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Detrital zircons and heavy minerals from the Palu Formation, Sulawesi, Indonesia: constraints on exhumation of the Palu Metamorphic Complex and drainage evolution

Abang Mansyursyah Surya Nugraha[1,2*], Juliane Hennig-Breitfeld[2,3], Riska Puspita[4], Adam D. Switzer[1,5] and Robert Hall[2]

[1] Earth Observatory of Singapore, Nanyang Technological University, Singapore 639798, Singapore
[2] SE Asia Research Group, Department of Earth Sciences, Royal Holloway University of London, Egham TW20 0EX, UK
[3] Institute of Geology, TU Bergakademie Freiberg, Bernhard-von-Cotta-Straße 2, D-09599 Freiberg, Germany
[4] Program Studi Teknik Geologi, Universitas Tadulako, Palu 94118, Indonesia
[5] Asian School of the Environment, Nanyang Technological University, Singapore 639798, Singapore
AMSN, 0000-0003-2162-9329; JH-B, 0000-0003-3866-4235; RP, 0009-0006-4391-1850; ADS, 0000-0002-4352-7852; RH, 0000-0003-1693-6914
* Correspondence: abang.nugraha@ntu.edu.sg

Abstract: The Palu Formation, previously known as the Celebes Molasse in the Palu area, is understudied and was previously considered to be associated with the Pliocene collision between an Australian-derived microcontinent (Banggai Sula) and the eastern margin of Sundaland (West Sulawesi). Here, we present sedimentological, heavy mineral and zircon geochronological data to provide insights into sediment provenance and to elucidate Neogene tectonic activity in Sulawesi. These analyses suggest that the Pleistocene Palu Formation comprises synorogenic alluvial fan to braided river deposits that record the rapid uplift of metamorphic and granitoid rocks in the Neck and west Central Sulawesi. The Palu Formation is characterized by predominant granitoid and metamorphic clasts and heavy mineral assemblages dominated by pyroxene, amphibole and garnet. Detrital zircons record youngest grain ages of *c.* 2.5 and 3.0 Ma with a significant Pliocene age population and subsidiary Eocene, Cretaceous, Jurassic and Late Triassic age peaks. Rapid uplift and erosion associated with mountain building shaped the topography and influenced the evolution of Palu River networks.

Supplementary material: Complete location, heavy mineral and detrital zircon geochronology datasets are available at https://doi.org/10.6084/m9.figshare.c.7033388

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Sulawesi is situated in a tectonically active convergent setting between the Indo-Australian, Eurasian and Philippine Sea plates. It is the world's 11th-largest island (*c.* 181 000 km^2) and has four distinctive elevated arms (named the North, East, South and SE arms). Tectonically, Sulawesi has been interpreted as the product of multiple collisions in the Cretaceous and Cenozoic (Smith and Silver 1991; Hall 1996; Villeneuve *et al.* 2001; Satyana 2006). The timing of the collisions between Australian-derived microcontinents and the eastern margin of Sundaland has been much discussed in recent years and the Celebes Molasse suggested to be the product of the collisions.

The term 'Celebes Molasse' was first introduced by Swiss naturalists Sarasin and Sarasin (1901), who had a prior knowledge of Swiss Alps Molasse. For several decades, the Celebes Molasse has been considered as synorogenic deposits (van Bemmelen 1949; Kündig 1956) related to continental block collision with the East Arm of Sulawesi (e.g. Davies 1990; Smith and Silver 1991; Villeneuve *et al.* 2001; Hasanusi *et al.* 2004; Satyana 2006; Kurniawan *et al.* 2019). However, because Neogene sedimentary deposits in western Sulawesi have very varied characteristics (for example, they include Pliocene turbiditic submarine fan and slope deposits of the Puna Formation east of the Tokorondo Mountains (Simandjuntak *et al.* 1997; Hennig 2015; Nugraha *et al.* 2023) as well as Plio-Pleistocene alluvial and braided river fan deposits in the Neck and west Central Sulawesi (van Leeuwen and Muhardjo 2005; Nugraha *et al.* 2022*a*)), this very general term tends to confuse rather than help.

In recent literature, the Celebes Molasse has remained a general stratigraphic term for the Neogene sedimentary rocks in the Neck. A recent detailed study of the Celebes Molasse in Central and SE Sulawesi by Nugraha and Hall (2022) and Nugraha *et al.* (2022*b*, 2023) presented new biostratigraphic data that demonstrate that Neogene sedimentary rocks were deposited diachronously and are related to different depositional systems and therefore should not be grouped under the same term. Deposits of the southern Neck have been referred to as the Palu Formation by Nugraha *et al.* (2022*b*) as they are found predominantly north and south of Palu city. Here, we describe sedimentological characteristics of the Palu Formation and present heavy mineral compositions and zircon geochronology to determine its provenance. These can provide insights into the geological evolution of the area and help to reconstruct the drainage pattern of the proto-Palu River.

Geological setting

Present-day Sulawesi and its surrounding area include microcontinental blocks of East Java, Paternoster, West Sulawesi, East Sulawesi, Banggai-Sula and Buton (Hall and Sevastjanova 2012; Metcalfe 2017), which are bounded by a complex system of strike-slip, normal and thrust faults (Sukamto 1975; Hamilton 1979; Silver *et al.* 1983; Hall 2002; Beaudouin *et al.* 2003; Bellier *et al.* 2006; Watkinson 2011). The study area of Palu Bay was formed as a result of transtensional tectonic activity along the major Palu–Koro Fault (Fig. 1; Tjia and Zakaria 1974), which, alongside the subparallel Tambarana Fault to the east of the Neck, passively bounds a region of lithospheric extension driven by northwards subduction rollback in the Celebes Sea (Bellier *et al.* 2006; Watkinson and Hall 2017; Hall 2019).

The Neck and west Central Sulawesi include a wide range of metamorphic, igneous and sedimentary rocks (Fig. 1). There are Cretaceous, Late Eocene and latest Miocene to Pliocene metamorphic rocks (van Leeuwen and Muhardjo 2005; Hennig *et al.* 2016), Paleogene basic to intermediate extrusive and intrusive rocks (Elburg *et al.* 2003; van Leeuwen and Muhardjo 2005) and Neogene granitoid and volcanic rocks (Priadi *et al.* 1994; Polvé *et al.* 1997; Elburg *et al.* 2003; Hennig *et al.* 2016). They are all overlain by the ‘Celebes Molasse of Sarasin and Sarasin’ (Sukamto 1973; Ratman 1976), which includes thick sandstone and conglomerate outcrops along the western flank of the southern Neck and eastern side of Palu valley (Fig. 1). The reported Pliocene to Pleistocene age is based on Pliocene foraminifera, a Pleistocene nannofossil and alunite clasts with a K–Ar age of *c*. 1.7 Ma (Ratman 1976; van Leeuwen and Muhardjo 2005).

