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The Kyaukkyan Fault

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Abbreviated title: Kyaukkyan Fault

The Kyaukkyan Fault is an active dextral strike-slip structure that passes 510 km N-S across the western Shan Plateau (e.g. Chibber, 1934; Le Dain *et al*. 1984; Wang *et al*. 2014) (Fig. 1a). It lies broadly parallel to and about 100-150 km east of the central Sagaing Fault. Unlike the rather discrete Sagaing Fault, the Kyaukkyan Fault is characterised by a broad array of splaying segments and basins, dominated by the Inle Lake releasing bend and associated extensional fault systems (Fig. 1b). In the north the fault terminates within the complex intersection between the sinistral Kyaukme and Momeik faults, the largely inactive Shan Scarp Fault Zone and the Sagaing Fault. In the south the fault curves to the SW and links with the Mae Ping Fault in Thailand, which itself terminates as it passes east into Cambodia and offshore into the Gulf of Thailand (e.g. Lacassin *et al*. 1997; Morley 2004; Morley *et al*. 2011). Like the Kyaukkyan Fault, several other faults of the western Shan Plateau, such as the Nampun and Taungoo faults, also converge with the western Mae Ping Fault in the region of Papun, indicating that the Mae Ping Fault dissipates or transfers much of the dextral strain of the western Shan Plateau.

Although it has been devoid of large seismic events for over 100 years, the Kyaukkyan Fault lies close to the focus of the 23rd May 1912 *Maymyo* (the former name of Pyin Oo Lwin city) earthquake, initially estimated at magnitude 8 (Gutenberg & Richter 1954); making it the largest instrumentally recorded earthquake in Myanmar and amongst the largest recorded strike-slip earthquakes on earth. More recent re-evaluation of records from 1912 suggest that M_s 7.6-7.7 was more likely (e.g. Abe & Noguchi 1983; Pacheco & Sykes 1992; Wang *et al*. 2009). Regardless of its exact magnitude, the large Maymyo event likely led to the Kyaukkyan Fault being recognised much earlier than other major faults in the region. La Touche (1913) introduced the name *Kyaukkyan Fault* for the northern part of the fault near Nawnghkio. Coggin Brown (1917) proposed that movement along the Kyaukkyan Fault caused the 1912 Maymyo earthquake. Chhibber (1934) described a deep-seated structure related to subsidence near Kyaukkyan village. More recently, related structures further south such as the Pindaya-Kaungpo Fault (Myint Lwin Thein 1973) and the Taunggyi Fault (Bender 1983) have been associated with a wider Kyaukkyan fault zone. Around the centenary of the Maymyo earthquake, Soe Min (2006) and Soe Thura Tun (2007) used satellite imagery to identify the Kyaukkyan Fault as a tectonically important, continuous, active dextral structure passing ~500 km from northern Shan State to Kayah State. More recently, Wang *et al.* (2014) evaluated the fault's seismic potential. However, many important questions remain about the fault's origin, kinematic history, relationship to regional tectonics, earthquake history and seismic behaviour.

This contribution aims to synthesise what is currently known about the Kyaukkyan Fault with new field observations and satellite image interpretation (including Shuttle Radar Topography Mission (SRTM) data) to document the current state of knowledge of this important structure. We anticipate such a synthesis will be of value for future tectonic studies and simulations of seismicity in Myanmar's eastern highlands and beyond.

Geologic setting

Shan Plateau

The Kyaukkyan Fault lies on the western Shan Plateau. The fault is the easternmost of a series of major, broadly N-S trending Cenozoic structural features within Myanmar, including the Indo-Myanmar Ranges, the Central Basin, the Sagaing Fault and the Shan Scarp fault zone (e.g. Hla Maung 1987; Pivnik *et al*. 1998; Bertrand & Rangin 2003). It cuts through the Gondwana-derived Sibumasu terrane, within which long-lived N-S trending structural fabrics have been inherited from Late Paleozoic rifting and Early Mesozoic suturing episodes (e.g. Ridd 1971, 2009; Bunopas 1981; Metcalfe 1984; Metcalfe 2011).

