microscope). Mineral separates were mounted in Araldite resin blocks, polished and imaged using cathodoluminescence (CL). Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) dating of zircons was performed on a New Wave NWR 213 nm laser ablation system coupled to an Agilent 7700 quadrupole-based ICP–MS at Birkbeck College, University of London (UCL). The Plešovice zircon standard (337.13 ± 0.37 Ma; Sláma et al., 2008) and a NIST 612 silicate glass bead (Pearce et al., 1997) were used to correct for instrumental mass bias and depth-dependent inter-element fractionation of Pb, Th and U.

Data reduction and common lead correction were performed using GLITTER™ software (Griffin et al., 2008) and Andersen (2002) methods. Concordant ages were accepted based on a 10% threshold (Supporting Information S3). Age histograms were created using an R script that adopts the approach of Sircombe (2004).

4 | RESULTS

4.1 | Sandstone framework petrography

4.1.1 | Bungku Formation

There is only one litharenite sandstone sample ES15-2 (a total of 550 grains) collected for the Bungku Formation from its only outcrop at Tanjung Losoni (Figure 5a). The results are summarised in Figures 4a and 5. This sample consist of serpentinite (75%), carbonate lithics (15%), mafic igneous lithics (2%), schist lithics (1%) and other grains (7%; including chrome spinel, pyroxene, amphibole, chlorite and altered grains). The sub-rounded to angular grains and moderately sorted nature suggest a sub-mature sandstone. Based on these results, the sample is a compositionally immature sandstone with a low quartz content (<1%). Sample ES15-2 has undissected arc and lithic recycled provenances on the QFL and QmFLt diagrams, respectively (Figure 5b). Compaction prior to cementation is suggested by bent serpentinite grains and concavo-convex grain contacts (Figure 6a).

4.1.2 | Pandua Formation

Point counting was performed on 12 thin sections (Figures 4a and 5) of fine- to coarse-grained sandstones. Between 500 and 625 grains were counted in each thin section and consist of serpentinite (8%–69%), polycrystalline quartz (10%–45%), monocrystalline quartz (2%–18%), metamorphic lithics (4%–37%), sedimentary lithics (up to 8%), potassium feldspar (up to 7%) and minor plagioclase feldspar, carbonates and accessory minerals including glaucophane (Figure 6b) and chrome spinel (Figure 6c). Serpentinite grains are the most common, followed by polycrystalline quartz (27%), metamorphic lithics (16%) and undulose monocrystalline quartz (9%). Serpentinite abundance decreases upwards while polycrystalline quartz and metamorphic lithics that commonly appear with glaucophane increase upwards to the uppermost part of the succession (Figure 4a). The sub-rounded to angular nature of the framework grains in these sandstones suggest sub-mature to immature sandstones (Figure 5a). The presence of easily altered grains such pyroxenes, amphiboles and serpentines is indicative of immature sandstones. Compaction prior to cementation is interpreted from bent mica and serpentine grains. The QFL plots show predominant recycled orogen to undissected arc origin provenances whereas on the QmFLt plot all samples fall in the lithic recycled origin field (Figure 5b).

4.1.3 | Langkowala Formation

A total of 7924 grains were counted from 16 samples which are classified as sub-litharenite and quartz arenite,

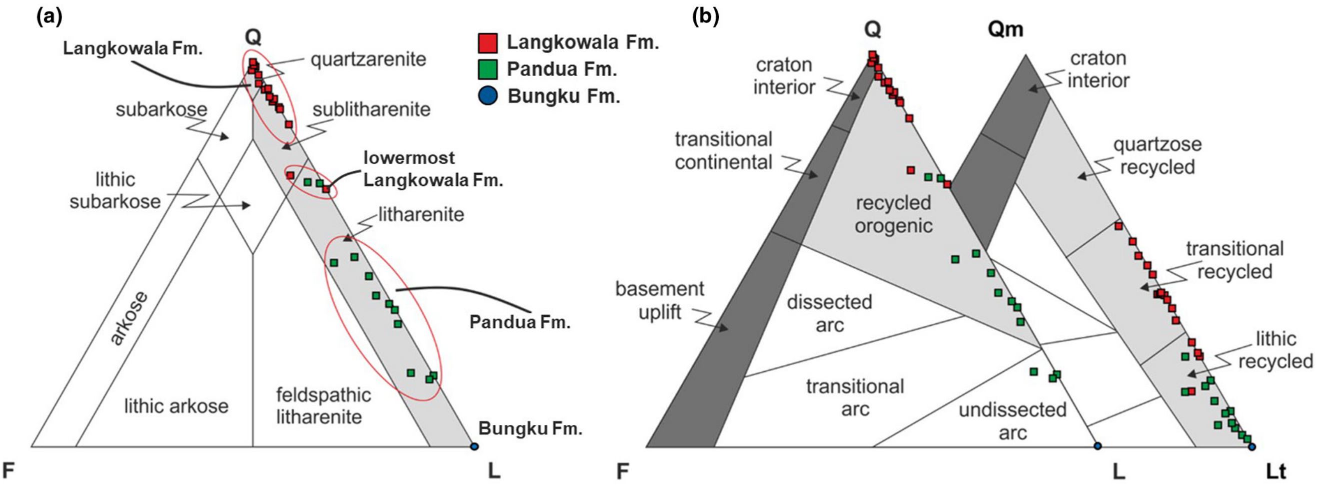

FIGURE 5 (a) QFL plot showing sandstones range from quartzarenite to litharenite (b) QFL plot showing craton interior, recycled orogenic and undissected arc provenances, and QmFLt plot showing transitional recycled and lithic recycled provenances.