Methods

Sedimentology

Fieldwork was carried out mainly on the west side of the southern Neck region in 2013, 2015 and 2023 to study new exposures provided by recent road reconstruction. Grain size, grain and clast compositions, variations in colour, sedimentary structures, bed thickness and the nature of boundary contacts are among the sedimentological observations obtained during fieldwork at 28 locations (Fig. 1, Supplementary data 1). Observations of conglomerates and breccias include clast size and angularity, clast composition, degree of sorting and determination of the proportion of clast types.

Heavy minerals

Sandstone samples were processed following the heavy mineral separation method of Mange and Maurer (1992). 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}). Grains were identified using an optical polarizing microscope (Nikon Eclipse Lv 100) with a ribbon counting method (Galehouse 1971; Supplementary data 2). Additionally, energy-dispersive spectroscopy (EDS, X-MaxN 50-silicon drift) was performed on a Hitachi S3000 SEM on selected grains to verify the optically identified heavy mineral species.

Zircon geochronology

Half of the heavy mineral fractions were treated further using Frantz magnetic separation (15° forward slope angle, 25° side tilt and ampere settings of 1.7 mA), diiodomethane (DIM, at a density of 3.3 g cm^{-3}) separation and zircon picking (using an Olympus SZx12 binocular microscope). Mineral separates were mounted in Araldite resin blocks, polished and imaged using cathodoluminescence (CL). CL imaging was performed on a Hitachi S3000N SEM. 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 system at Birkbeck College, University of London (UCL). The Plešovice zircon standard (337.13 ± 0.37 Ma; Sláma *et al.* 2008) and an 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 (Supplementary data 3). Age histograms were created using DensityPlotter (Vermeesch 2012).

Results

Field observations

We follow the proposed nomenclature of Nugraha *et al.* (2022*a*) and refer to the sedimentary deposits as the Palu Formation. They are exposed along the road crossing the Neck between Palu city and Parigi town and consist of interbedded conglomerates, sandstones and mudstones (Fig. 2). The maximum thickness of individual

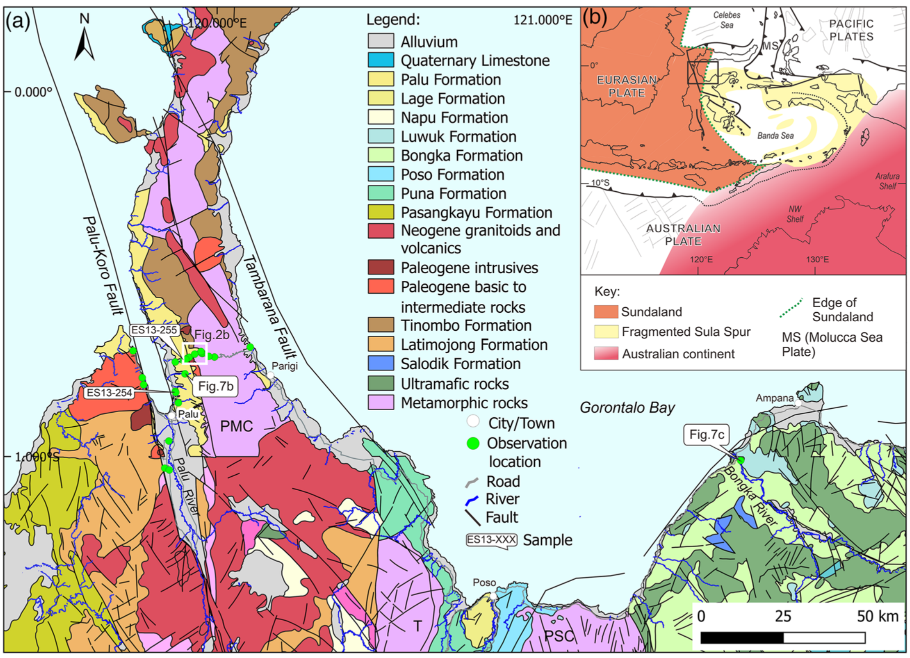

Fig. 1. (**a**) Geological map of the Neck. (**b**) The principal tectonic blocks of eastern Indonesia on a present-day map. PMC, Palu Metamorphic Complex; T, Tokorondo Metamorphic Complex; PSC, Pompangeo Schist Complex. Sources: (a) modified after Sukamto (1973), van Leeuwen and Muhardjo (2005) and Hennig *et al.* (2016); (b) modified after Watkinson (2011) and Hall and Sevastjanova (2012).

