Ductile flow in the metamorphic rocks of central Sulawesi

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Abstract: Metamorphic rocks exposed along the Palu-Koro Fault of west-central Sulawesi, Indonesia, show abundant evidence of non-coaxial ductile deformation. The deformed rocks include gneisses, amphibolites and schists, that form part of a regionally metamorphosed basement complex of Mesozoic–Precambrian Australian (Gondwanan) origin. In the Palu and Neck regions of Sulawesi, ductile shear fabrics record low-angle westward extension. Further south in the Palu valley, extension is directed towards the south and SW, along with gently-dipping ductile thrust fabrics. Vergence exceptions are common at both outcrop and kilometre scale. Cross-cutting granitic dykes place some constraint on the timing of ductile foliation formation. In the neck region of Sulawesi, it occurred before *c.* 44–33.7 Ma. In the central and northern Palu valley, to the south, it occurred before 5–3.5 Ma. The timing and orientation of non-coaxial strain precludes its origin as a result of Palu-Koro Fault activity. Instead, ductile flow occurred during either Eocene–Miocene mid-crustal extension above a metamorphic core complex, Cretaceous subduction-related deformation in the over-riding plate, or intracontinental deformation within Gondwana.

Ductile flow and associated shear zones are common in metamorphic basement rocks around the world. Examples exposing small-scale, poly-generational shear zones have been recorded from the Variscan of Spain (e.g. Carreras 2001); a regional shear zone which controls fluid flux in the Bohemian Massif (Vrána & Bártek 2005); shearing controlling melt extraction in the Canadian Cordillera (Nyman *et al.* 1995); both discrete and diffuse shear zones (Goscombe *et al.* 2006), and mid-crustal channel flow (Langille *et al.* 2010), in the Himalayas. Lower- to mid-crustal rocks in which these processes occur can be uplifted by orogenic folding, thrusting, oversteps/bends along major strike-slip faults, or by metamorphic core complex exhumation. Of these mechanisms, major strike-slip faults in particular can provide important information on deep crustal non-coaxial strain, because they can facilitate rapid vertical movement of their roots, which often include ductile shear zones penetrating most, or all of the lithosphere (e.g. Hanmer *et al.* 1992; Leloup *et al.* 1995; Vauchez & Tommasi 2003; Watkinson *et al.* 2008).

The Palu-Koro fault of central Sulawesi is an active, north–south-trending high strain rate sinistral strike-slip fault, which cuts through a suite of rapidly exhumed metamorphic rocks of low to high grade (e.g. Egeler 1947; Katili 1970; Sukamto 1973; Helmers *et al.* 1990; Sukido *et al.* 1993; Walpersdorf *et al.* 1998; Bellier *et al.* 2001, 2006). It is an ideal place to examine the timing and kinematics of ductile deformation in the metamorphic basement of this under-studied area, to help understand the complex history of Sulawesi and east Indonesia.

Geological setting

Sulawesi lies at the convergence of the Eurasian, Indo-Australian and Philippine tectonic plates. Its tectonic evolution has been influenced not just by broad external forces exerted by their convergence, but by a complex history of subduction, extension, ophiolite obduction and collision of continental fragments (e.g. Katili 1978; Hamilton 1979; Silver *et al.* 1983*a*, *b*; Hall 1996, 2002; Parkinson 1998; Calvert & Hall 2003; van Leeuwen & Muhardjo 2005). The island is composed of four elongate 'arms', which broadly correspond to lithotectonic units (e.g. Sukamto 1975; Hamilton 1979; Fig. 1). The north arm consists of a Neogene island arc underlain by oceanic crust, with small fragments of continental crust (Taylor & van Leeuwen 1980; Elburg *et al.* 2003; van Leeuwen *et al.* 2007). The north arm is linked to the rest of the island by the 'neck', a narrow, mountainous ridge largely underlain by metamorphic basement (e.g. Sukamto 1973). The east arm is dominated by a highly tectonized ophiolite, inter-thrust with Mesozoic and Cenozoic sediments (e.g. Hamilton 1979; Simandjuntak 1986; Parkinson 1991), which also crops out on the SE arm.

West Sulawesi, commonly referred to as a magmatic arc of Miocene–Pliocene age, is dominated by very young granitoid intrusions (*c.* 14–3 Ma) (Elburg *et al.* 2003) which have been intruded into a suite of Cenozoic volcaniclastic and Precambrian–Mesozoic metamorphic rocks (Fig. 2). The metamorphic basement originated in Gondwana (Bergman *et al.* 1996; Smyth *et al.* 2007; van Leeuwen *et al.* 2007). These continental fragments
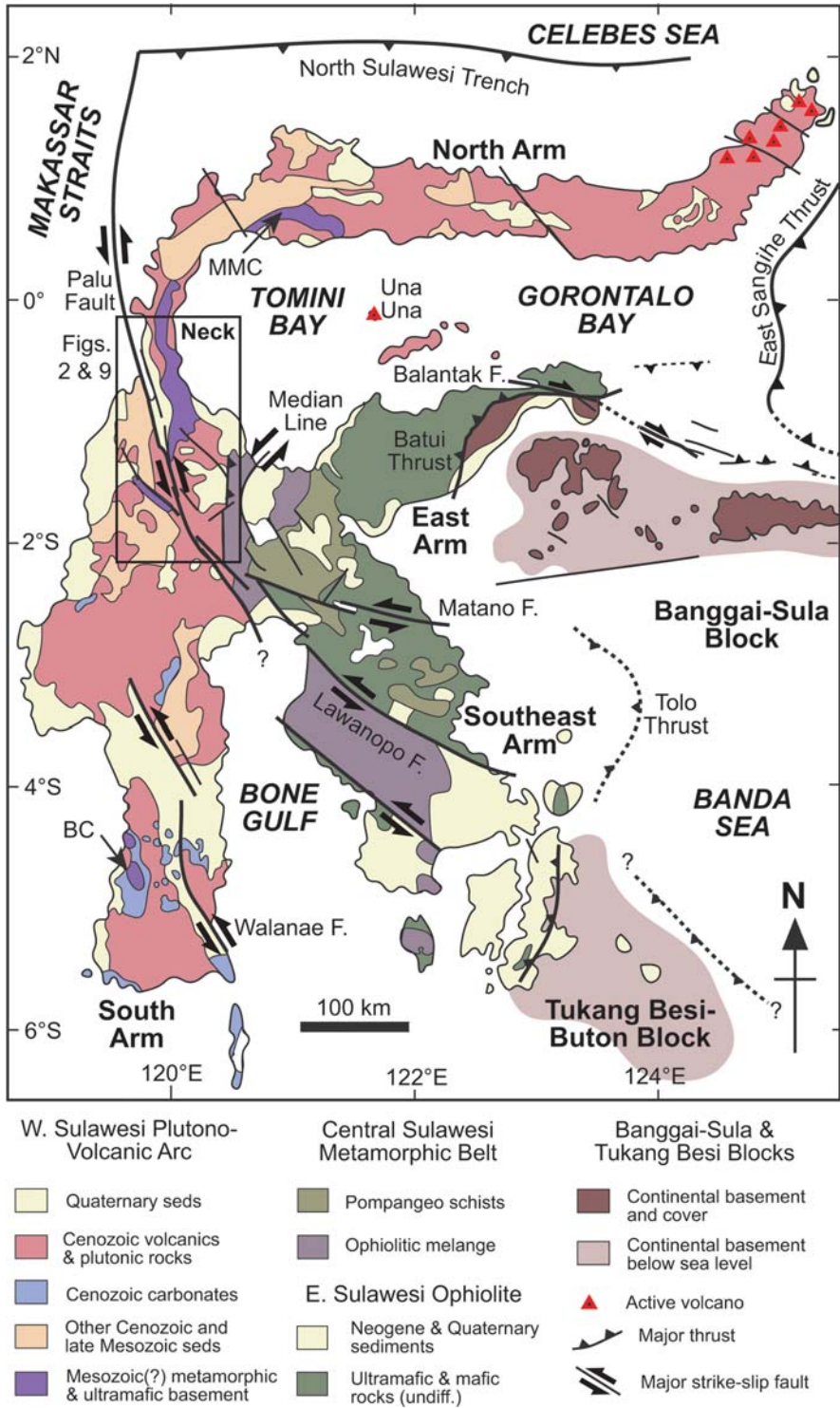
Fig. 1. Summary of the geology of Sulawesi, showing principal structures and geographical features. Modified after Hall & Wilson (2000). MMC, Malino Metamorphic Complex; BC, Bantimala Complex.
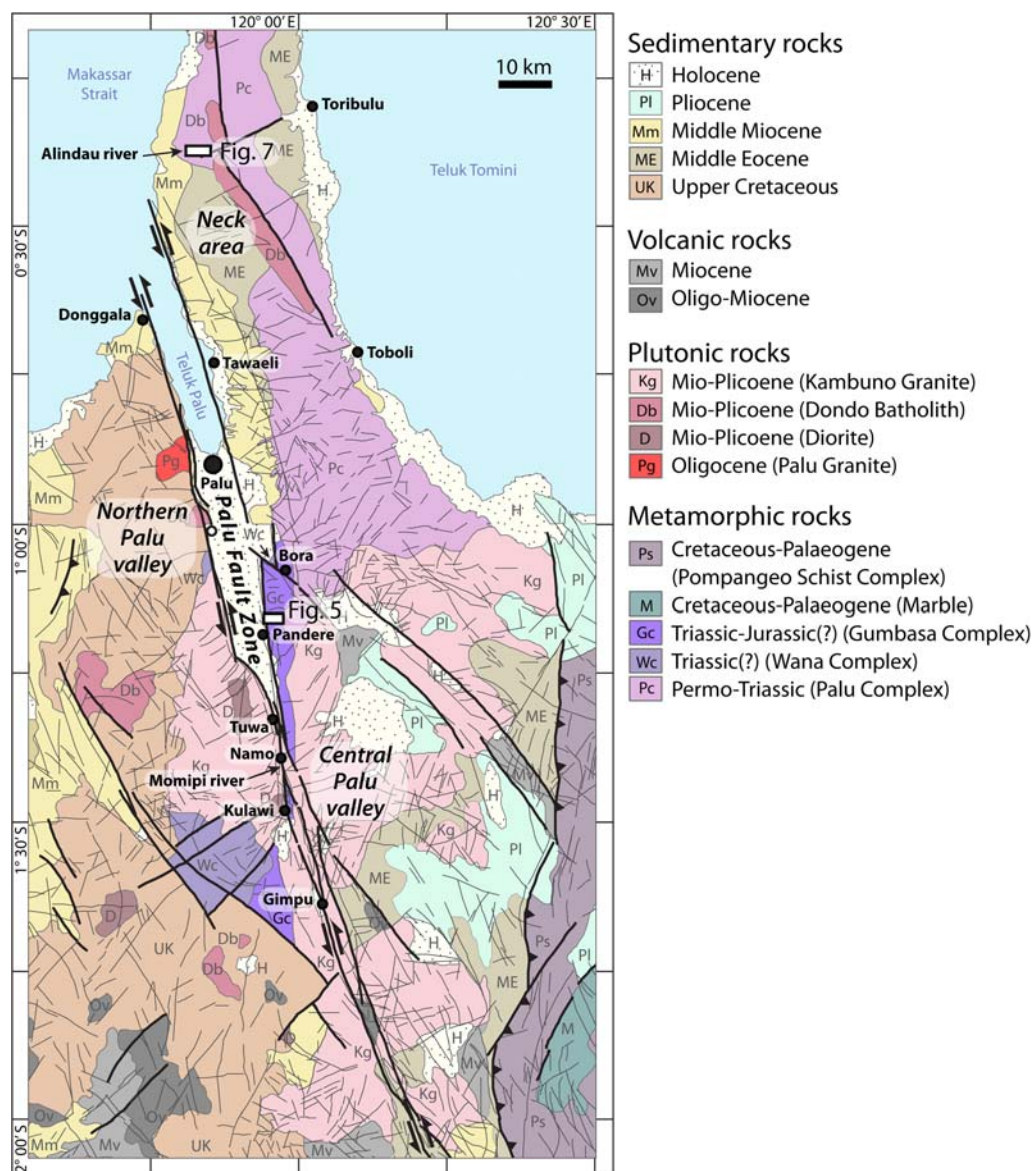
Fig. 2. Geological map of the Palu area. See box in Figure 1 for location. Modified after SULAROX; Sukamto (1973, 1975); Sukido *et al.* (1993); and van Leeuwen & Muhardjo (2005).