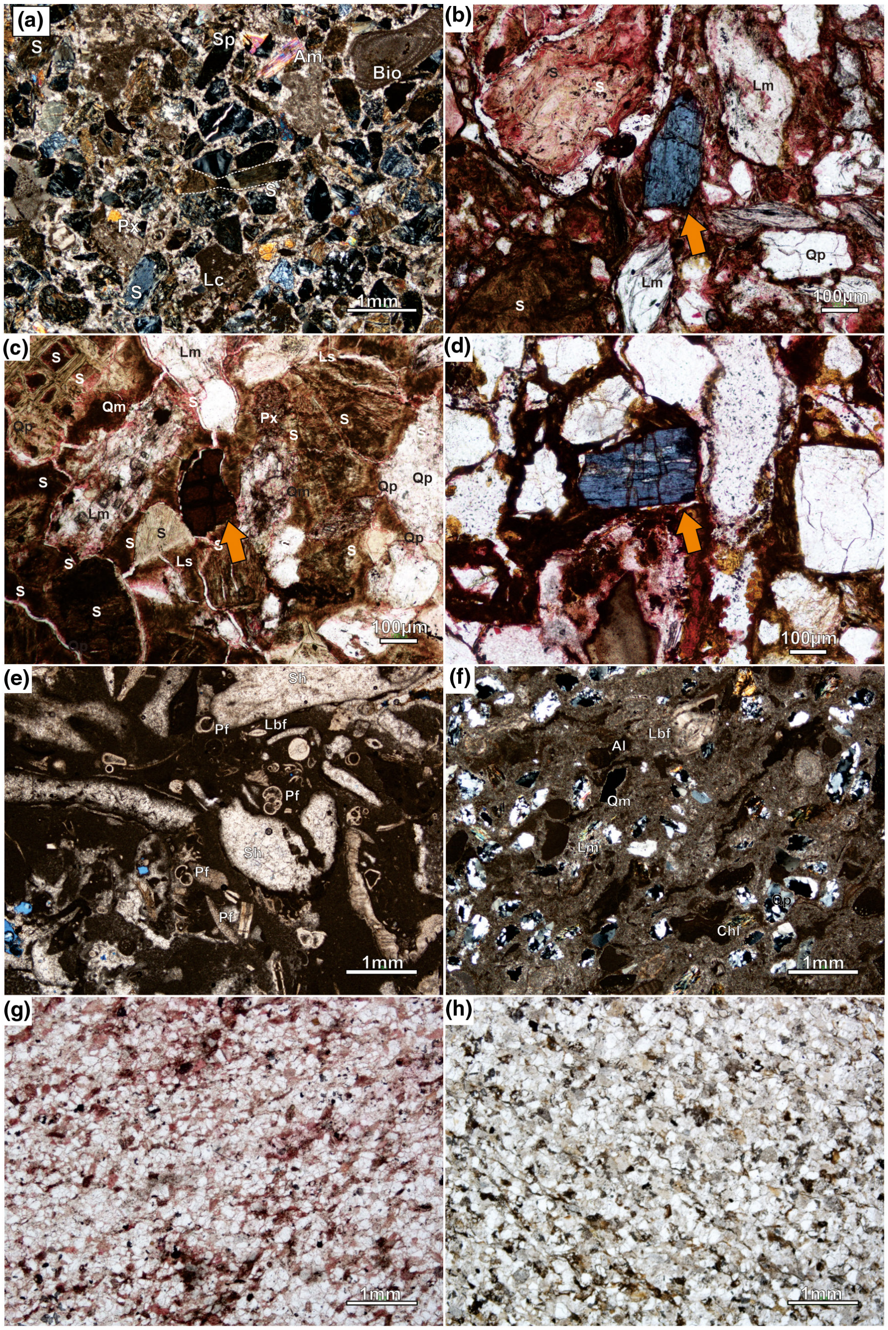

FIGURE 6 Representative photomicrographs of (a) Bungku formation (sample ES15) in XPL showing minor pyroxene (px), amphibole (am), limestone clasts (Lc) and bioclast (bio), note the kinked serpentinite (S) in the middle. (b) Sandstones in the Pandua formation (ES13-184) in PPL shows blue coloured glaucophane and (c) dark brown spinel. (d) Blue coloured glaucophane from the Langkowala formation (ES13-28). XPL photomicrographs of (e) quartz-rich packstone (ES12-13) and (f) bioclastic packstone (ES13-119) of the Eemoiko formation. Comparison of (g) sandstone clast from conglomerate of the Langkowala formation (ES13-57) with (h) sandstone of the Meluhu formation (ES12-01). Al, Algae; am, Amphibole; bf, Benthic foraminifera; Chl, Chlorite; lbf, Large benthic foraminifera; Lm, Metamorphic lithic; ls, Sedimentary lithic; pf, Planktonic foraminifera; px, Pyroxene; Qm, Monocrystalline quartz, Qp, Polycrystalline quartz; Sh, Shells.

except for one sample (ES13-89) which is a litharenite (Figures 4a and 5). Grains consist of polycrystalline quartz (47%), monocrystalline quartz (33%), potassium feldspar (1%), metamorphic lithics (5%), sedimentary lithics (2%), carbonate lithics (1%), serpentine (1%) and minor minerals such as micas, glaucophane and chrome spinel. The sandstones are compositionally mature and dominated by quartz grains (Figure 5a). Blue glaucophane grains are also observed in this formation (Figure 6d). Texturally, there is a bimodal character to quartz grains with two groups: rounded and angular. Most of the larger quartz clasts are rounded to sub-rounded while smaller quartz grains are predominantly sub-angular. The predominance of quartz indicates craton interior and recycled orogenic provenances on the QFL diagram (Figure 5b). On the QmFLt diagram, samples plot in the transitional recycled, quartzose recycled and craton interior fields.

4.1.4 | Eemoiko Formation

Microfacies were assessed with the biostratigraphic analysis based on petrographic study. There are three major microfacies: (1) packstone, (2) micritic packstone and (3) micritic wackestone (Supporting Information