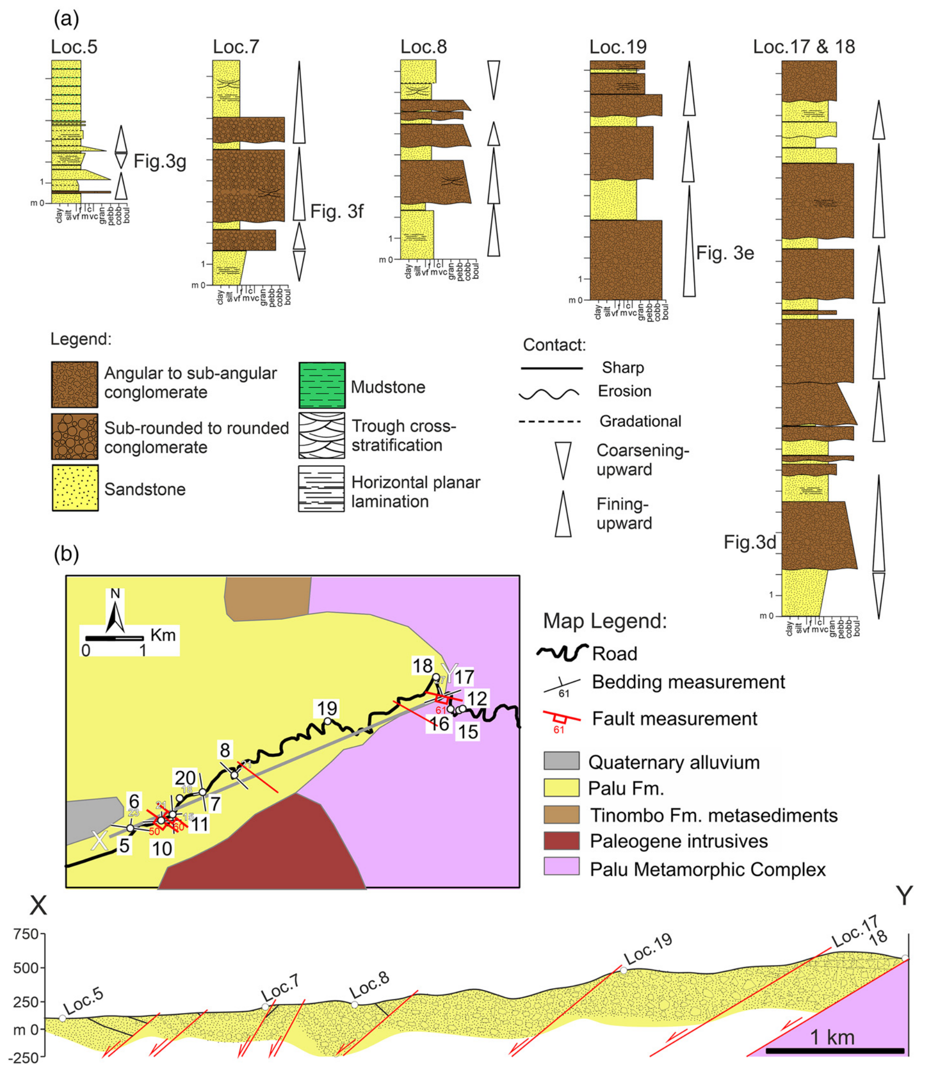

Fig. 2. (**a**) Stratigraphic logs of the Palu Formation showing decreasing grain size in proximal to distal alluvial fan and braided river deposits. (**b**) Schematic geological cross-section along the western flank of the southern Neck. Normal faults are associated with extension-related exhumation of the Palu Metamorphic Complex. Modified after Sukamto (1973) and Pramumijoyo *et al.* (1995).

sections observed in road cuts is about 400 m. An estimated total thickness based on a reconstructed cross-section shows a total thickness of around 900 m. The sedimentary successions are subdivided into proximal, middle and distal parts from east to west (Fig. 3a–c). These sedimentary beds are often cut by westward-dipping normal faults (Fig. 2b).

The proximal part consists of thickly (19–380 cm) bedded and poorly sorted boulder to cobble conglomerates (Figs 2 and 3a). They are exposed at the basin margin in fault contact with the Palu Metamorphic Complex (van Leeuwen and Muhardjo 2005; van Leeuwen *et al.* 2016) and consist of angular to subrounded clasts of schists, gneisses, amphibolites, quartz, granites and granodiorites in coarse- to very coarse-grained sand matrix (Fig. 3d). Conglomerate clasts become finer and more rounded westwards, moving up-section. Lenses of clast-supported conglomerates appear locally. Amalgamated clast- and matrix-supported conglomerates were also observed in this unit. Conglomerate beds show a mix of reverse and normal grading. Coarse- to medium-grained sandstone beds are tens of centimetres thick and are laterally discontinuous. Planar horizontal stratifications and floated cobble to pebble clasts occur in the sandstone beds.

In the middle part, matrix-supported conglomerates are still dominant but show more laterally continuous beds that can be traced for more than 10 m (Fig. 3b). They are poorly sorted and commonly interbedded with sandstone beds to form stratified conglomerate and pebbly sandstone layers. Clast-supported conglomerates occur as lenses within the thickly bedded matrix-supported conglomerates. Alternations of cobble to pebble conglomerates commonly form crudely planar horizontal and cross-stratifications. The conglomerate beds often scour underlying sandstone beds. The abundance of granitoid clasts, the roundness of clasts and the proportion of sandstone beds increase towards the west, again moving up-section. Conversely, the size of clasts, the abundance of metamorphic clasts and conglomerate proportion decrease westwards. Altered rounded garnet peridotite clasts and abundant peridotite, gabbro and amphibolite clasts were observed within the conglomerate beds (Fig. 3e).

The distal part consists mainly of medium to thickly bedded (10–58 cm) sandstones and conglomerates (10 cm thick) with subsidiary thin (less than 10 cm) mudstone beds (Fig. 3c). The proportion of conglomerates decreases significantly and is replaced by bedded sandstone with minor conglomerate and mudstone beds westwards (Fig. 2a). Clast-supported conglomerates are poorly sorted and have subrounded clasts (Fig. 3f). They show laterally continuous beds with erosive bases. The conglomerate beds scour down to underlying sandy beds as channelized bodies. Matrix-supported conglomerates and horizontally floating clasts within the sandstone beds appear rarely. They have limited lateral continuity and commonly appear to be lenses or channelized bodies. The stratified conglomerate and sandstone beds have planar horizontal stratification and sometimes show planar cross stratifications. Sandstone beds are laterally continuous and show planar horizontal to planar cross stratifications (Fig. 3g). The most distal lithologies consist of medium- to thick-bedded sandstone and conglomerate with subsidiary thin mudstone beds towards the most distal parts. The mudstone beds contain plant debris locally.