accreted to the SE Sundaland margin during the Middle Cretaceous (Hamilton 1979; Manur & Barraclough 1994; Parkinson *et al.* 1998; Hall *et al.* 2009). All these rocks are cut by the Palu-Koro Fault, a major, strike-slip fault which may penetrate the whole lithosphere (e.g. Brouwer *et al.* 1947; Hamilton 1979; Walpersdorf *et al.* 1998; Bellier *et al.* 2001). Limited existing fission-track data indicates that the Neogene intrusives and their

metamorphic hosts along the Palu Fault were rapidly uplifted during the Pliocene, and geomorphic studies indicate that uplift continues to the present day (Bellier *et al.* 2006).

Most of the basement rocks have been subjected to regional metamorphism, and many have a thermal overprint due to the Neogene magmatism (e.g. Egeler 1947; Sopaheluwakan *et al.* 1995). In between these metamorphic periods, evidence of

non-coaxial ductile deformation can also be recognized in many places. This study aims to describe its nature, and to speculate on its timing and tectonic causes.

Metamorphic basement of west-central Sulawesi

Large regions of west Sulawesi's metamorphic basement rocks crop out along the Palu valley and along the neck that connects the main island to the north arm. Names, locations and contacts between metamorphic complexes in the area vary significantly between authors. In this study, the map and nomenclature of van Leeuwen & Muhardjo (2005) is used for the area north and east of Palu, and of Sukido *et al.* (1993) for the area south of Palu and west of the fault valley, with small modifications following recent fieldwork (Fig. 2). For simplicity, when discussed together, all the rocks of the present study are termed the Palu metamorphic rocks, though this should not be considered a new litho-stratigraphic term. In the following descriptions of the individual units, a distinction is made between a *metamorphic complex* (an association of metamorphic rocks in any tectonic setting) and a *metamorphic core complex* (an association of metamorphic rocks exhumed by supra-crustal extension along a low-angle fault). Six metamorphic complexes have been defined from areas adjacent to the Palu-Koro Fault. From north to south, these are:

Malino Metamorphic Complex

The Malino Metamorphic Complex lies at the northeastern end of the Palu fault valley, along the northern edge of Tomini Bay (Ratman 1976; van Leeuwen *et al.* 2007; Fig. 1). It is composed of mica schists, gneisses, greenschist, amphibolite, marble and quartzite, which formed under conditions of regional metamorphism ranging from 300–350 °C and 0.3–0.5 GPa to 646–617 °C and 0.75–0.96 GPa (van Leeuwen *et al.* 2007).

Zircons from metagranitoids that intrude the Malino Metamorphic Complex indicate that it is in part of Devonian to early Carboniferous age, and includes inherited Proterozoic and Archaean zircons. Isotopes of Sr and Nd have similar characteristics to northern Australian river sediments, and geological similarities to the Bird's Head region of New Guinea all suggest that the complex is an allochthonous terrane derived from Australia (van Leeuwen *et al.* 2007). A greenschist facies carapace around the Malino Metamorphic Complex core is derived from the adjacent Palaeogene Tinombo Formation. van Leeuwen *et al.* (2007) interpret the contact between the core and carapace to be a dome-shaped low angle normal fault, formed

during exhumation of the Cretaceous accreted metamorphic core as a metamorphic core complex during the Miocene. Those authors also describe an alternative whereby the Malino Metamorphic Complex is a Bird's Head-derived fragment subducted beneath the north arm, and immediately exhumed during the Late Oligocene–Middle Miocene. This is supported by evidence of deformation and uplift in the western and central north arm (van Leeuwen *et al.* 2007).

Palu Metamorphic Complex

The Palu Metamorphic Complex extends along the neck to about 40 km south of Palu, on the eastern side of the Palu-Koro Fault only (Fig. 2). It is composed of biotite schists, paragneisses, amphibolitic schists, marble and orthogneisses (Egeler 1947; Sukamto 1973). The metasediments and metagranitoids are of Permo-Triassic continental Australian age and affinity, but rocks of Sundaland and MORB affinity also occur (van Leeuwen & Muhardjo 2005).

The Palu metamorphic rocks are overlain by the Late Cretaceous Latimojong Formation and the Palaeogene Tinombo Formation, a folded sequence of volcanic and marine sedimentary rocks which have been metamorphosed to greenschist facies (van Leeuwen & Muhardjo 2005).

Karossa Metamorphic Complex

The Karossa Metamorphic Complex lies west of the Palu-Koro Fault, in the Lariang region. It is dominated by metapelites, and also contains MORB affinity metabasites. The Palu and Karossa Metamorphic Complexes are possibly young metamorphic core complexes (van Leeuwen & Muhardjo 2005).

Wana and Gumbassa Metamorphic Complexes

The Wana and Gumbassa Metamorphic Complexes contain metamorphic rocks similar to the Palu Metamorphic Complex, and are combined with the latter by van Leeuwen & Muhardjo (2005). Nonetheless, a distinction is convenient from a geographical perspective at least. The Wana Metamorphic Complex crops in small areas on both sides of the Palu-Koro Fault about 20 km south of Palu, and more extensively west of Gimpu (Fig. 2). It is dominantly composed of schistose rocks, including mica schist, amphibole schist, quartzite and gneiss, inferred to be of Triassic age (Sukido *et al.* 1993). The Gumbassa Metamorphic Complex crops out west of Gimpu and in slivers along the centre and east side of the Palu-Koro Fault (Fig. 2). It is dominantly composed of gneissic rocks, including gneissic granite and diorite, gneiss and schist, inferred to

be of Triassic–Jurassic age (Sukido *et al.* 1993). Ages assigned to the complexes should be viewed as provisional, as Sukido *et al.* (1993) provide no supporting evidence for them.

Lenses of granulite, eclogite and garnet peridotite are tectonically intercalated with the lower grade metamorphic rocks along the southern parts of the Palu fault valley (Kadarusman & Parkinson 2000; van Leeuwen & Muhardjo 2005). They represent the deepest rocks exposed in the area. Helmers *et al.* (1990) determined rapid uplift of the garnet peridotites from peak P–T conditions of 1050–1100 °C and 1.5–2 GPa, or about 60 km depth, Kadarusman & Parkinson (2000) estimated peak P–T conditions of 1025–1210 °C and 1.9–3.2 GPa. The eclogites may have experienced pressures of 2.8 GPa (Liou & Zhang 1995; Kadarusman & Parkinson 2000). Kadarusman & Parkinson (2000) described ductile deformation of olivine, garnet, clinopyroxene and orthopyroxene in the garnet peridotites, and inferred that these formed between garnet–lherzolite assemblage metamorphism and spinel–garnet–lherzolite assemblage metamorphism. Both of these stages preceded granulite and amphibolite facies events. Younger, brittle deformation occurred during greenschist facies retrograde metamorphism, and later, under shallow level, serpentinite-forming conditions.