S1, Figure 5e). Bioclastic components including benthic and planktonic foraminifera indicate inner neritic/inner platform, reefal area and fore-reef environments. The presence of monocrystalline quartz, polycrystalline quartz, metamorphic lithic, chlorite and amphibole grains suggest a subordinate clastic input (Figure 5f).

4.2 | Lithoclasts

4.2.1 | Bungku Formation

The Bungku Formation conglomerate clasts include ultramafic and mafic rocks, limestones, siltstones and cherts. Clasts are subrounded to rounded and their size ranges from pebble to cobble.

4.2.2 | Pandua Formation

The Pandua Formation conglomerate clasts are serpentinites, partly serpentinised ultramafics, mafic rocks, quartz, red chert, metamorphic rocks, siltstones and limestones. The quartz clasts are commonly sub-angular, whereas other clasts are commonly sub-rounded to rounded. Clast size ranges from granule to cobble.

4.2.3 | Langkowala Formation

The Langkowala Formation conglomerate clasts are predominantly quartz, subsidiary quartz rich-sandstone, metamorphic rocks and minor mudstone. Ultramafic clasts are very rarely found in conglomerates of the Langkowala Formation. Almost all conglomerate fragments have sub-rounded to rounded shapes but some quartz clasts are locally sub-angular to angular. Clast sizes range from granule to cobble.

4.3 | Heavy minerals

4.3.1 | Pandua Formation

A total of 1025 grains were counted. Representative photomicrographs are shown in Figures 6 and 7, and the results of point counting are summarised in Figure 4b. The most relevant heavy minerals for provenance analysis are chrome spinel with an abundance of 10.8% to 51.4%, followed by serpentine, hornblende, pyroxene, olivine, zircon, tourmaline, rutile, garnet, detrital micas, glaucophane and other accessory minerals (Figure 7). Common heavy minerals were grouped by their most likely protoliths, based on suggested source rock associations (Feo-Codecido, 1956; Mange, 2002; Nichols, 2009). Serpentine, chrome spinel, pyroxene and hornblende indicate ultramafic and mafic rock sources. Zircon, tourmaline and rutile suggest reworked sedimentary or an acid igneous source. Glaucophane and lawsonite indicate a high pressure and low temperature (HP-LT) blueschist metamorphic source. Garnet, blue tourmaline, chloritoid, chlorite, titanite, muscovite and other amphiboles suggest other metamorphic sources.