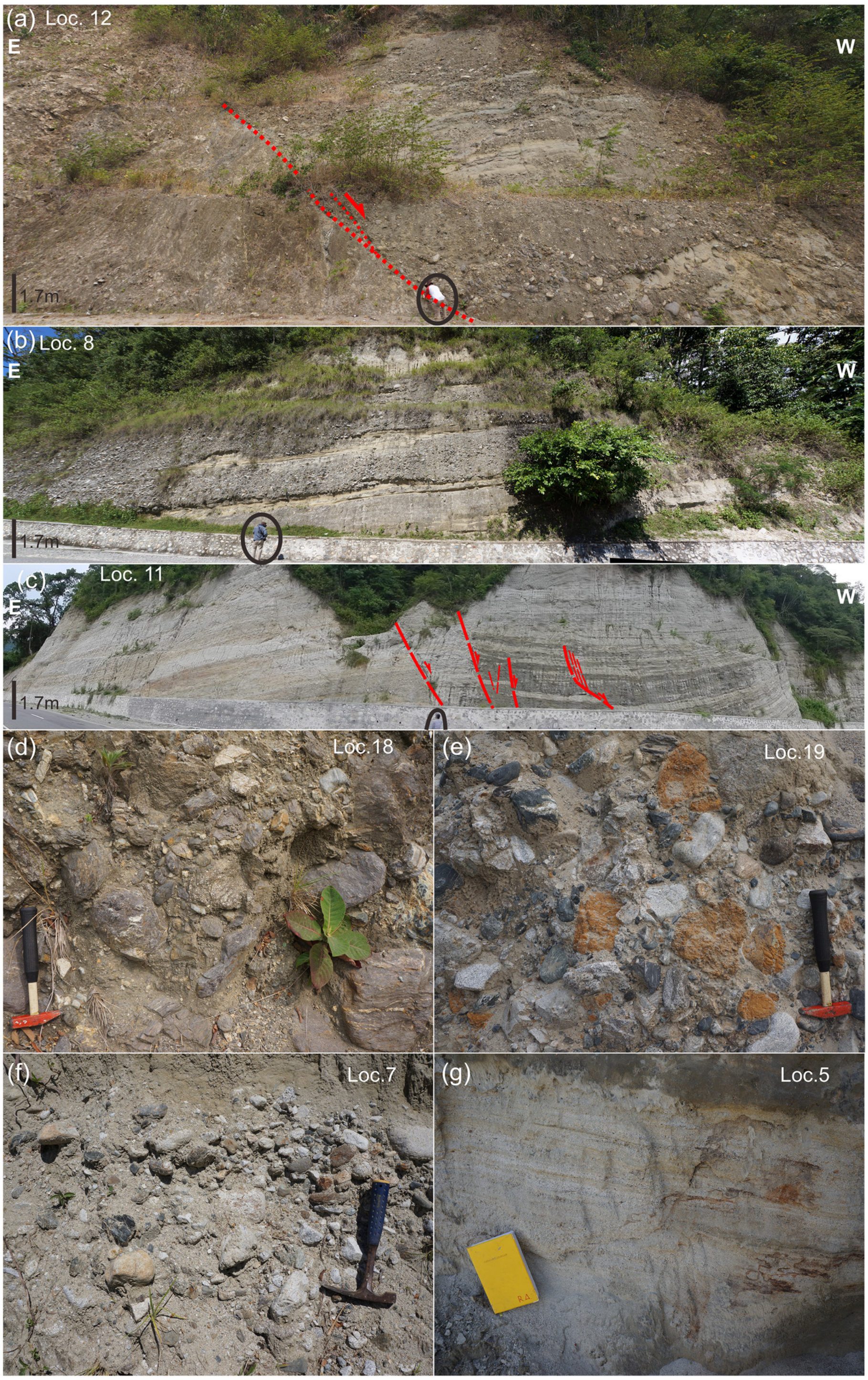

Fig. 3. Representative exposures of the (**a**) proximal, (**b**) medial and (**c**) distal parts of the Palu Formation on the western flank of the southern Neck. There is a decreasing proportion of conglomerate beds from proximal to distal parts. (**d**) Conglomerates with predominant sub-angular metamorphic clasts in the proximal part. (**e**) Garnet peridotite clasts (orange) within the conglomerates in the middle of the Palu Formation succession. (**f**) Poorly sorted granitoid-rich conglomerates. (**g**) Horizontally stratified medium- to coarse-grained sandstones in the distal part. Hammer length is 279 mm and book length is 190 mm.

Heavy mineral analysis

About 600 grains of heavy minerals were counted in samples ES13-254 and ES13-255 from locations 2 and 5 respectively (Figs 1 and 4). They were collected from the middle and upper part of the Palu Formation respectively. The heavy minerals identified on analysis are amphibole (mainly hornblende; 18.2–48.6%), pyroxene (13–26.5%), mica (including chlorite and biotite; 0.7–16%), zircon (2.3–7%), apatite (4.7–5.6%), tourmaline (0.3–3.7%), titanite (1–2%), rutile (0.3–0.7%), epidote (0.3–0.7%), sillimanite (0–1.7%) and staurolite (0–0.3%). Some mineral species (e.g. amphiboles, titanite, garnet and biotite) were confirmed by backscatter imaging and energy-dispersive X-ray spectroscopy (SEM-EDS) analysis. SEM-EDS analysis of selected garnet shows predominant Fe and Mn with low Mg and variable Ca (Fig. 5).

U–Pb detrital zircon dating

A total of 275 U–Pb zircon concordant ages were recorded in samples ES13-254 and ES13-255 (Fig. 6a). The zircons analysed from sample ES13-254 are dominated by euhedral and subhedral crystals with oscillatory zoning to patchy and irregular zoning structures (Fig. 6d). Subsidiary elongate, subrounded, rounded and anhedral zircons are colourless, brown, red and purple. Elongate zircons yield mainly Pliocene age, whereas subrounded to rounded zircons are mostly pre-Neogene. A single Proterozoic zircon was found in sample ES13-254 (1539 ± 11 Ma; Fig. 6a). This sample has main age populations in the late Neogene (*c.* 5 Ma) and Late Triassic (*c.* 222 Ma). A detailed plot shows Neogene age peaks at 3.80 ± 0.02 and 6.90 ± 0.03 Ma (Fig. 6b). A Paleogene to Triassic zircon age histogram shows several minor peaks in the Eocene