Pompangeo Schist Complex

The Pompangeo Schist Complex is part of Sulawesi's north–south striking central metamorphic belt which lies east of the Palu fault valley, adjacent to the plutono-metamorphic belt of central and western Sulawesi (Fig. 1). It is composed of marble, calcareous phyllite, quartz–mica schist, phyllite, metaconglomerate, metabasic intrusions and metatuffs. West of lake Poso, quartzo-feldspathic schist and quartzite also become abundant. Metabasic and serpentinitic intercalations (but not ophiolitic rocks) increase in abundance westward. The contacts between many lithologies are defined by east-verging thrusts, parallel to a strong, compositional layering-parallel transpositional foliation, which dips WSW (Parkinson 1998). Asymmetric folds and quartz segregations in the schist show that early folding and transposition occurred during non-coaxial deformation, associated with localized mylonitic zones which indicate a top-to-the-east shear sense (Parkinson 1998).

Metamorphic grade increases from east to west across the metamorphic belt. The highest grade rocks, closest to the Palu-Koro fault, have been interpreted as underthrusted accretionary complex slices above a west-dipping subduction zone, metamorphosed during the Middle Cretaceous (Parkinson 1998; Parkinson *et al.* 1998). The surface contact

between the Pompangeo Schist and the plutono-metamorphic rocks of central and western Sulawesi is inferred to be an east-dipping thrust, which must have formed after the Mio–Pliocene intrusion of the granitoids (Simandjuntak *et al.* 1991; Parkinson 1998).

Non-coaxial strain in the metamorphic rocks of the Palu-Koro fault zone

Northern Palu valley

Metamorphic rocks in the northern Palu valley include quartz and quartz-biotite slates, schists, amphibole schists, garnet–mica schists, and bands of foliated granitoid. Along the northwestern side of the valley, young and mostly unfoliated granitoids of the Dondo Suite dominate, and metamorphic rocks are limited to a few small relics which have a strong thermal overprint (Egeler 1947).

Schists composed of acicular green amphibole, K-feldspar and plagioclase possess a strong L-S tectonite fabric. Their foliation generally dips steeply east, and mineral lineations plunge moderately towards the east and NE (Fig. 3a). Many amphiboles are euhedral, but in places form asymmetric lenticular fish, indicating non-coaxial strain (Fig. 4a). Sigma-type porphyroclasts of individual feldspar crystals or feldspar aggregates, with recrystallized tails, deflect the aligned amphiboles (Fig. 4b). Large quartzo-feldspathic masses with asymmetric tails up to 0.5 m long have a similar geometry, and may be boudins of pre-kinematic veins or dykes (Fig. 4c). Kinematic indicators along the NW Palu valley show top-to-the WSW and NW ductile thrusting, locally with a significant dextral strike-slip component, together with top to the NE and SE ductile extension (Fig. 3a, Table 1). In places where compositional banding is prominent, intense folding tends to form instead of the laminar flow of more homogeneous parts of the schist. Folds are disharmonic and often ptygmatic.

On the eastern side of the valley, north of Pandere, metamorphic rocks are much more widespread. These are mapped as the Wana Complex, Gumbasa Complex, and Latimojong Formation by Sukido *et al.* (1993). van Leeuwen & Muhardjo (2005) class all of the metamorphic rocks on the eastern side of the valley as the Palu Metamorphic Complex.

A suite of schistose rocks crops out along the road in the linear, NW-trending valley which intersects the Palu valley from the east near Bora. In the north, these possess a moderately south to SW-dipping foliation defined by alternations of layers rich in garnet, quartz and feldspar, and layers rich in aligned biotite and sillimanite. A coarse but discontinuous lineation is formed by
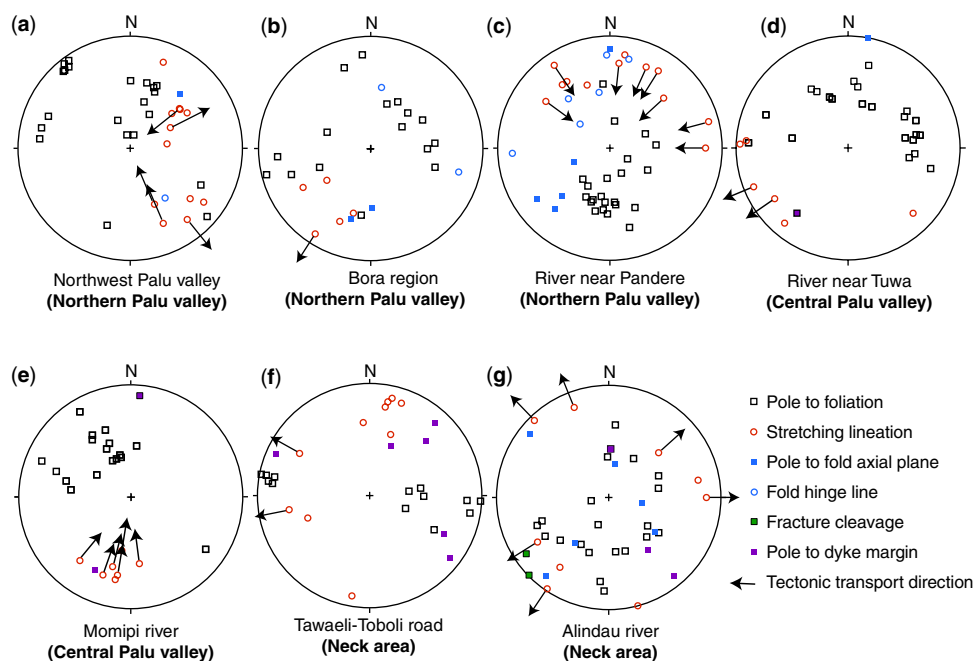
Fig. 3. Equal area lower hemisphere stereonets showing the orientation of mylonitic foliation, stretching lineation, and other structural elements for regions referred to in the text. Planes are represented as poles. Black arrows indicate the tectonic transport direction where known, up-plunge (towards the centre of the stereonet) or down-plunge (away from the centre of the stereonet).

aggregates of all these minerals, which plunges to the SW. Garnet forms fractured porphyroclasts that deflect the foliation and lack parallel inclusion trails, suggesting that they predate the foliation. They possess slightly asymmetric sigma-type tails of staurolite, biotite partly replaced by sillimanite, unstrained (i.e. wholly recrystallized) quartz, and garnet fragments. Their asymmetry, and that of small plagioclase porphyroclasts, mica fish and shear bands, indicates a top-to-the SW extensional ductile fabric (Fig. 3b, Table 1).

Further south along the valley, the schists are dominated by green amphibole, K-feldspar and plagioclase. A strong foliation is defined by bands rich in feldspar. Alignment of partly acicular amphiboles forms a SW-plunging mineral lineation (Fig. 3b). There is little evidence of non-coaxial strain in these rocks. However, they were observed 2 km east of the mountain upon which the stream transect north of Pandere, described below, lies. Float in the west-flowing stream is dominated by proto-mylonitic, coarse grained amphibole-feldspar gneisses and schists. It is likely that the higher parts of the mountain are composed of a strongly sheared correlative of the amphibole schist, which are being washed west into the Palu valley.

A stream transect (Fig. 5) up the side of the Palu valley north of Pandere reveals a sequence of deformed and variably mylonitic schists with a broadly north-dipping foliation and NW, north, NE and east-plunging mineral lineations (Fig. 3c). Both metamorphic grade and strain increase eastwards, and some of the most strongly mylonitic rocks in the Palu valley occur near the top (east) of the transect. These rocks are biotite–quartz–garnet schists which also contain muscovite, aegirine augite, calcite and chlorite. Garnets up to 3 mm in diameter form prominent porphyroclasts which commonly retain their euhedral shape, and deflect the surrounding foliation (Fig. 4d). Their asymmetric, sigma-type tails are composed of small quartz grains formed by bulging recrystallization of matrix quartz, and muscovite. The garnets are corroded on faces attached to their tails, and this occasionally emphasizes curved inclusion trails which are continuous with elongation of quartz in the tails, and indicate that the garnets rotated during growth, and are therefore syntectonic (Fig. 4e).