4.3.2 | Langkowala Formation

A total of 1084 grains were counted for heavy mineral analysis. The results are summarised in Figure 4b. The most relevant heavy minerals for provenance analysis are zircon, tourmaline, rutile, apatite, titanite, serpentine, epidotes (including clinozoisite and zoisite), garnet, staurolite, kyanite, sillimanite, amphiboles (including hornblende and glaucophane), pyroxenes (clino- and ortho-pyroxenes) and spinel (Figure 7). Zircon, tourmaline and rutile are ultrastable minerals that can be derived from acid igneous sources and reworked sedimentary rocks. Although zircons were originally derived from acid igneous sources, detrital zircon U–Pb ages show that Permo-Triassic zircons with predominant rounded to sub-rounded grains were reworked. Distinctive blue amphiboles (glaucophane-crossite) represent HP-LT metamorphic rocks of blueschist facies. Kyanite, sillimanite, staurolite and chlorite suggest a relatively high temperature–pressure and different metamorphic source. Garnet could be derived from both metamorphic parentages. Titanite was probably derived from a metabasite source. Epidote is considered to be an alteration product of amphibole or feldspar, or derived from an igneous rock or hydrothermal veins. Chrome spinel was derived directly from an ultramafic source or by reworking of sediments from the Pandua Formation.

4.4 | Zircon geochronology

4.4.1 | Meluhu Formation

A total of 291 zircon ages were recorded from samples two quartz-rich sandstone samples (ES12-2 and ES12-6). The results of zircon geochronology are shown in Figure 4c.

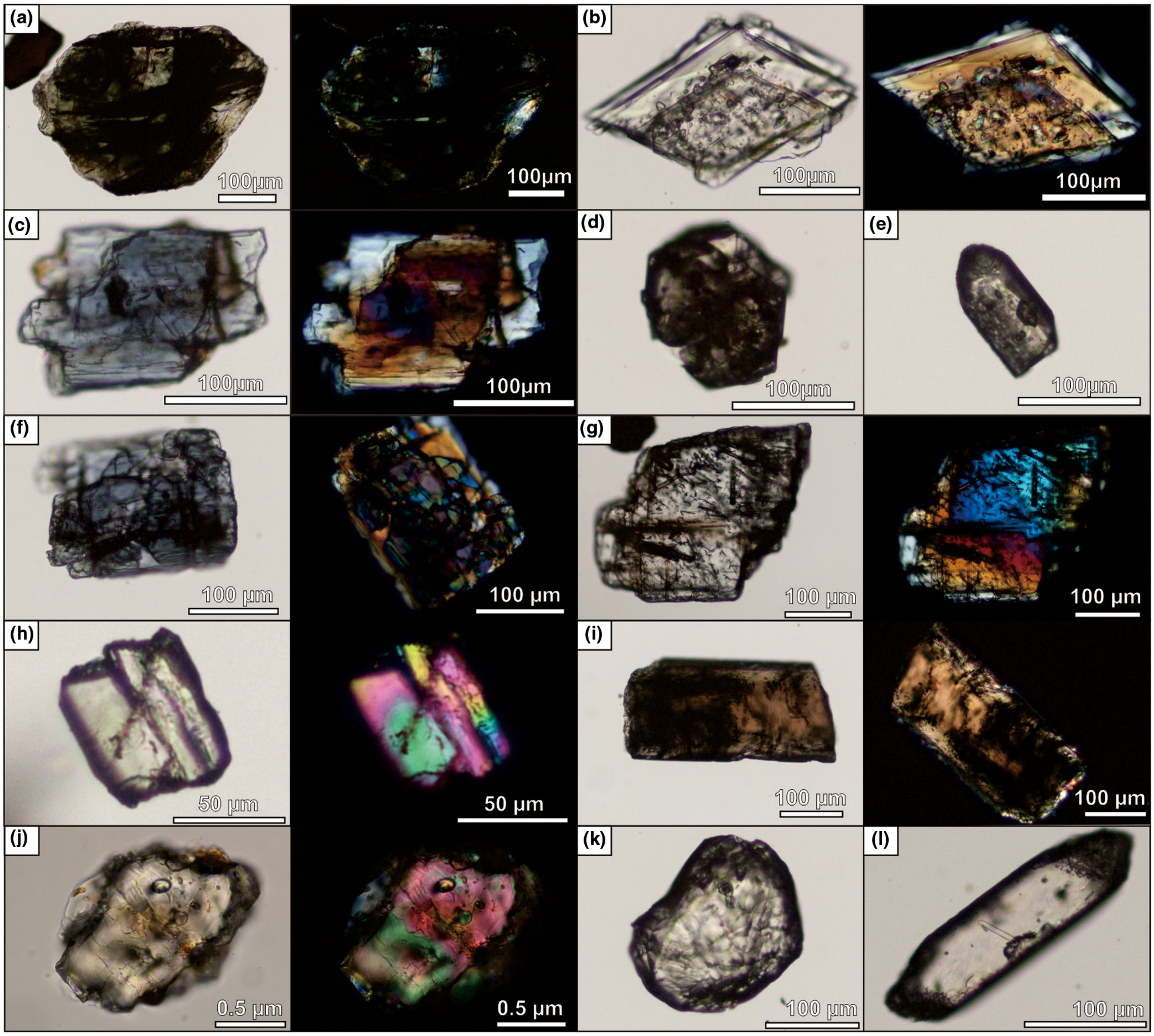

FIGURE 7 Photomicrographs of several representative heavy minerals from the Pandua formation: (a) serpentine with isotropic chrome spinel in the background, (b) platy and colourless lawsonite, (c) blue coloured prismatic glaucophane, (d) euhedral garnet and (e) very high relief subhedral zircon. From the Langkowala formation: (f) glaucophane, (g) stepped and prismatic colourless kyanite, (h) short, prismatic sillimanite, (i) colourless amphibole (tremolite) with weak birefringence, (j) irregular grain of epidote-group (k) rounded garnet with etching surface (l) subhedral elongate zircon. White background is PPL and black is XPL.