The Shan Plateau has an average elevation of almost 1km, and occupies eastern Myanmar, western Laos and part of NW Thailand (Fig. 1a). Stratigraphically above presumed Precambrian Chaung Magyi metasediments the plateau is largely composed of Paleozoic metamorphic and sedimentary rocks, notably an Upper Cambrian to mid-Devonian sequence dominated by quartzites and carbonates, unconformably overlain by the mid-Permian to mid-Triassic Plateau Limestone (reviewed in Boucot 2002). Upper Triassic to Cretaceous marine clastics, carbonates and continental red beds are deformed and locally preserved above the Plateau Limestone (e.g. Mitchell *et al*. 2012). The western edge of the plateau is marked by the Slate Belt - a sliver of Late Palaeozoic glacial marine pebbly mudstones that comprise the Karen-Tenasserim Unit of Bender (1983) or the Mergui Group of Mitchell *et al*. (2002, 2007), and the Mogok Metamorphic Belt (e.g. Searle & Ba Than Haq 1964; Mitchell *et al*. 2007), whose protolith may be the Cambrian to Devonian succession and Plateau Limestone (Mitchell *et al*. 2012). Mesozoic and Early Cenozoic granitoids are intruded across the Shan Plateau and scarp region (e.g. Barley *et al*. 2003).

Structural evolution of the Shan Plateau

A zone of thrusting, folding and dextral strike-slip, the Shan Scarp fault system lies between the Kyaukkyan Fault and the Sagaing Fault, and marks the main topographic break of the Shan Plateau (e.g. Khin Maung Latt 1991; Bertrand & Rangin 2003) (Fig. 1a). The principal bounding structure is the steeply-dipping Panlaung Fault (e.g. Garson *et al*. 1976; Mitchell *et al*. 2004), which separates distinctive Plateau stratigraphy in the east from a thin strip of Mesozoic sedimentary rocks

(Paunglaung Mawchi Zone of Mitchell *et al*. (2004)) and the linear Slate Belt and Mogok Metamorphic Belt in the west. The Shan Scarp fault system has been considered to form an important terrane boundary (Mitchell *et al*. 2002) and may have formed part of the eastern boundary of the Phuket-Slate Belt Terrane, likely translated to its present position during the Late Cretaceous to Paleocene (Ridd & Watkinson 2013). A major phase of metamorphism in the Mogok Metamorphic Belt, sealed by an unfoliated biotite granite dyke emplaced at 59.5 ± 0.9 Ma (Searle *et al*. 2007) may be associated with terrane emplacement.

The Shan Scarp fault system, the Kyaukkyan Fault and other N-S trending faults of the western Shan Plateau such as the Nampun Fault make up a 250 km wide system of splays and strike-slip duplexes at the western end of the Mae Ping Fault (Morley 2004) (Fig. 1a). The initially sinistral Mae Ping Fault has long been associated with Oligocene-Recent escape tectonics in response to India-Asia collision (e.g. Tapponnier *et al*. 1986; Polachan *et al*. 1991; Huchon *et al*. 1994; Lacassin *et al*. 1997). However, more recent studies suggest that the Mae Ping Fault and others along the western margin of Sibumasu initiated much earlier, during Late Cretaceous to Paleogene transpression along the pre-collision Andean-type margin of Sundaland (e.g. Barley *et al*. 2003; Morley 2004; Morley *et al*. 2007; Searle & Morley 2011; Watkinson *et al*. 2011; Morley 2012; Palin *et al*. 2013). It remains to be demonstrated that the Kyaukkyan Fault was involved with this early deformation.