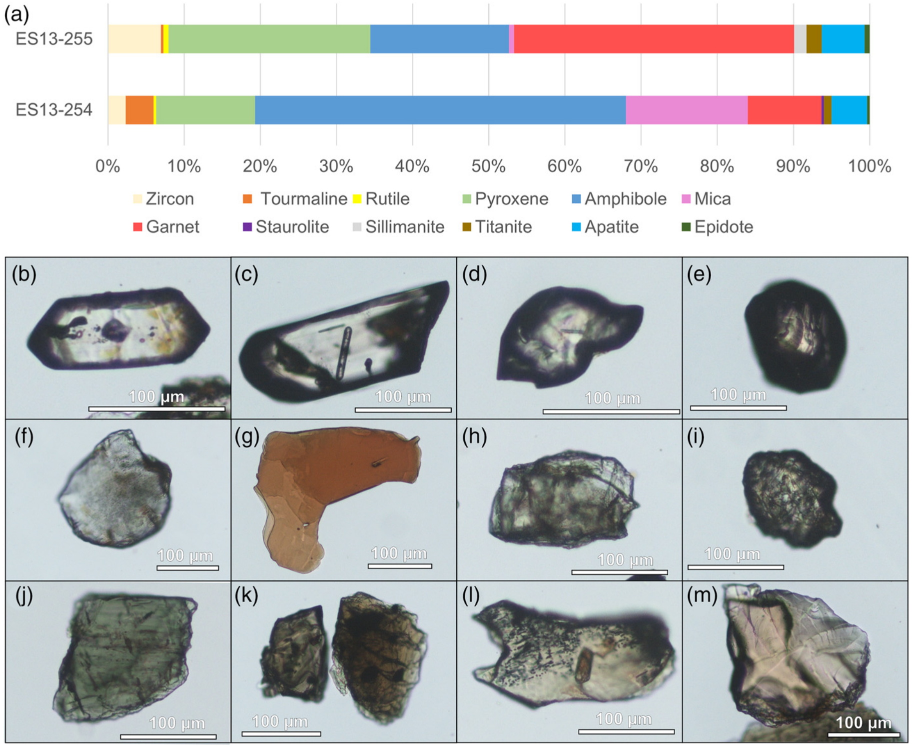

Fig. 4. (**a**) Bar graphs showing heavy mineral species from the Palu Formation. (**b**–**m**) Photomicrographs of representative heavy minerals: (**b**) euhedral zircon; (**c**) subhedral zircon; (**d**) anhedral zircon; (**e**) rounded zircon; (**f**) apatite; (**g**) biotite; (**h**) pyroxene; (**i**) titanite; (**j**) hornblende; (**k**) tourmaline (left) and hornblende (right); (**l**) staurolite; (**m**) garnet.

(*c.* 36 Ma), Late Cretaceous (*c.* 92 Ma), Early Cretaceous (*c.* 120 Ma), Late Jurassic (*c.* 155 Ma) and Early Jurassic (*c.* 181 Ma).

In sample ES13-255, the zircons are mainly subhedral to euhedral with oscillatory zoning to irregular internal structures (Fig. 6d). Subrounded and rounded anhedral grains are generally pre-Neogene zircons that are colourless, brown, purple and reddish. This sample has main age populations in the Pliocene (*c.* 3.2 Ma), Eocene (*c.* 42.4 Ma) and Late Cretaceous (*c.* 102.3 Ma), and wider populations from Early Cretaceous to Middle Jurassic (*c.* 120–170 Ma) and between Early Jurassic and Middle Triassic (*c.* 180 and 240 Ma). A detailed plot shows a Neogene peak at 3.9 ± 0.04 Ma (Fig. 6c). Several notable subpeaks within the wider Mesozoic populations include Early Cretaceous (*c.* 122.1 Ma), Middle Jurassic (*c.* 164.3 Ma) and Early Jurassic (*c.* 183.6 Ma) The youngest zircon grains are 2.5 ± 0.1 Ma and 3.0 ± 0.1 Ma from samples ES13-254 and 255 respectively, confirming a previously reported depositional age of 1.7 Ma (van Leeuwen and Muhardjo 2005).

Discussion

Depositional environments

Conglomerates and sandstones with poor to medium sorting, poorly developed bedding, reverse grading and outsize boulder clasts indicate debris-flow deposits. Increased dispersive pressures in the gravel traction carpet can cause inverse grading (Lowe 1982). Outsized clasts are interpreted to be transported along the rheological interface between the basal inertia flow (traction carpet) and the lower-density faster-moving turbulent overflow (Postma *et al.* 1988). Lenses or lenticular geometry of clast-supported conglomerates represent lag deposition through the winnowing of the debris-flow deposits by channel discharge or possibly from additions to the channel bed by gravel transported from the drainage basin (Blair and McPherson 1994). Angular and large-size metamorphic clasts suggest proximity to the source at the basin margin.

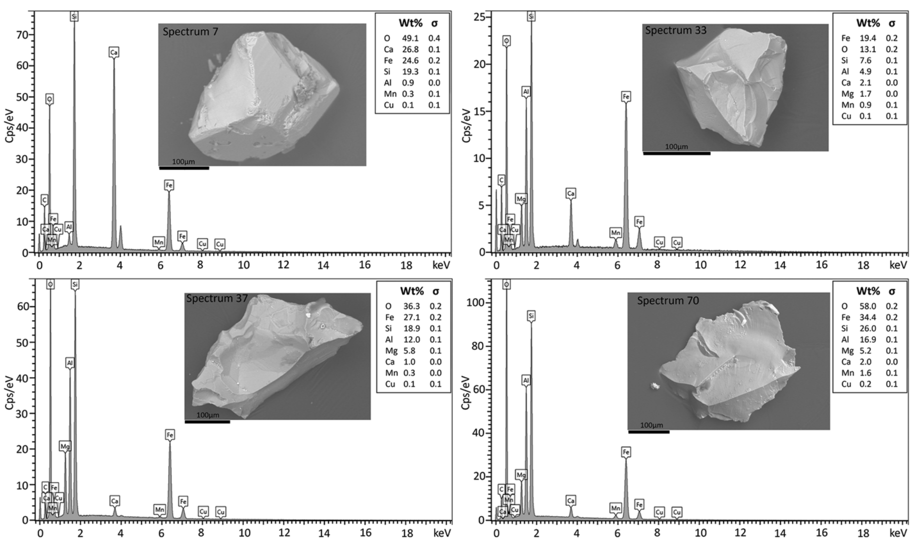

Fig. 5. SEM images of selected garnets (samples 7, 33, 37 and 70). The relatively high Fe and low Mg suggest that garnets come from regionally metamorphosed sediments or basic rocks, not from peridotites such as those shown in Figures 3e and 7.