Coarse ridges formed by the deflection of foliation over the garnets and their tails form a conspicuous lineation, which plunges gently to the NW
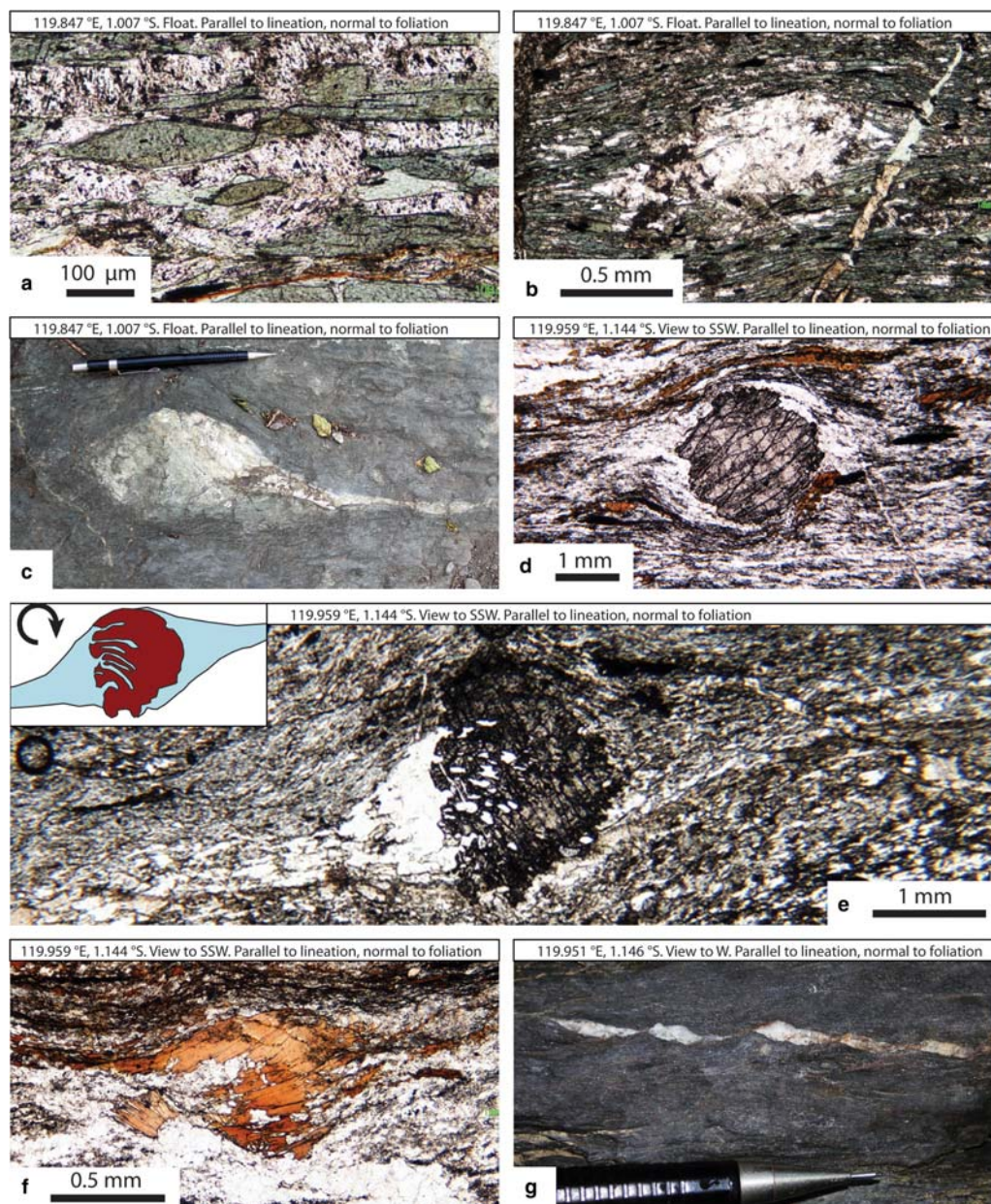
Fig. 4. Characteristics of ductile shear from the northern Palu valley. Latitude, longitude, view direction (if *in situ*) and orientation relative to ductile fabrics is shown above each image. (**a**) Hornblende fish and (**b**) feldspar porphyroclast in an amphibole schist. Top-to-the-right shear sense. Plane polarized light (PPL). (**c**) Asymmetric ductile boudin of quartzofeldspathic material in a large boulder. (**d**) Garnet porphyroclast in mylonitic garnet-mica schist. Top-to-the-right shear sense. PPL. (**e**) Curved inclusion trails in a garnet porphyroclast, indicating syn-kinematic origin. Top-to-the-right shear sense. PPL. (**f**) Biotite fish in mylonitic garnet-mica schist. Top-to-the-right shear sense. PPL. (**g**) Quartz-rich asymmetric boudin train. Top-to-the-left shear sense.

(Fig. 5). Kinematic indicators such as asymmetry of sigmoidal garnet inclusion trails, asymmetry of their sigma-type tails, S–C′ fabrics and well developed biotite fish (Fig. 4f) all consistently indicate top-to-the SE ductile thrusting parallel to the lineation (Fig. 5, Table 1). In the central part of the

Table 1. *Summary of kinematic indicators and overall shear sense from parts of the Palu valley and neck metamorphic rocks*

Area	Location		Lineation	Shear-sense options	Kinematic indicators					
					Mica fish	Amphibole fish	Delta porphyroclast	Sigma porphyroclast	Spiral inclusion trails	Rotated inclusion trails
Northern Palu valley	NW Palu valley		40–058	Thrust (top-to-WSW)		5	1	32		
				Extension (top-to-ENE)		3		12		
	Bora region		10–213	Thrust (top-to-NE)	1			15		
				Extension (top-to-SW)	4			35		
	River near Pandere	West	30–306	Thrust (top-to-SE)				5		
				Extension (top-to-NW)				19		
		Centre	35–047	Thrust (top-to-SW)	15		6	11	2	1
				Extension (top-to-NE)	1		1	1	3	
		East	30–323	Thrust (top-to-SE)	4		18	1	22	
				Extension (top-to-NW)						
Central Palu valley	River near Tuwa		12–221	Thrust (top-to-NE)						
				Extension (top-to-SW)						
	Momipi river		28–219	Thrust (top-to-NE)						
				Extension (top-to-SW)						
Neck area	Tawaeli-Toboli Road		28–260	Thrust (top-to-E)						
				Extension (top-to-W)	1			3		
	Alindau river	West	05–316	Thrust (top-to-SE)				1		
				Extension (top-to-NW)			1	4		
		Centre	02–214	Thrust (top-to-NE)						
				Extension (top-to-SW)						
		East	40–048	Thrust (top-to-SW)						
				Extension (top-to-NE)						

Lineation, representative mineral stretching lineation from each location. Kinematic indicators, observed parallel to the lineation, on

transect, ductile thrusting has a more SSW–SW direction (Fig. 5, Table 1).

Very fine grained, dark grey rocks crop out at the bottom (west) of the section. A fine, slatey foliation is pervasive, and a mineral lineation defined by elongated biotite is commonly developed parallel or oblique to the foliation dip direction (Fig. 5).

The rock is streaked with foliation-parallel quartz veins, typically stretched into lenticular ductile boudins joined by biotite-rich shear planes (Fig. 4g). Shear plane-foliation angles, boudin asymmetry, S–C′ fabrics, rotated opaque grains and spiral mica cleavage all indicate top-to-the SE ductile thrusting (Fig. 5, Table 1). Small, semi-ductile thrust faults cut across the foliation and have a similar vergence direction. These may represent continued, broadly south directed thrusting under retrograde conditions.

Central Palu valley

Gneisses and schists exposed in the central Palu valley between Tuwa and Gimpu (Fig. 2) show signs of non-coaxial strain. Migmatitic paragneisses exposed in a west-flowing stream south of Tuwa are strongly foliated by discontinuous melt lenses and alignment of biotite and a brown amphibole in dark melanosomes. Elsewhere, a gneissic banded texture is developed by more systematic segregation of quartzo-feldspathic and mafic minerals. Thicker leucocratic veins with an assemblage identical to that in the melt lenses lie parallel to the foliation. These are only weakly foliated, so were probably

Kinematic indicators											Overall shear-sense
Spiral mica cleavage	Rotated amphibole grains	Rotated opaque grains	Biotite strain shadows	Asymmetric quartz segregations	Asymmetric folds	Asymmetric boudinage	Shear band	S–C' fabric	Oblique foliation in quartz	Displaced broken grains	
							4	2			Dextral/thrust (top-to-WSW)
			1				4				Extension (top-to-SW)
		7					2				
8		4					4	5			Thrust (top-to-SE)
		2						1			
	1			1	4		3	1	1		Thrust (top-to-SW)
	4				2						
								1			Thrust (top-to-SE)
									2		
				1	1						Extension (top-to-SW)
				8	5	1	3				
				8	3	1	1	3			Thrust (top-to-NE)
			1	1	4					1	
				3			1		1		Extension (top-to-W)
				25			1	1			
				17	7						Extension (top-to-NW)
				19	3		7				
				6							Extension (top-to-SW)
				11			2				
									1		Extension (top-to-NE)
				8			2		4		

foliation-normal surfaces. Numbers represent the number of each kinematic indicator observed at each location.

injected along an existing metamorphic fabric rather than being transposed by post-anatexis shear and flattening.

Melt lenses commonly form en-echelon veins. Some larger leucosome veins have been stretched into trains of ductile boudins (Fig. 6a). These also have a stair-stepping geometry. Shear bands between boudins have a shear sense consistent with that of the stair-stepping elements. Highly asymmetric intrafolial folds are common (Fig. 6b). All these criteria show a consistently down-dip, extensional shear sense parallel to a weak biotite aggregate lineation which plunges to the SW (Fig. 3d, Table 1).

Straight, sharp sided dykes of unfoliated biotite granite and aplite cut the foliation (Fig. 6c), and larger bodies dominate the lower part of the river.

These post-date the regional metamorphism and ductile fabric, and are interpreted to relate to the Pliocene Dondo Suite intrusives. Garnet peridotite boulders in the stream may be from tectonic slivers within the gneiss, or may have been exhumed by and eroded from the younger intrusives.