The main population of Phanerozoic age ranges from Carboniferous to Jurassic with main peaks at Triassic (210–220 Ma). Proterozoic ages have Mesoproterozoic (1070–1090 Ma) and Paleoproterozoic (1560–1580 Ma) peaks. The youngest zircons from this formation yield ages ($n = 5$) which range from 200 to 175 Ma confirming a maximum depositional age (MDA) of Early Jurassic for the two sandstone samples. This is a new discovery showing that the Meluhu Formation extends from the Late Triassic into the Early Jurassic.

4.4.2 | Pandua Formation

A total of 290 U–Pb zircon ages were collected from two sandstone samples (Figure 4c, samples ES13-184 and ES14-6). Sample locations were chosen with the aim of representing the lower (ES14-6) and upper part (ES13-184) of the Pandua Formation. Two major Phanerozoic zircon age populations are Carboniferous-Jurassic and Late Cenozoic. The Carboniferous to Jurassic population contains a Triassic peak (between 210 and 240 Ma). A Late

Cenozoic population appears only in sample ES13-184 and shows a main peak at around 10 Ma. The MDA from this sample is 6 ± 0.1 Ma.

4.4.3 | Langkowala Formation

A total of 239 U–Pb zircon ages were recorded from two sandstone samples ES13-202 and ES13-55 of the Langkowala Formation (Figure 4c). Samples ES13-202 and ES13-55 represent the lower and upper parts of succession, respectively. The main population of Phanerozoic age ranges from Carboniferous to Jurassic with main peaks of Triassic age (240–260 Ma). A Late Carboniferous peak (ca. 340 Ma) is recorded in sample ES13-55. The youngest age determination of 6.8 ± 0.2 Ma from sample ES13-55 gives the maximum depositional age. The youngest zircon from sample ES13-202 is 52.9 ± 0.8 Ma. Zircon populations from both samples show age populations generally similar to the Pandua and Meluhu Formations (Figure 4c).

5 | DISCUSSION

5.1 | Possible sediment sources

5.1.1 | Bungku Formation

This study shows that sandstones from the Lower Miocene Bungku and Upper Miocene Pandua Formations contain serpentine grains. A previous study (van der Vlerk & Dozy, 1934) indicates that Bungku limestones also contain serpentine as allogenics. The switch from limestones to siliciclastics of the Bungku Formation indicates that clastic input was significant enough to stop limestone production. The presence of serpentinite, olivine, chrome spinel and pyroxene grains suggest uplift and erosion of ESO synchronous with deposition of the Bungku and Pandua Formations.

The ESO source is also supported by the conglomerate clasts with an ophiolite provenance. The carbonate grains suggest uplift and erosion of an older carbonate source such as the Tokala, Matano and Tampakura Formations, which also indicate significant uplift and erosion. Minor schist lithics were possibly derived from the metamorphic rocks exhumed during Early Miocene collision and ophiolite emplacement.

5.1.2 | Pandua Formation

Conglomerate clasts (ultramafic rocks, mafic rocks and red radiolarian chert) and sandstone grains (olivine, chrome spinel, serpentine, pyroxenes and hornblende) from the Pandua Formation suggest that the ESO was still the main sediment source. Metamorphic lithics, polycrystalline quartz, undulose monocrystalline quartz, stretched and schistose metamorphic quartz seen in the Pandua Formation but not in the older Bungku Formation suggest a new metamorphic sediment source had been unroofed/eroded in the Late Miocene. This is supported by the heavy mineral assemblages, particularly glaucophane and lawsonite that represent a HP-LT (blueschist) metamorphic rock source. These minerals were probably derived from the Mekongga and Rumbia metamorphic complexes, in which blueschists are exposed (de Roever, 1950, 1956; Helmers et al., 1989; Mawaleda et al., 2016, 2018; Wijbrans et al., 1994). Garnet could have been derived from a multitude of metamorphic rocks, as well as garnet-bearing peridotites reported in Central Sulawesi close to the Palu-Koro Fault and in the East Arm where they are associated with the ophiolite (Kadarusman & Parkinson, 2000; Parkinson, 1996).

Another source of sediment includes older siliciclastic sedimentary rocks characterised by the presence of ultrastable minerals such as zircon, tourmaline and rutile. The principal zircon populations reveal reworked Permo-Triassic grains that are similar to zircons from the Meluhu Formation sandstones. The carbonate clasts and grains were derived from older carbonates including the Lower Miocene Bungku, Palaeogene Salodik, Cretaceous Matano and/or Triassic-Lower Jurassic Tokala Formations.