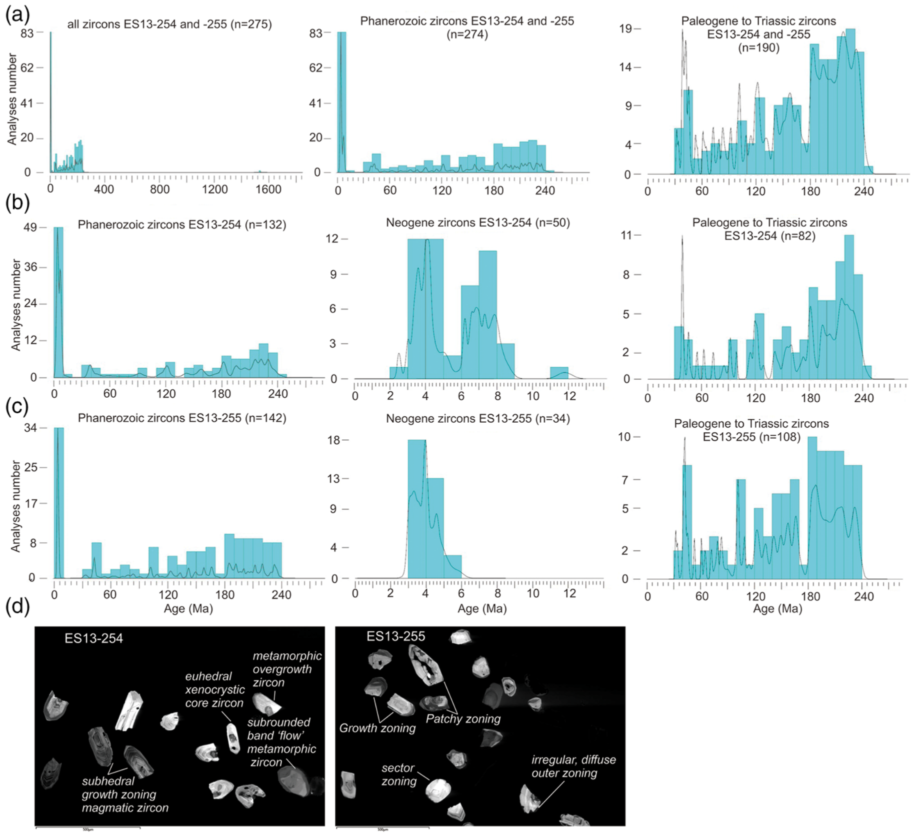

Fig. 6. (**a**) U–Pb zircon age histograms and probability density plots of two samples analysed in this study using DensityPlotter. (**b**) U–Pb zircon age histograms and probability density plots of sample ES13-254 that shows Neogene age peaks at 3.8 ± 0.02 and 6.9 ± 0.03 Ma and subsidiary Paleogene to Triassic peaks in the Late Triassic (*c.* 222 Ma), Early Jurassic (*c.* 180 Ma), Late Jurassic (*c.* 149 Ma), Early Cretaceous (*c.* 124 Ma) and Eocene (*c.* 36 Ma). (**c**) U–Pb zircon age histograms and probability density plots of sample ES13-255 that show a significant Neogene peak at 3.9 ± 0.04 Ma and subsidiary peaks between Triassic and Jurassic (*c.* 240 and 180 Ma) and between Jurassic and Cretaceous (*c.* 156 and 120 Ma). (**d**) Representative CL photomicrograph of samples ES13-254 and ES13-255. Sources: (a) modified after Sukamto (1973), van Leeuwen and Muhardjo (2005) and Hennig *et al.* (2016); (b) modified after Watkinson (2011) and Hall and Sevastjanova (2012).

Interstratified conglomerate and sandstone beds indicate deposition by a high-density turbidity current comprising a gravel traction carpet with an overflowing sandy turbulent suspension (Lowe 1982; Postma *et al.* 1988). These couplets of conglomerate in planar beds interstratified with pebbly sandstone beds of thicker or similar thickness are interpreted as sheetflood deposits (Blair and McPherson 1994, 2009). The surface may have been incised during the falling flood stage, forming channels where clast-supported conglomerates were concentrated. The sandstone beds indicate waning stage deposition of flow events (Nichols and Thompson 2005). Alternatively, scoured channel-like lenses of clast-supported conglomerate beds may have formed in braided river channels (Boothroyd and Nummedal 1977; Nemec and Postma 1993) where planar horizontal and cross-bed stratifications are typical of gravel bar deposits (Allen 1983). The downstream change from gravel- to sand-dominated deposition indicates a loss of stream power downflow as the gradient decreases. Sandstone and other fine-grained sediments can be deposited because of lateral amalgamation of channel, overbank and alluvial plain deposition. The river channel is represented by lenticular to sheet-like bodies with scoured bases and is commonly filled by structureless or cross-bedded pebble conglomerates and coarse-grained sandstones. The thin mudstone beds represent a progressive decrease in flow velocity over successive flood events. They were possibly deposited in a low-energy area such as a channel-fill plug, overbank or flood plain.

The transition from proximal to distal parts indicates alluvial fan and braided river settings. The succession exposed next to the uplifted bedrock indicates a proximal alluvial fan deposit. The medial part contains a transition zone from the proximal to the distal part of the alluvial fan. It includes mud-poor debris flows and sheet-flood deposits that were gradually succeeded by fluviatile deposition in the distal part. Increasing granitoid clasts indicate expanding exhumation of a granite source. Garnet peridotites that appear locally in the middle part might have been derived originally from west Central Sulawesi, where they have been reported in the Palu-Koro fault valley (Helmers *et al.* 1990; Kadarusman and Parkinson 2000), or from the East Arm, where they are now common as boulders in the Bongka River. We discuss this issue in the following discussion.

Sediment provenance

Predominant granitoid and metamorphic clasts within the Palu Formation indicate a significant contribution from igneous and metamorphic sources. A major proportion of pyroxene, amphibole, garnet and mica also indicate a significant contribution from igneous rocks and metasedimentary or meta-igneous sources. Pyroxene can be associated with mica (especially biotite) and amphibole minerals (largely hornblende) in igneous rocks. The presence of pyroxene with amphibole and the absence of olivine and chrome spinel suggests possible mafic to intermediate igneous sources. Basaltic to rhyolitic rocks are found in the weakly metamorphosed greenschist-facies metasediments of the Tinombo Formation in the Neck region (Ahlburg 1913; Brouwer 1934; Elburg *et al.* 2003; van Leeuwen and Muhardjo 2005). The volcanic rocks in the Neck and west of Palu also include basaltic to andesitic lavas, and volcaniclastic deposits, of tholeiitic and calc-alkaline composition (Priadi *et al.* 1994; Polvé *et al.* 1997; Elburg *et al.* 2003; van Leeuwen and Muhardjo 2005). Hornblende, the predominant amphibole in this study, can occur in felsic igneous rocks and amphibolites. Biotite and white mica are found in a wide range of igneous and metamorphic rocks. The metamorphic rocks in the Neck consist of mainly amphibolite and pyroxene gneisses (Hennig *et al.* 2016). Moreover, SEM-EDS analysis of selected garnets shows predominant Fe and Mn with low Mg and variable Ca that suggest amphibolite-facies metasediments, metabasic rocks and/or an intermediate–acidic igneous rock source (Fig. 5; Mange and Morton 2007; Suggate and Hall 2014).