Metamorphic rocks crop out in the Momipi river near Namo. Gneissic segregation is more advanced than in the Tuwa example, biotite and garnet are much more prevalent, and kinematic indicators are more conspicuous. In addition to well developed examples of the kinematic indicators described above, discrete shear bands and large scale S–C' fabrics extend and deflect the gneissic fabric (Fig. 6d). An aggregate mineral lineation plunges moderately to the south and SW. In contrast to the Tuwa gneisses, kinematic indicators in the Momipi
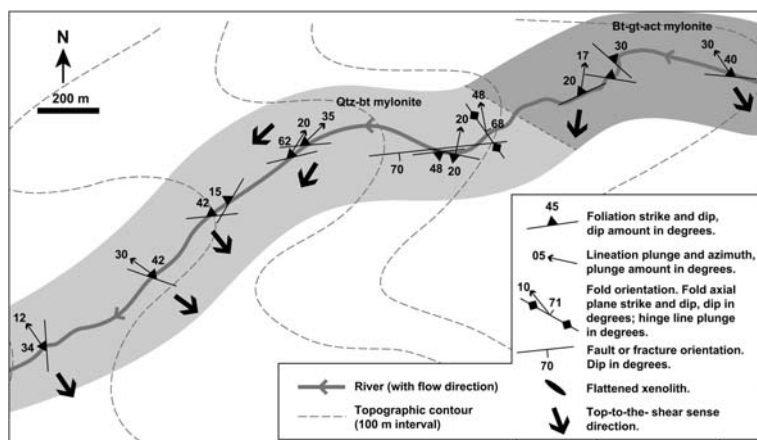
Fig. 5. Map showing features along a stream transect up the eastern Palu valley side north of Pandere. Representative structural data and shear sense indicated. For location see Figure 2. Qtz-bt, quartz–biotite; Bt-gt-act, biotite–garnet–actinolite.

river gneisses show a consistent top-to-the north and NE ductile thrust geometry (Fig. 3e, Table 1).

A major brittle NE-striking fault zone composed of vertical and steeply-dipping faults cuts through the gneisses and post-metamorphic granite dykes. Oblique slickenside lineations plunge south, and individual strands truncate and juxtapose lithological units, with a small extensional component. The whole system brings large unfoliated biotite granite bodies into tectonic contact with an 8 m wide sliver of the gneisses (Fig. 6e, f). The fault zone's orientation indicates that it may be a synthetic strand of the Palu-Koro Fault.

Large, proximally-derived boulders in the Palu river north of Tuwa provide clear examples of strain style in the gneissic rocks eroded from the central part of the Palu valley. A boulder of well foliated amphibole–plagioclase gneiss contains angular and rounded fragments of amphibolite, wrapped by the dominant foliation. Highly leucocratic material, which may have been melt segregations, forms asymmetric strain shadows around these 'mega-porphyroclasts', and includes amphibolite fragments mechanically removed from the core (Fig. 6g). A boulder of migmatitic gneiss, similar to the Tuwa gneisses, shows well developed shear bands that deform the dominant foliation. Leucocratic material lines the shear planes, showing that a period of melt mobilization, and perhaps generation, was syn-kinematic with respect to ductile fabric formation (Fig. 6h). This does not imply that shear zone heating caused melting, simply that shear occurred in rocks which were already melting during regional metamorphism. Amphibolite breccias with an aplitic cement are common. The prevalence of massive, or weakly foliated amphibolite as clasts in both breccias and gneisses

indicates that an amphibolitic terrane was later subjected to further regional metamorphism and non-coaxial strain to produce the strongly foliated amphibole schists and gneisses in which evidence of non-coaxial strain is common.

Neck area

Schists and migmatitic paragneisses are exposed in the southern and central part of Sulawesi's 'neck' (Fig. 2). These are included, by van Leeuwen & Muhardjo (2005), in the Palu Metamorphic Complex. Egeler (1947) described in detail the petrography of andalusite, amphibole, augite and garnet schists and amphibolites from the Tawaeli-Toboli road, and from the Boemboe river, close to Toribulu.

Recent development of the Tawaeli-Toboli road has revealed many new outcrops, and the Alindau river, a major west-flowing river south of the Boemboe river, also provides excellent exposures. Most rocks possess a strong foliation, defined by one or more of the following fabrics: compositional banding (pelitic/psammitic alternations or schistose and gneissic segregation), mica alignment, alignment of quartzo-feldspathic segregations or melt lenses. Foliations in rocks exposed along the Tawaeli-Toboli road generally dip westwards at moderate to steep angles (Fig. 3f). Strong lineations are common on foliation surfaces, sometimes in the form of fine crenulations, otherwise as polymineralic aggregates. These plunge to the north, west and south (Fig. 3f). En-echelon quartzo-feldspathic segregations, some of which are boudins of stretched veins, mica fish, porphyroclasts and shear bands indicate top-to-the west extension, parallel to west-plunging lineations (Fig. 3f, Table 1).
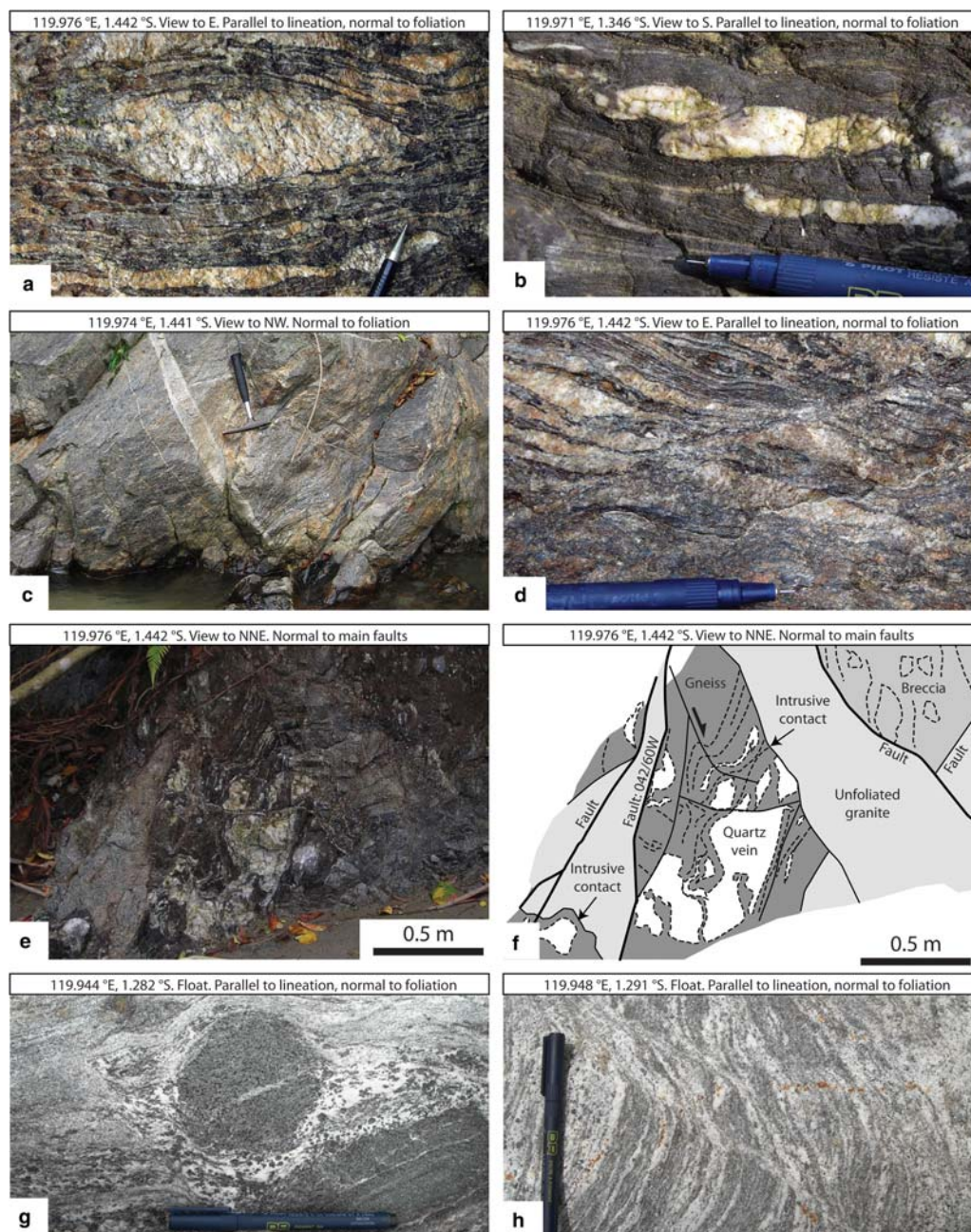
Fig. 6. Characteristics of ductile shear from the central Palu valley. Latitude, longitude, view direction (if *in situ*) and orientation relative to ductile fabrics is shown above each image. (**a**) Sheared felsic boudin in migmatites. Top-to-the-left shear sense. (**b**) Asymmetric intrafolial fold. Top-to-the-right shear sense. (**c**) Biotite granite dyke cutting gneissic foliation (top left-bottom right). Note hammer in centre of view for scale. (**d**) Large-scale shear bands (top right-bottom left) extending older gneissic foliation (top left-bottom right). Top-to-the-left shear sense. (**e**) Part of brittle fault zone near Namo, juxtaposing unfoliated granite with non-coaxially deformed gneiss. (**f**) Interpretation of Figure 6e showing the nature and orientation of contacts. (**g**) Amphibolite porphyroclast in a sheared feldspar-amphibole matrix. Unoriented boulder. (**h**) Felsic melt within shear planes (top left-bottom right) in a migmatitic gneiss. Unoriented boulder.

Extensive exposures along the Alindau river reveal similar, dark, fine grained rocks, often with a phyllitic, schistose, or locally gneissic appearance. A wide range of foliation orientations include moderate westerly dips, moderate to steep northerly, and moderate to shallow northwesterly dips (Figs 3g & 7). The foliation is folded by a penetrative folding fabric typified by small, open similar folds. Recumbent, tight folds with wavelengths in the order of 10 m appear to fold these fabrics. Fold axial planes lie close to the bulk foliation orientation. Additionally, parallel, locally disharmonic and ptygmatic folds are common. Strongly attenuated shear bands have developed in the hinge regions of some of these folds.