5.1.3 | Langkowala Formation

Predominant rounded to sub-rounded quartz clasts in the Langkowala Formation were possibly derived from recycled quartz clasts of the Meluhu Formation, quartz clasts of the Pandua Formation and/or quartz vein from metamorphic rocks. A source in the Meluhu Formation is indicated by the similarity of sandstone clasts from conglomerates of the Langkowala Formation to sandstones of the Meluhu Formation (Figures 6g,h). Detrital zircon U–Pb ages also include a significant population of reworked Permo-Triassic zircons, and a Meluhu Formation source is supported by the heavy mineral assemblage including zircon, tourmaline and rutile.

Petrographic studies show quartz grains are dominated by recrystallized, stretched and schistose metamorphic quartz. These indicate a metamorphic rock source and this is supported by clasts of metamorphic slates and schists. Distinctive blue amphiboles (glaucophane-crossite) represent high pressure-low temperature blueschist metamorphic rocks. Kyanite, sillimanite, staurolite and chlorite indicate a different high temperature–pressure metamorphic source. These metamorphic rocks were probably derived from the Mekongga and Rumbia metamorphic complexes.

The presence of chrome spinel without other ultramafic rock clasts suggests that chrome spinel is a product of reworking of ultramafic materials from older sedimentary formations, from which less stable olivine and pyroxene grains were eliminated, interpreted to be the Pandua Formation. Alternatively, chrome spinel could have been derived from a diminishing local ultramafic source during the early stages of deposition since detrital grains of pyroxene, hornblende and serpentine are observed only in the lowermost part of the Langkowala Formation (sample ES13-202).

5.2 | Sedimentation change in provenance and paleogeographic reconstructions

The integrated provenance techniques reveal at least three significant shifts in the provenance. The first occurred in the Early Miocene, where significant ophiolitic siliciclastic input ended deposition of the lower carbonate unit of the Bungku Formation. The timing of this change strongly suggests a link between the Early Miocene collision and ESO emplacement. The ophiolitic grains (e.g., serpentine, olivine and chert) in the Lower Miocene carbonates (ca. 18 Ma, Nugraha, Hall, & BouDagher-Fadel, 2022, Figure 8a) are the earliest grains reworked from the uplifted ESO providing a new more precise age estimate for its uplift.

Thick Miocene sediments in Buton are difficult to explain by local uplift and erosion alone. Ultramafic rich sediments in Buton appear to have the same source as those in SE Sulawesi. Significant uplift of SE Sulawesi and the wider eastern Sulawesi area—as suggested by our new data—are suggested as a potential new source for some of the thick Buton sediments. We propose that SE Sulawesi on land was the basin margin of the greater Buton and eastern Bone Basins (Figure 1).

The second provenance shift is recorded in the Late Miocene when there was an increase in metamorphic detritus input to the Pandua Formation (Figure 8b). However, the ESO remained the main source until the Late Miocene, supported by the presence of ultramafic rocks, mafic rocks and red chert as conglomerate clasts and chrome spinel as the most abundant heavy mineral in sandstones of the Pandua Formation. An increasing input of LT-HP metamorphic rocks towards the end of Miocene is indicated by the presence of glaucophane and lawsonite. These minerals are interpreted to reflect the exhumation of the glaucophane-bearing blueschists that are now exposed as part of the Pompangeo Schist, Mekongga and Rumbia Metamorphic Complexes. The Upper Miocene Pandua Formation records detrital zircon age spectra with Proterozoic, Triassic and Late Miocene peaks. The Proterozoic and Triassic peaks suggest recycling of the Meluhu Formation, while the Late Miocene peak probably represents magmatism and volcanic activity that are recorded in west Sulawesi (Hennig et al., 2016; White et al., 2017; Zhang et al., 2020) and SE Sulawesi (White et al., 2014).

The third significant provenance change is marked by (1) compositional change from ultramafic-rich Pandua Formation to the quartz-rich Langkowala Formation and (2) depositional environment change from coastal deposits of the Pandua Formation to fluviatile Langkowala Formation (Figure 8c,d). The coastal deposits of the Pandua Formation that are overlain by the fluvial deposits of the Langkowala Formation also suggests a regional uplift of SE Sulawesi, which became largely subaerial, and marks the Mio-Pliocene unconformity (Figure 8c). The exhumation of the basement including metamorphic and Mesozoic rocks is interpreted to be responsible for the Mio-Pliocene unconformity. Uplift of these rocks bounded by the Kolaka and Lawanopo Faults in the central part of the SE Arm blocked the pathway of ultramafic-rich sediment from the north. Paleocurrent data indicate predominantly southeastward flow in the Pandua Formation (Nugraha, Hall, BouDagher-Fadel, Todd, & Switzer, 2022). This blockage explains the significant sedimentation change to the quartz-rich Plio-Pleistocene Langkowala Formation that was deposited unconformably over the ultramafic- and blueschist-rich Upper Miocene Pandua Formation.