Magmatic and metamorphic sources are also reflected in the subordinate heavy mineral assemblages of zircon, tourmaline, rutile and apatite, as well as minor occurrences of titanite, sillimanite, staurolite and epidote. Cathodoluminescence images of the detrital zircons show typical features of igneous zircons with oscillatory zoning and a xenocrystic core, and metamorphic zircons with distorted internal texture, and irregular and thickened bands. Zircon U–Pb age dating reveals dominant Neogene age populations in both samples with peaks at *c.* 3.9 and *c.* 6.9 Ma. The notable peak at *c.* 3.9 Ma resembles reported U–Pb zircon mean ages between *c.* 4 and 3 Ma for Neogene felsic granitoid intrusions (S-type) in the southern Neck and to the east of the Palu-Koro Fault (Hennig *et al.* 2016). The secondary peak at *c.* 6.9 Ma resembles calculated mean ages of *c.* 7.5–5 Ma for Neogene intermediate granitoid and diorite intrusions (I-type and silica-rich I-type) in the western side of the Neck and along the west side of the Palu-Koro Fault (Hennig *et al.* 2016). Another possible source is the metamorphic rocks in the eastern side of the Neck, which yield *c.* 3.6 Ma ages from the gneisses of the Palu Metamorphic Complex (Hennig *et al.* 2016).

The minor detrital zircon peak at *c.* 42.1 Ma is possibly derived from the Paleogene granitic stocks and sills to the west of Palu Valley and NE of Palu with a Late Eocene to Early Oligocene age (Polvé *et al.* 1997; van Leeuwen and Muhardjo 2005; Hennig *et al.* 2016). Alternatively, the Eocene zircons could be inherited from granitoids and metamorphic rocks that are now widely exposed in the Neck. Basement granitoid and metamorphic rocks along the Neck yield similar inherited age peaks of Eocene (*c.* 30–40 Ma), Late Cretaceous (*c.* 80–90 Ma), Middle Jurassic (*c.* 160–170 Ma) and Late Triassic (*c.* 210–220 Ma). Acidic to basic rocks and metamorphic rocks are now widely exposed in the Neck and west Central Sulawesi and are interpreted as the main sources for the materials of the Palu Formation.

Unusual orange garnet peridotite clasts are present in beds a few metres thick in the middle of the Palu Formation succession and could have been derived from garnet peridotites that are now exposed as slivers in the Palu-Koro fault zone in the south Palu Valley (Helmers *et al.* 1990; Kadarusman and Parkinson 2000) where they are associated with pyroxenite, dunite, spinel peridotite, quartz–mica schist, garnet granulite, pyrope–kyanite eclogite and amphibolite. However, these peridotites tend to be finer grained than the distinctive boulders in the Palu Formation. Alternatively, the Palu Formation garnet peridotites closely resemble distinctive coarse garnet peridotites that are now found in the Bongka River in the East Arm as well-rounded pebbles and cobbles (Fig. 7a and b), and in fault-bounded outcrops associated with mica schists, quartzo-feldspathic gneisses, hornblende gabbros and spinel peridotites of the East Arm ophiolite (Kadarusman and Parkinson 2000). The Palu Formation garnet peridotite boulders in the Neck are also associated with hornblende gabbros and peridotites like those of the Bongka River. Similar garnet peridotite boulders are also found in the nearby Bale River further south in the Neck (Fig. 7c). The distinctive orange colour of the garnet peridotite clasts in the Palu Formation is probably the result of alteration or laterization. We suggest that they were eroded from the East Arm and transported into western Sulawesi before being altered during a prolonged period of tropical weathering. Coarse ophiolite conglomerates are now found on the west side of the Poso Depression, at the foot of the Tokorondo Mountains, along the road crossing from Poso to Palu, showing that ophiolites were eroded and transported from the East Arm to western Sulawesi earlier in the Neogene. Garnet compositions listed by Kadarusman and Parkinson (2000) from the Bongka River and the Palu Valley are very pyrope rich, typical of peridotites. EDS analyses of the detrital garnets in this study have no significant Mg, which indicates that they are not from peridotites.

Implication for tectonic history and palaeo-drainage

Collision of Australian-derived microcontinents (e.g. Sula-Spur, Banggai-Sula and Tokala blocks) with eastern Sundaland probably began in Sulawesi, but despite decades of studies, the timing and number of collisions remains a subject of debate (Audley-Charles 1974; Hamilton 1979; Davies 1990; Davidson 1991; Smith and Silver 1991; Hall 1996, 2002; Parkinson 1998; Hall and Wilson 2000; Villeneuve *et al.* 2001; Hasanusi *et al.* 2004; Satyana 2006; Cottam *et al.* 2011; Kurniawan *et al.* 2019). The Celebes Molasse, a general term for Neogene sedimentary strata that are widely distributed throughout Sulawesi (Sarasin and Sarasin 1901), has for many years been thought to be the result of orogeny (e.g. Kündig 1956). Consequently, all syn- to post-orogenic sediments were considered to be of similar age and character across Sulawesi (e.g. Wanner 1910; van Bemmelen 1949; Milsom *et al.* 1999).

However, contrary to popular belief, the composition, sedimentary character, depositional environment and age of the Celebes Molasse are not the same across Sulawesi. Our study shows that the Celebes Molasse in the Palu area consists of quartz-rich sandstones

Fig. 7. Photographs of (**a**) altered garnet peridotite clast in the Palu Formation and present-day pebbles of garnet peridotite from the (**b**) Bongka and (**c**) Bale Rivers (detailed locations are shown in Fig. 1).