Macroscopic shear sense indicators are well developed, including asymmetric folds, asymmetric quartzo-feldspathic segregations, asymmetric boudinage, and shear bands (Fig. 8a, b). In thin section, S−C′ fabrics and an oblique foliation in recrystallized quartz segregations indicate a shear sense consistent with the macroscopic structures. Overall, kinematic indicators show top-to-the NW ductile extension in the lower (west) parts of the river, top-to-the SW ductile extension in the middle part of the river, and top-to-the NE ductile

extension in the upper (east) parts of the river (Figs 3g & 7, Table 1). However, in all cases there are a significant number of kinematic indicators showing an opposite (thrust) shear sense. This may be due in part to re-orientation caused by post-simple shear penetrative folding. All shear bands which extend the folds have a consistent shear sense.

Quartz grains in quartzo-feldspathic segregations and boudin trains generally have a strain free appearance, indicating complete recrystallization and annealing (Fig. 8c). Grain boundaries are irregular and lobate, due to grain boundary migration recrystallization (Fig. 8d), a process characteristic of temperatures above 500 °C. Locally, chessboard sub-grains are developed, indicative of temperatures exceeding c. 650 °C (Stipp et al. 2002).

A float sample from the Alindau river contains sheared quartzo-feldspathic segregations within a schistose foliation, both of which have been cut at an angle of c. 20° by a thin granitic dyke. This has itself been stretched and slightly sheared by continued deformation, indicating that it was intruded syn- or inter-kinematically (Fig. 8e, f). All metamorphic fabrics have been cut by younger unfoliated granitic dykes (Fig. 8g).
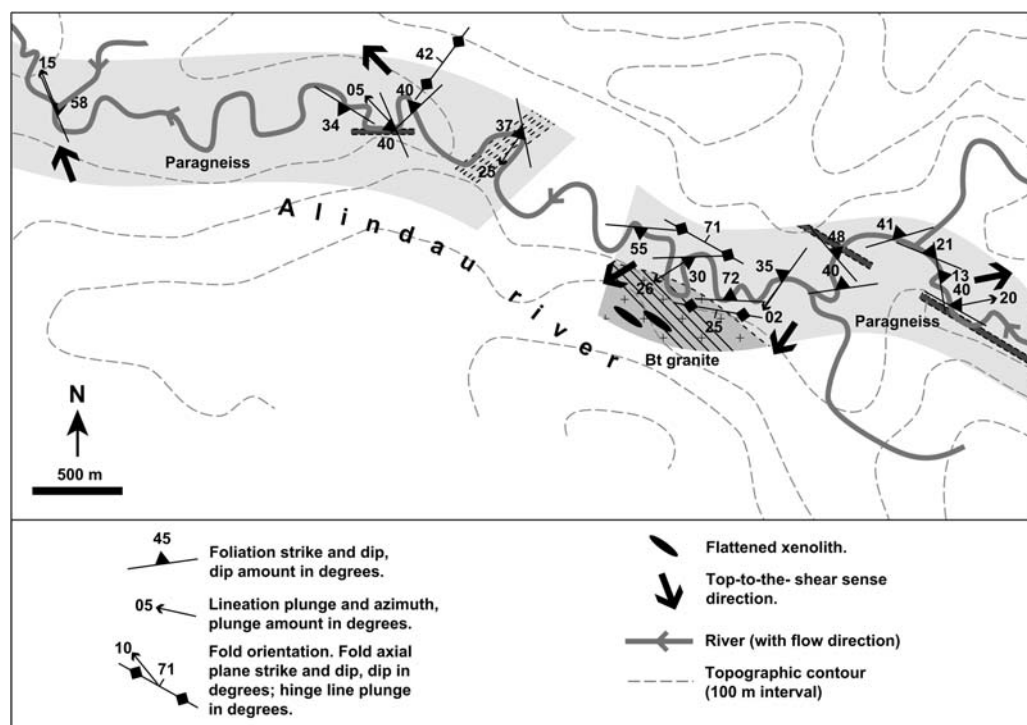

Fig. 7. Map showing features along a stream transect up the Alindau river, on the western side of the neck. Representative structural data and shear sense indicated. For location see Figure 2. Bt, biotite.

Constraints on the causes and timing of non-coaxial deformation

There are two broad scenarios for the formation of ductile shear fabrics in the Palu area. In the first, fabrics formed before, and are unrelated to Neogene deformation and uplift, and were subsequently exhumed, undergoing static retrograde metamorphism that passively overprinted their deformation fabrics. Alternatively, fabrics formed during their Neogene exhumation.

No data directly date the timing of metamorphism or ductile deformation in the Palu valley. However, the tectono-magmatic evolution of the area is becoming increasingly well known. A summary is provided here in order to place constraints on the causes and timing of ductile fabric development.

Origin of the western metamorphic rocks

Many of the metamorphic rocks of Sulawesi's basement are of Mesozoic, Palaeozoic, and probably also Precambrian origin. A fragment of Gondwanan continental crust probably lies beneath western Sulawesi (Elburg *et al.* 2003; van Leeuwen *et al.* 2007). This fragment, the Argo block, which may underlie much of east Java as well as west Sulawesi, bears zircons with Archaean–Cambrian age peaks (Bergman *et al.* 1996; Smyth *et al.* 2007; van Leeuwen *et al.* 2007) which correspond to periods of orogenic growth characteristic of the Gondwana margin. Potassic calc-alkaline to ultrapotassic intrusions within the metamorphic rocks of west Sulawesi yield Sr, Nd and Pb isotopic ratios which indicate that they have incorporated crust of Australian origin, presumably the metamorphic basement (Priadi *et al.* 1993, 1994; Bergman *et al.* 1996; Polvé *et al.* 1997, 2001; Elburg & Foden 1999; Elburg *et al.* 2003). This continental fragment rifted from the northern margin of Australia during the late Jurassic (Powell *et al.* 1988; Hall *et al.* 2009), and, alongside others in the East Java Sea, SE Kalimantan and the southern Makassar Straits, accreted to the SE Sundaland margin during the Middle Cretaceous (Hamilton 1979; Manur & Barraclough 1994; Parkinson *et al.* 1998; Hall *et al.* 2009).

The Palu, Malino and Karossa metamorphic complexes of western Sulawesi are composed of pieces of this continental fragment (van Leeuwen & Muhardjo 2005; van Leeuwen *et al.* 2007). They form a distinctive belt dominated by staurolite and sillimanite + andalusite + cordierite-bearing amphibolites (Egeler 1947). The age of the metamorphic rocks (Archaean–Cambrian) provides an upper age limit for ductile deformation in these rocks. It is possible that deformation observed in the Palu metamorphic rocks occurred during an intracontinental tectonic event prior to the breakup of Gondwana. Significant folding and local faulting during younger tectonic events could explain the diverse orientations of observed ductile fabrics (Figs 3 & 9).

The Central Sulawesi Metamorphic Belt

Mélange, ultramafic rocks, radiolarian cherts and high pressure metamorphic rocks, including blueschists and eclogites, make up a dismembered accretionary complex within, and around the eastern margin of the metamorphic complexes. These rocks are exposed in the Bantimala Mélange Complex, the Latimojong mountains, and the Pompangeo Schist Complex of the Central Sulawesi Metamorphic Belt (Sukamto 1975; Parkinson 1991, 1998; Bergman *et al.* 1996; Wakita *et al.* 1996). As glaucophane-bearing rocks associated with massive ultramafic bodies (Brouwer *et al.* 1947) and high shear strains (Parkinson 1998), these units are characteristic of rocks formed in a subduction zone. They yield Aptian–Albian white mica and whole rock K–Ar ages, indicating that metamorphism associated with subduction occurred during the Middle Cretaceous (Parkinson 1998). An east-verging ductile shear sense has been described from these rocks (Parkinson 1998), and it is possible that ductile fabrics in the Palu metamorphic rocks represent contemporaneous deformation in the middle crust of the over-riding plate. In particular, west to south-verging thrusting in the metamorphic rocks of the Palu valley (Fig. 9) could represent back-thrusting in such a setting. Similarly directed extensional fabrics, particularly along the neck and near Bora and Tuwa, may have originated in the same thrust setting, but were later rotated into their present orientation.