In the Early Pliocene, the Meluhu Formation and metamorphic rocks were the main sediment source for the Langkowala Formation (Figure 8e). Chrome spinel in this formation was the product of reworking of ultramafic-rich sediments of the Pandua Formation. The presence of glaucophane and an increase in kyanite in the upper part of the Langkowala Formation are interpreted as the result of a progressive unroofing of low- to high-grade metamorphic rocks of the Mekongga and Rumbia complexes. The timing of this unroofing supports previous suggestions (Helmers et al., 1989) that the Neogene blueschists in SE Sulawesi were exhumed by uplift due to extensional tectonics and were associated with large amounts of sediments deposited during the Neogene.

The shallow marine Eemoiko Formation suggests that Mio-Pliocene uplift was followed by a transgressive event that started in the Early Pliocene and continued at least to the Middle Pliocene (Figure 8f). This event is recorded by the landward-indented shapes of the carbonate outcrops of the Eemoiko Formation (Nugraha, Hall, BouDagher-Fadel, Todd, & Switzer, 2022). Offshore seismic lines also show the Mio-Pliocene unconformity surface (Figure 3)

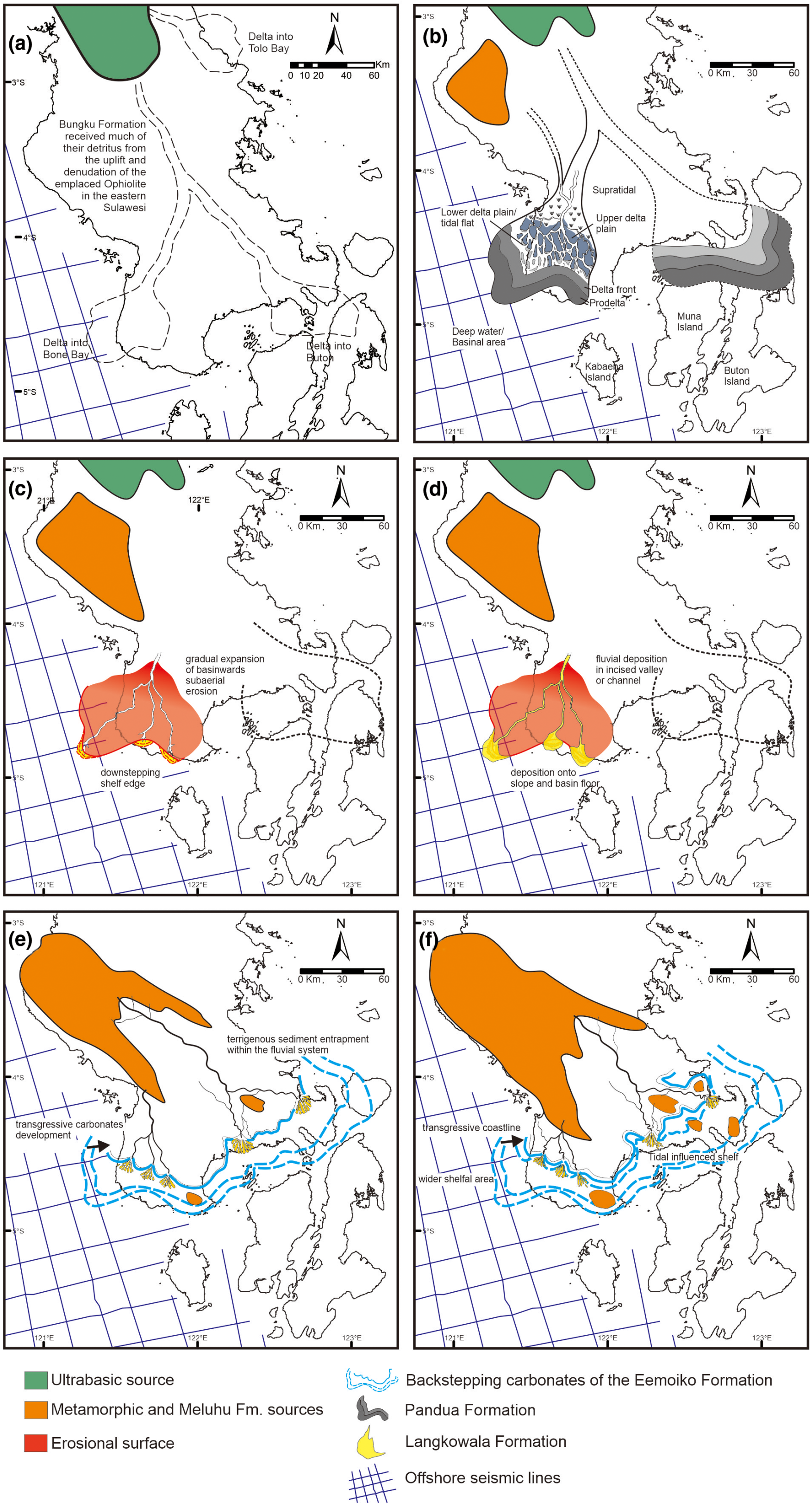

FIGURE 8 Paleogeographic reconstruction of SE Sulawesi Neogene geologic history: (a) early Miocene (b) late Miocene, (c) latest Miocene, (d) very latest Miocene, (e) early Pliocene and (f) middle Pliocene. Note that a significant sedimentation change where the ultramafic source from the north was diminished in the Pliocene due to uplifted local sources.