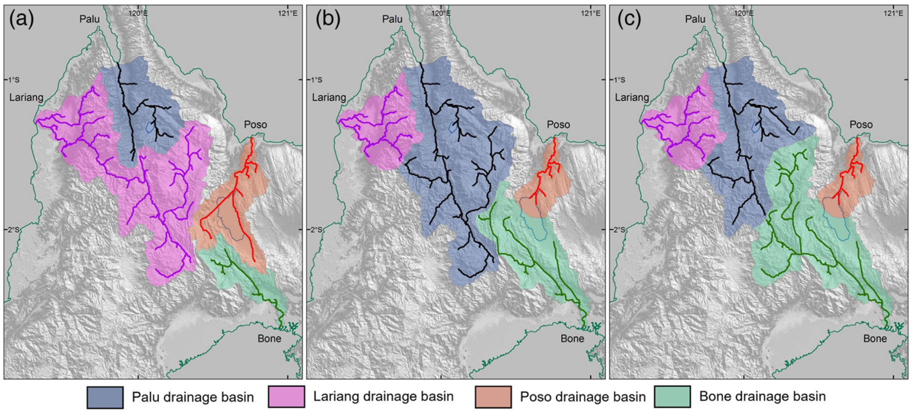

Fig. 8. (**a**) Present-day major drainage basins in the Neck and west Central Sulawesi based on drainage analysis using hydrology tools in ArcGIS. (**b**) and (**c**) show basins inferred for progressively earlier stages in drainage development based on interpreted reversals and headwater captures. The ages of the basins in (**b**) and (**c**) are unknown but interpreted to be Pleistocene. The changing drainage patterns are likely to be reflected in sediment provenance.

and conglomerates with predominant metamorphic and granitoid clasts that were deposited in alluvial to braided river environments. They are different from the sandstone and conglomerate compositions of the so-called 'Celebes Molasse' in eastern Sulawesi (e.g. Bungku and Bongka formations). The Bungku Formation contains ultrabasic-rich conglomerates and serpentinite-rich sandstones that were deposited in delta to marine environments during the Early to Middle Miocene (Nugraha *et al.* 2022*a*, *b*). The Bongka Formation includes ophiolite-rich siliciclastic rocks that were deposited in terrestrial to marine environments during the Pliocene (Kündig 1956; Nugraha *et al.* 2022*a*). Based on their heavy minerals, the Bongka and Bungku formations are characterized by predominant serpentine and chrome spinel, whereas the Palu Formation is dominated by amphibole, pyroxene and garnet with a minor contribution from ultramafic sources at certain times.

The Palu Formation, previously mapped as the 'Celebes Molasse of Sarasin and Sarasin' (Sukamto 1973), was deposited in the Pleistocene based on the youngest detrital zircon ages and the Pleistocene age proposed from nannofossils and K–Ar dating by van Leeuwen and Muhardjo (2005). It is younger than the comparable so-called Celebes Molasse sedimentary unit of the Lower Miocene Bungku Formation in eastern Sulawesi (Surono and Sukarna 1995; Nugraha *et al.* 2022*b*). This supports the suggestion of diachronous ages of Celebes Molasse deposition across Sulawesi (Hall and Wilson 2000). Furthermore, heavy mineral assemblages and detrital zircon ages suggest that the so-called Celebes Molasse in the Palu Valley was derived mainly from the Palu Metamorphic Complex and Neogene granitoid rocks that were exhumed in the Late Pliocene during upper lithospheric stretching (Hennig *et al.* 2016, 2017; Hall 2019). This contradicts previous interpretations of the Celebes Molasse as syn- to post-orogenic products of the Banggai-Sula collision, including thrusting at *c.* 5 Ma (Smith and Silver 1991; Bergman *et al.* 1996; Hall 1996; Satyana 2006).

The Palu Formation also preserves some evidence of an earlier drainage history that was previously unknown. There must have been an earlier Neogene first-cycle period of erosion and transport of ophiolitic rocks from the East Arm and their deposition in western Sulawesi, west of the present-day Poso Depression. Remnants of these sediments are preserved at the foot of the Tokorondo Mountains (Fig. 7). Some of these were altered during a prolonged period of tropical weathering, and then there was a brief interval in which they were eroded and second-cycle sediments of ophiolitic and garnet peridotite clasts were deposited in the Palu Formation. The first-cycle sedimentation probably occurred between 10 and 6 Ma where the ophiolites were widely exposed in eastern Sulawesi and were the main source for reworked ophiolitic materials carried westward into the area of the present Neck and Tokorondo Mountains. The rapid uplift of the Neck and core complexes, specifically the Tokorondo Mountains (Spencer 2010; Hennig *et al.* 2016, 2017), around 2 myr ago resulted in the erosion of clasts of previously deposited granites, metamorphic rocks and minor ophiolitic conglomerates in west Sulawesi. These eroded materials were then deposited into what is now known as the Palu Formation.

The Pleistocene Palu Formation records the young and rapid exhumation of the metamorphic complex. It unconformably overlies the metamorphic rocks of the Palu Metamorphic Complex and the granites of only slightly greater age. The sediments containing zircons with an age range of 2.5–3 Ma were derived from the granites that intruded the Palu Metamorphic Complex around 3 myr ago (Hennig *et al.* 2017). These granites were then rapidly exhumed at *c.* 2 Ma, indicating an exceptionally fast exhumation process. This rapid uplift and erosion associated with mountain building shaped the topography and influenced the patterns of river networks.

Mountains act as divides, directing the flow of water within drainage basins. The present-day drainage pattern in central Sulawesi (Fig. 8a) is very complex and includes several features that suggest drainage reversals, river captures and significant changes in shapes and sizes of basins. For example, the present-day Lariang River appears to have captured the headwaters of the Palu River about halfway down the Palu Valley (Fig. 8b). At an earlier stage (Fig. 8c) the Palu River basin appears to have acquired the headwaters of the Bone River drainage basin. These changes are likely to be reflected in the provenance of sediments. For example, peridotite clasts could have been derived from the foot of the Tokorondo Mountains at the west side of the Poso Depression and transported south in the Bone River (Fig. 8c) before capture and transport north in the Palu River at a later stage (Fig. 8b). The age of these changes is uncertain but likely to be Pleistocene.

Conclusions

The term 'Celebes Molasse' for sediments in the Neck is too general and fails to offer substantial insights into the depositional and tectonic history of Sulawesi. The term 'Palu Formation' is proposed instead. This formation was deposited in an alluvial fan to braided river setting and heavy minerals consist mainly of pyroxene, amphibole and garnet. The main sources of granitoid and metamorphic clasts, as well as heavy mineral assemblages, were the granitoids and metamorphic rocks that are now extensively exposed in the Neck and west Central Sulawesi regions. Additionally, there are secondary sources of metasediments and basic to intermediate igneous rocks present in this region. The youngest zircon age (*c.* 2.5 and 3.0 Ma) of this study gives the maximum depositional age for the Palu Formation. Sedimentological, heavy mineral and zircon geochronological analyses suggest that the Pleistocene Palu Formation is a synorogenic deposit that records the rapid uplift of the metamorphic and granitoid rocks during upper lithospheric stretching in the Neck and west Central Sulawesi. This rapid uplift and erosion associated with mountain building shaped the topography and influenced the evolution of Palu River networks.

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