Mesozoic shallow marine or continental margin sedimentary rocks inter-thrust with the high pressure metamorphic belt represent the parental material of the complex, which may be a microcontinental fragment that was incompletely subducted (Wakita *et al.* 1996; Parkinson 1998; Parkinson *et al.* 1998). Continental arc magmatism above this Cretaceous subduction system is probably represented by granitoids of central Kalimantan, which yield Barremian to Cenomanian ages (Pieters & Supratna 1990), and not the magmatic arc of western Sulawesi, which is of Neogene age (see below). A deep marine fore-arc basin west of this NW-dipping subduction zone was filled with clastic turbidites of the Latimojong Formation during the Late Cretaceous (van Leeuwen 1981; Hasan 1991; Sukamto & Simandjuntak 1983; Bergman *et al.* 1996; Calvert 2000). Both the Bantimala Mélange Complex and the Pompangeo Schist
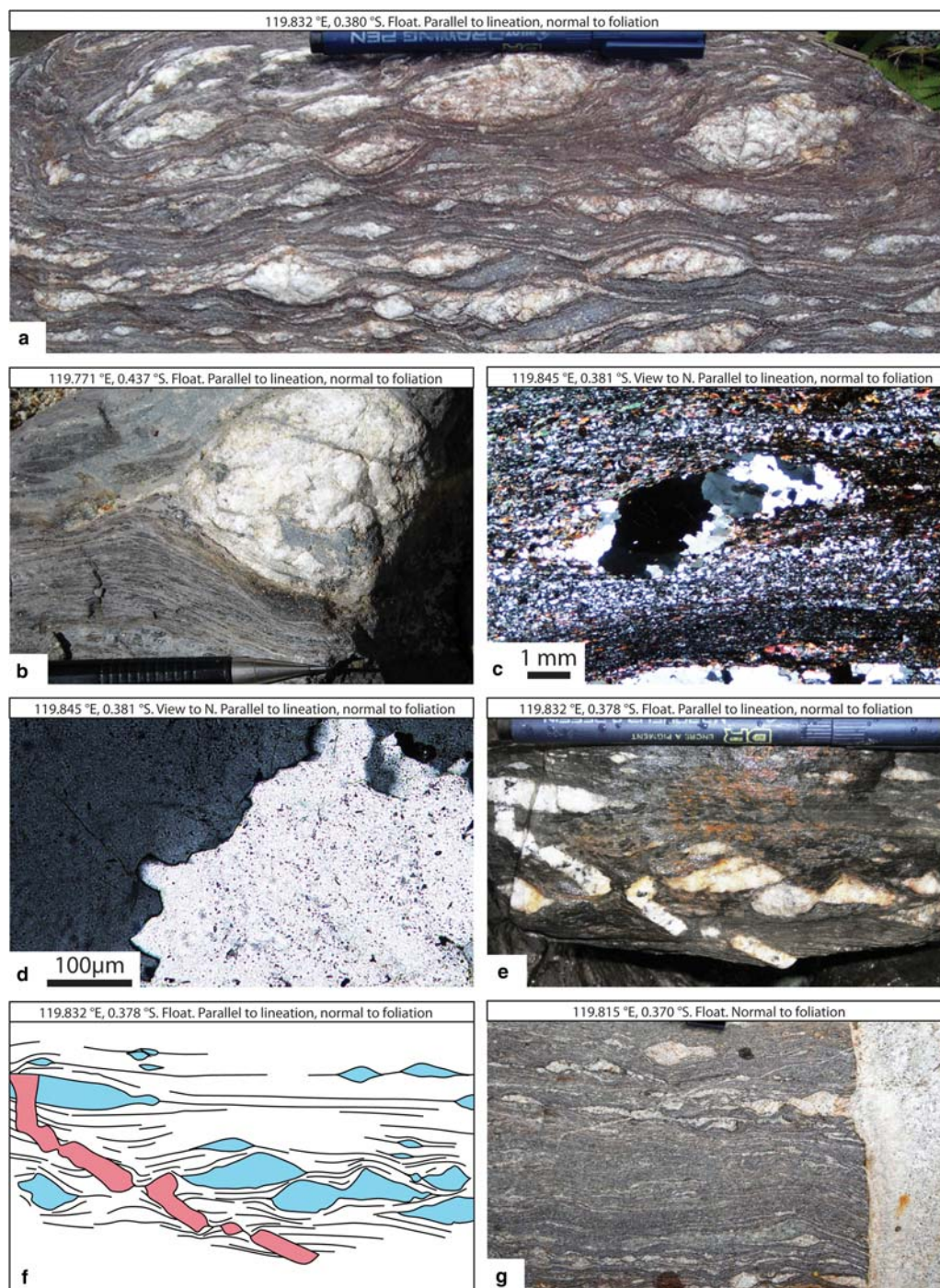
Fig. 8. Characteristics of ductile shear from the neck metamorphic rocks. Latitude, longitude, view direction (if *in situ*) and orientation relative to ductile fabrics is shown above each image. (**a**) Biotite schist boulder showing sheared, lenticular quartz segregations, some with recrystallized tails. Weak shear bands dip to the right. Top-to-the-right shear sense. (**b**) Rounded, quartzofeldspathic ductile boudin with thin, recrystallized tail, in amphibole–biotite schist. (**c**) Quartz segregation in thin section, showing recrystallization of quartz. Crossed polars. Top-to-the-right shear sense.
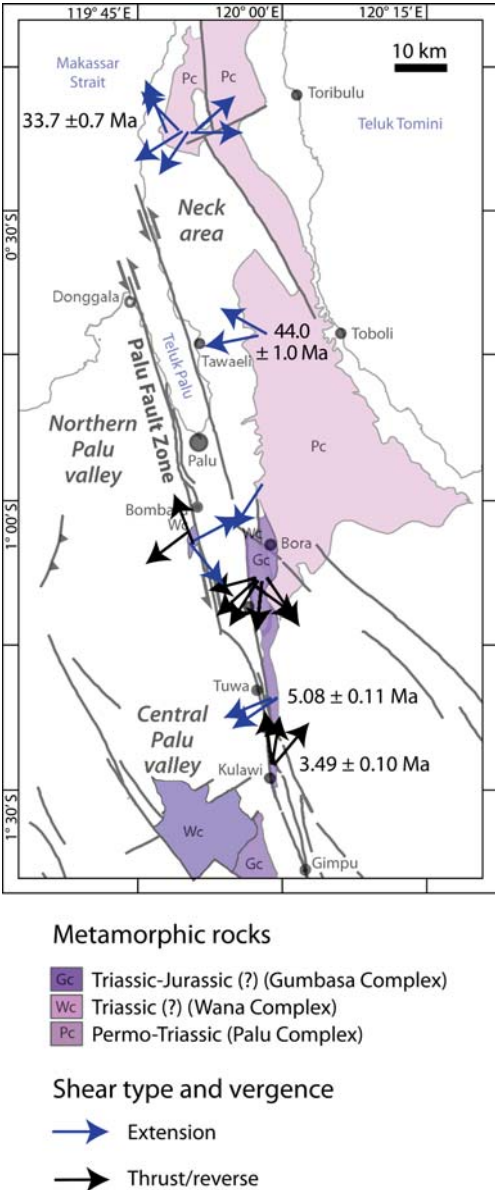
Fig. 9. Summary map showing orientation, type, and minimum age constraints for shear in the Palu metamorphic rocks. Ages refer to dykes which cross-cut the sheared fabric. See text for details and references. See Figure 1 for location.

Complex are unconformably overlain by Albian to Cenomanian radiolarian cherts (Silver *et al.* 1983*a*; Wakita *et al.* 1996; Parkinson 1998). This provides an upper age constraint on the back-thrust hypothesis for the Palu metamorphic rocks described above.

Palaeogene events

Late Cretaceous and Paleocene to Eocene deposits in western Sulawesi are separated by an unconformity, indicating that deformation and/or uplift occurred at the end of the Cretaceous (van Leeuwen & Muhardjo 2005).

The Makassar Straits opened during the Middle Eocene, separating Sulawesi from Borneo, and the Mesozoic subduction complex from its magmatic arc (Hamilton 1979; Situmorang 1982; Cloke *et al.* 1999). Half graben trending NE–SW formed in NW Sulawesi from the Middle to Late Eocene (Calvert & Hall 2003). Localized subduction-related volcanism in western Sulawesi had ceased by the Oligocene or early Miocene (Elburg *et al.* 2003; van Leeuwen & Muhardjo 2005; van Leeuwen *et al.* 2007), as the continental margin changed from active subduction to dominantly strike-slip (Rangin *et al.* 1990; Hall 1996, 2002). Muscovite from a two-mica granite dyke near Tompe, on the western side of Sulawesi's neck, yielded K–Ar ages of 33.4 ± 0.2 and 33.7 ± 0.7 Ma (Elburg *et al.* 2003). These samples originated about 15 km north of the Alindau river, where similar dykes have been observed to cut the metamorphic fabric (Fig. 8g), and to be late syn-kinematic with respect to ductile shear (Fig. 8e, f). Assuming the samples dated by Elburg *et al.* (2003) are the same age as the Alindau river dykes, and have the same relationship to the metamorphics, then the variably-oriented extensional shear observed in Alindau river schists must have occurred at, or shortly before *c.* 33.7 Ma (Fig. 9). Hornblende from a quartz diorite, probably collected from the same Tawaeli-Toboli road across the neck north of Palu described above, yielded a K–Ar age of 44.0 ± 1.0 Ma (Elburg *et al.* 2003). This is a minimum age for top-to-the-west extensional shear in schists exposed along this road (Fig. 9).

Isotopic ages from the Malino Metamorphic Complex indicate that it cooled through the K–Ar closure temperature for hornblende ($c.\,500 \pm 50\ ^{\circ}$C)

Fig. 8. (*Continued*) (**d**) Grain boundary migration between two quartz grains. Crossed polars. (**e**) Float sample showing sheared quartz-biotite schist (left-right foliation) cut by a weakly sheared biotite granite vein (top left-bottom right), interpreted to be late syn-kinematic. (**f**) Interpretation of (e), showing strongly sheared quartz segregations (blue) and weakly sheared granite vein (pink). (**g**) Granite dyke (top to bottom) cutting sheared gneiss (left-right foliation).

at 33.0 ± 1.2 Ma to 9.30 ± 0.6 Ma; and for musco-vite (*c.* 350 ± 50 °C) at 19.7 ± 0.2 Ma to 14.1 ± 0.2 Ma (van Leeuwen *et al.* 2007). van Leeuwen *et al.* (2007) interpret these ages as recording uplift of the metamorphic complex. Since the granitoid dykes of the neck were intruded during the late Eocene, it is also possible that the neck metamorphic rocks were uplifted at a similar time. A Middle Eocene–early Oligocene, possibly northward-younging sequence of mid-crustal, low-angle extension, decompression melting and dyke-intrusion, and subsequent exhumation is therefore possible for both the Malino Metamorphic Complex, and the northern part of the Palu Metamorphic Complex in the neck.