Monazite Th-Pb ages of 44.5 ± 6.1 to 37.1 ± 1.5 Ma (Mid Eocene) and biotite ^{39}Ar-^{40}Ar plateaux from 33.1 ± 0.4 to 30.6 ± 0.3 Ma (Early Oligocene) from mylonitic gneisses within the Mae Ping Fault in Thailand indicate that sinistral shear occurred after ~37 Ma and was complete by ~30 Ma (Lacassin *et al*. 1997; Palin *et al*. 2013). Late Oligocene to Early Miocene strike-slip basins are associated with subsequent dextral shear along the Mae Ping Fault (Morley *et al*. 2011), which may be coeval with onset of dextral shear along the Kyaukkyan Fault. At the same time, mica ^{39}Ar-^{40}Ar plateau ages of 26.9 ± 0.9 to 15.8 ± 1.1 Ma associated with ductile dextral shear within the Mogok Metamorphic Belt (Bertrand *et al*. 2001; Bertrand & Rangin 2003; Socquet & Pubellier, 2005) may record dextral transpression distributed across structures of the western Shan Plateau including the Kyaukkyan Fault. Dextral shear later became focused further west along the Sagaing Fault during the Mid to Late Miocene (e.g. Socquet & Pubellier 2005; Soe Thura Tun & Watkinson, *this volume*).

Other prominent faults of the Shan Plateau include NE-SW trending structures such as the Kyaukme, Momeik (Nanting), Nam Ma and Mae Chan faults which show clear geomorphic evidence of sinistral shear (e.g. Zhu *et al*. 1994; Wang & Burchfiel 1997; Wang *et al*. 2014) (Fig. 1a). Ongoing sinistral motion is supported by coseismic offsets formed during the 2011Tarlay earthquake (e.g. Soe Thura Tun *et al*. 2014). These NE-SW trending faults curve around the eastern Himalayan syntaxis, and are related to gravitational crustal flow from the eastern Tibet Plateau (e.g. Royden 1996; Niu *et al*. 2005; Copley & McKenzie 2007; Rangin *et al*. 2013). Previously proposed as conjugate to NW-SE trending faults such as the Mae Ping (e.g. Tapponnier *et al*. 1986; Polachan *et al*. 1991), there is no clear kinematic, mechanical or temporal relationship between these sets of fault systems, so a conjugate origin seems unlikely (e.g. Morley *et al*. 2011).

Active tectonics

Despite its position surrounded by major active structures and evidence of Late Quaternary tectonic activity (Wang *et al*. 2014), the Kyaukkyan Fault experiences little significant modern seismicity (Fig. 1b) and there is little geodetic evidence of motion across it (e.g. Vigny *et al*. 2003; Socquet *et al*. 2006). Global Positioning System (GPS) models suggest that at the latitude of Myanmar there is presently 35-36 mm/yr of motion between stable India and Sundaland along an azimuth of 011°-014° (Socquet *et al*. 2006). The Sagaing Fault accommodates 18-20 mm/yr of this motion both at the latitude of Mandalay and further north at Indawgyi Lake (Vigny *et al*. 2003; Socquet *et al*. 2006; Maurin *et al*. 2010). The remainder is accommodated on strike-slip structures within the Indo-Myanmar Ranges and by highly oblique slip within or elastic loading of the Andaman Trench (Le Dain *et al*. 1984; Hla Maung 1987; Pivnik *et al*. 1998; Nielsen *et al*. 2004; Socquet *et al*. 2006; Wang *et al*. 2014), leaving little residual to be accommodated on the Shan Plateau. Nonetheless, at Mandalay the position of maximum modelled shear stress is 17 km east of the Sagaing Fault trace, suggesting the possibility of dextral strain across the Shan Scarp fault system (Vigny *et al*. 2003) or possibly even further east across the Kyaukkyan Fault.