is overlain by transgressive shallow marine carbonates (Camplin & Hall, 2014) that are the equivalent of the Eemoiko Formation. Further east, well Abuki-1 to the east of the SE Arm penetrates inner to middle neritic transgressive sediments deposited during the Early Pliocene to Middle Pleistocene, based on foraminifera and nannofossil analyses (Amoseas Indonesia Inc., 1990), which are the equivalents of the Langkowala Formation.

Our results show a dynamic sedimentation history for SE Sulawesi. Timing of key events suggest they were associated with important regional geological events including (1) Early Miocene collision of the Australian-origin continental Sula Spur with the North Arm that caused ophiolite emplacement and (2) Mio-Pliocene extension linked to opening of the South Banda Basin from ca. 6.5 to 3.5 Ma (Hinschberger et al., 2005) during Banda rollback, and possibly North Sulawesi subduction rollback at ca. 5 Ma (Djajadihardja et al., 2004; Hall, 2018; Silver et al., 1983; Surmont et al., 1994).

Sulawesi is unusual because molasse-type sedimentation resulting from uplift-following collision was modified by major extension driven by rollback of the North Sulawesi and Banda subduction zones. Both are still active. We do not know of exact parallels to the Kendari basin elsewhere, but the application of multiple provenance techniques provides detailed constraints on the syn-tectonic sedimentation and its linkage to the tectonic evolution of SE Sulawesi, and this approach can be useful in other basins and other tectonic settings. The classic provenance techniques using sandstone framework ternary plots (e.g., Dickinson, 1985; Dickinson et al., 1983; Dickinson & Suczek, 1979), rely on the relative abundance of quartz and feldspars and are sensitive to tropical processes (e.g., Hall & Smyth, 2008; Sevastjanova et al., 2012; Smyth et al., 2008a, 2008b; van Hattum et al., 2006). They can mislead and in Sulawesi would fail to identify some important provenance changes. The use of multiple provenance proxies provides the ability to both detect provenance changes and characterise evolving source areas based on differences in mineralogy, age and stratigraphy, especially where there are distinctive sources such as those in Sulawesi which include ophiolitic, recycled sedimentary rocks, magmatic arc and exhumed metamorphic rocks.

6 | CONCLUSIONS

The application of multiple provenance techniques in this study reveals a series of provenance shifts related to the tectonic history of Sulawesi. The first provenance shift recorded by the ophiolitic-rich Bungku Formation was related to the Early Miocene collision and East Sulawesi Ophiolite emplacement. The second is marked by Late Miocene input of metamorphic detritus including blueschists and is attributed to exhumation of Oligo-Miocene subduction zone material during extension. The third Mio-Pliocene provenance change between the Pandua and Langkowala Formations indicates progressive unroofing of low- to high-grade metamorphic rocks and significant uplift of Sula Spur Mesozoic rocks, interpreted as exhumation caused by continued extension driven by Banda rollback.

ACKNOWLEDGEMENTS

This project was funded by the SE Asia Research Group of Royal Holloway University of London Earth Observatory of Singapore, Nanyang Technological University, which is supported by a consortium of oil companies. We are grateful to TGS for the provision of seismic data under an academic licence agreement and thank Ian Deighton for his help. This research was also supported by the Earth Observatory of Singapore with contribution number 426. Institut Teknologi Bandung and Benyamin Sapiie are thanked for making the fieldwork possible. We thank Darmawan Ramade and local guides for field assistance. Inga Sevastjanova is thanked for assistance with heavy mineral separation. Martin Rittner is thanked for assistance with LA-ICP-MS U–Pb zircon analysis. Adam Switzer is thanked for helpful review comments. Enry Horas Sihombing, Mike Cottam and an anonymous reviewer are thanked for their valuable input that improved text and figures. Atle Rotevatn is thanked for handling manuscript and editorial input.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/bre.12682.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Supporting Information of this article.

ORCID

Abang Mansyursyah Surya Nugraha https://orcid.org/0000-0003-2162-9329

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How to cite this article: Nugraha, A. M., & Hall, R. (2022). Neogene sediment provenance and paleogeography of SE Sulawesi, Indonesia. *Basin Research*, *34*, 1714–1730. https://doi.org/10.1111/bre.12682