Neogene collisions

A large ophiolite body was obducted onto eastern Sulawesi during the Neogene. It may have originated in the Banda Sea (e.g. Katili 1978; Hamilton 1979), in the Gorontalo Basin (Silver *et al.* 1983*a*), or near the northern margin of Australia (Mubroto *et al.* 1994). The age of the oceanic crust comprising the ophiolite is not well known (e.g. Mubroto *et al.* 1994; Parkinson 1998). Biostratigraphy indicates an Early Cretaceous age (Simandjuntak 1992), while K–Ar ages from the mafic rocks range from Middle Cretaceous to Miocene (Binsil & Batusimpang, reported in Simandjuntak 1986; Mubroto *et al.* 1994). It is likely that the ophiolite is composite, partly explaining the wide age range (Parkinson 1998). K–Ar isotopic dating of hornblende from amphibolites of the metamorphic sole below the ophiolite indicate that it was thrust onto the Pompangeo Schist Complex during the Oligocene (Parkinson 1996, 1998).

Continental fragments to the east of Sulawesi, including the Banggai-Sula and Buton-Tukang Besi microcontinents, were sliced from the Australian northern continental margin in New Guinea, and travelled westwards between 1300 and 2500 km (e.g. Visser & Hermes 1962; Hamilton 1979; Silver & Smith 1983; Pigram *et al.* 1985; Garrard *et al.* 1988). These fragments collided with, and were thrust below, the obducted ophiolite (Hamilton 1979; Silver *et al.* 1983*a*). The timing of this collision is debated, and may have begun in the Middle Miocene or earlier (Wilson & Moss 1999), during the Middle Miocene (Kündig 1956; Sukamto & Simandjuntak 1983; Simandjuntak 1986), Middle Miocene to Pliocene (Garrard *et al.* 1988), or during the Late to latest Miocene (Hamilton 1979; Davies 1990; Longley 1997; Kadarusman *et al.* 2004). These collisions caused local deformation in the east arm of Sulawesi. Additionally, numerous events across Sulawesi and beyond have been attributed to the collisions. These include overthrusting of the Central Sulawesi Metamorphic Belt onto west Sulawesi (Simandjuntak & Barber 1996), magmatism in West Sulawesi and the opening of the Bone Gulf (Bergman *et al.* 1996), inversion in east Kalimantan, including in the Kutai Basin (e.g. van de Weerd & Armin 1992; Cloke *et al.* 1997; Longley 1997; McClay *et al.* 2000). If it is accepted that the collision caused such far-field effects, it could be argued that non-coaxial strain in the Palu metamorphic rocks was, in part, an early result of the collision. Although this model would predict west-directed thrusting in the upper crust, deformation in the middle to lower crust might be absent or coaxial, inconsistent with observed ductile fabrics.

Thermal subsidence in NW Sulawesi continued through the Oligocene and Miocene, with no angular unconformities or major breaks in sedimentation (Calvert & Hall 2003). The absence of Miocene syn-orogenic sediments in the area indicate that non-deformation, or extension was dominant in the west at this time (Calvert & Hall 2003). Conversely, at the western end of the north arm, an angular unconformity above an intensely folded and thrusted Palaeogene succession is synchronous with the 23–11 Ma uplift of the Malino Metamorphic Complex, indicating a major localized early Miocene tectonic event in this area (van Leeuwen *et al.* 2007). This event may also have affected the metamorphic rocks of the neck, and low-angle extensional fabrics described herein from the neck region north of Palu (Fig. 9) may be related to metamorphic core complex development proposed by van Leeuwen *et al.* (2007). However, extension in the Malino Metamorphic Complex must have been directed north or south, that is, normal to its east–west elongated dome. This is inconsistent with kinematic observations in the neck showing broadly west-directed extension.

Neogene intrusive rocks and exhumation

Neogene high potassium calc-alkaline magmatism, starting at *c.* 13–14 Ma, was widespread in western Sulawesi (van Leeuwen 1981; Polvé *et al.* 1997; Harahap *et al.* 1999; Elburg *et al.* 2003). These rocks probably formed in an extensional setting (Yuwono *et al.* 1988; Priadi *et al.* 1994; Polvé *et al.* 1997; Macpherson & Hall 1999; Elburg *et al.* 2003), and were sourced from mid-crustal continental rocks of Australian affinity (Bergman *et al.* 1996; Elburg & Foden 1999; Elburg *et al.* 2003), not from the lower crustal granulites, which show little evidence of anatexis (Helmers *et al.* 1990).

The Neogene magmatism included widespread potassic to ultra-potassic volcanic and volcaniclastic sediments, minor felsic volcanic rocks,

granodiorites and granitic plutons, stocks and veins. No intermediate or mafic bodies have been described (Polvé *et al.* 2001). In west Sulawesi, two potassic suites can be identified (van Leeuwen & Muhardjo 2005): a Miocene high K suite, and a Pliocene potassic calc-alkaline suite. All potassic calc-alkaline granitoids of the Palu area were intruded between 5 and 3.4 Ma, and geochemically similar rhyolites erupted at 1.9 Ma (Polvé *et al.* 1997).

Intrusions into the metamorphic rocks formed a post-regional metamorphism low-pressure overprint in many of the metamorphic complexes in the Palu area, and intrusions and metamorphic rocks were both affected by late low-grade metamorphism (Egeler 1947; Helmers *et al.* 1990). Thin, straight-sided dykes of biotite granite and two mica granite cut across the ductile foliation of metamorphic rocks in the central Palu valley (Fig. 6c), and include xenoliths of the sheared rocks. The dykes show very limited evidence of ductile deformation, and are clearly post-tectonic with respect to the ductile fabric. An aplite dyke dated by Polvé *et al.* (1997) from Kulawi, north of Gimpu in the Palu valley, yielded a whole rock K–Ar age of 3.49 ± 0.10 Ma. This is a minimum age for the top-to-the-north and NE ductile thrusting in the metamorphic rocks nearby (Fig. 9). Granitic intrusions at Tuwa and Gimpu, nearby, yielded a whole rock K–Ar age of 5.08 ± 0.11 Ma and a biotite K–Ar age of 3.95 ± 0.19 Ma respectively (Polvé *et al.* 1997). A minimum age for the top to the SW ductile extension at Tuwa is therefore *c.* 5 Ma (Fig. 9).

The Palu-Koro, Lawanopo and Matano faults of central Sulawesi are considered to form the small circle around a rotation pole about which north and east Sulawesi rotates clockwise (Hamilton 1979; Silver *et al.* 1983*b*; Surmont *et al.* 1994). Based on geological reconstructions, about 250 km of sinistral slip along these structures may have occurred since their initiation at about 5 Ma (Silver *et al.* 1983*b*). Since non-coaxial strain in the Palu metamorphic rocks certainly occurred before *c.* 3.5 Ma, and probably before *c.* 5 Ma, it is unlikely that it is the result of strike-slip movement along the Palu-Koro Fault. The absence of steeply-dipping ductile strike-slip fabrics, or a consistent obliquity in low-angle fabrics, also suggests that the observed ductile strain is not due to the Palu-Koro Fault. The main expression of this structure at the surface is an array of steeply-dipping brittle fault zones, indicating that its mid- or lower-crustal roots have not yet been exhumed.

Thick-skinned folding and thrusting inverted the Palaeogene basins of NW Sulawesi towards the end of the early Pliocene (Calvert & Hall 2003). This was the result of a tectonic event which continued through the Pleistocene, formed

the present-day 3 km high mountains in Sulawesi's central and neck regions, and led to the deposition of widespread, thick syn-orogenic sediments above a regional unconformity (Bergman *et al.* 1996; Hall 2002; Calvert & Hall 2003; Fraser *et al.* 2003). Although Calvert & Hall (2003) show that thrusting involved the basement, crystalline rocks were by that time already at a relatively shallow crustal level (see their Fig. 4), and it is likely that deformation was limited to the upper crust, incompatible with the high temperature ductile fabrics observed in the Palu metamorphic rocks. It is therefore considered that this thrusting event was not responsible for ductile non-coaxial deformation in the metamorphic rocks.

Fission track ages from granitoids in central Sulawesi indicate rapid uplift (200–700 m/Ma) between 7–5 and 2 Ma (Bergman *et al.* 1996; Bellier *et al.* 1998). Unpublished data by van Leeuwen *et al.* suggest cooling of the Palu metamorphic rocks at the same time. Exhumation of the Palu metamorphic rocks by the later stages of metamorphic core complex development, alongside voluminous granite magmatism, may have contributed to the rapid elevation of western and central Sulawesi during the late Neogene (van Leeuwen & Muhardjo 2005).

Conclusions

Metamorphic rocks along the Palu-Koro Fault show abundant evidence of non-coaxial ductile strain. Low-angle extension, directed mostly towards the west, occurred before *c.* 44–33.7 Ma in the Palu Metamorphic Complex of the neck area. This is before the Middle Miocene onset of cooling in the Malino Metamorphic Complex of the north arm (van Leeuwen *et al.* 2007). However, it is possible that it represents early, possibly aborted, west-directed extension in the middle crust as a precursor to this later event. Top-to-the SW to top-to-the SE ductile thrusting and extension in the metamorphic complexes of the northern Palu valley, and top-to-the SW extension and top-to-the NE thrusting in the central Palu valley occurred before 5–3.5 Ma. This may be due to the same event, or may be an older inherited fabric. It is more likely that west-verging thrusting in this area was related to deformation in the over-riding plate of the Cretaceous subduction zone which formed the Central Sulawesi Metamorphic Belt to the east. However, the possibility remains that any or all of the deformation occurred during intracontinental deformation within Gondwana during the Mesozoic, Palaeozoic or Precambrian. What is clear is that none of the observed non-coaxial ductile strain fabrics can be correlated to the Palu-Koro Fault,

and it is likely that its deep crustal roots, if they exist at all, have not yet been exhumed.

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