By assuming the Kyaukkyan Fault has been dextral for ~5 Ma, and using their maximum observed geomorphic offset of 5 km, Wang *et al*. (2014) calculated a slip rate of ~1 mm/yr across the fault. This figure is similar to other intraplate faults (e.g. Walker *et al*. 2006; Densmore *et al*. 2007), though the seismic hazard from such slow faults should not be underestimated (Zhang 2013). By assuming complete segment rupture, Wang *et al*. (2014) estimated maximum earthquake magnitudes of 6.8 to 8.4 for the three main segments of the Kyaukkyan Fault.

Data sources

Field observations were made along the Kyaukkyan Fault between the latitudes of Kyaukkyan village and Inle Lake during 2006-2008. Structural and geomorphological data collected during those campaigns forms the basis for this chapter. We also report remote observations made using the 30 m ASTER Global Digital Elevation Model (jspacesystems.or.jp), 90 m Shuttle Radar Topography Mission data (Farr *et al*. 2007), the ESRI World Imagery compilation (www.arcgis.com), which includes 2.5 m SPOT and <1 m DigitalGlobe imagery, and Google Earth imagery. Digital data were processed and integrated using ArcGIS. Geomorphic offsets were measured from these data. Stated offsets are averages of maximum and minimum measurements, and offset uncertainties (±) represent half the measured range.

Tectonic geomorphology – overview

Tectonic geomorphology is the study of landscape and its formative processes resulting from tectonic uplift, subsidence and lateral motion (Bull 2007). It has been used to study the structural evolution of major strike-slip faults (e.g. Wallace 1991) and their earthquake history (Grant & Sieh 1994). Geomorphic features such as drainage offset, linear valleys and ridges, scarps, benches, springs, shutter ridges (Vedder & Wallace 1970) and offset alluvial fans (e.g. Bellier *et al*. 2001) are critical to recognise strike-slip faults and assess their activity. Availability of high quality digital elevation data such as the 90 m Shuttle Radar Topography Mission enable complete, detailed geomorphic studies of otherwise inaccessible structures (e.g. Lin *et al*. 2008; Spencer 2011) such as the Kyaukkyan Fault.

The Kyaukkyan Fault can be divided into three domains on the basis of geomorphic characteristics. The northern domain is marked by narrow linear valleys, flat topped plateaux and mountain ranges formed by folded sediments. Topographic offsets, particularly of river valleys and palaeo-plateau tops, are common. Right-lateral offsets of up to 6.4 ± 1.0 km are preserved, and can be related to neotectonic fault activity. Rectangular shaped plateau tops, deeply incised valleys and preservation of active fault scarps indicate progressive and widespread uplift and localised subsidence.

The central domain is characterised by extension: rhomboidal basins are separated by elongate mountain ranges bounded by normal fault scarps. Right-stepping strike-slip segments along the NNW-trending ranges indicate that this topography represents a wide shear zone comprising nested strike-slip basins subsiding from the elevated Shan Plateau level. For example, the rhomboidal Heho Basin is bounded by a NNE-trending range and a N-S trending normal fault, forming a releasing geometry under dextral shear; similarly, the low-lying Inle Basin and its bounding ranges and normal faults define a releasing geometry under dextral shear along the Kyaukkyan Fault.

The southern domain is characterised by linear basins and a prominent, deep curvilinear fault valley. Tectonically inactive fault valleys following the same trend as the active fault valley, rotation of all structural elements into parallelism with the wide fault zone and the convergence of several other fault systems (e.g. Papun and Taungoo faults, Fig. 1a) indicate that a long-lived strike-slip regime dominates the southern part of this domain where the Kyaukkyan Fault merges, via a series of restraining bends, with the Mae Ping Fault.

Structural observations

By integrating the new structural observations with geomorphic evidence of tectonic activity, historical seismicity and the three geomorphic domains outlined above, the Kyaukkyan Fault can be divided into three structural segments (Fig.1b). From north to south these are: the Kyaukkyan-Indaw segment, the Yaksawk-Inle segment, and the Mobye-Hpansang segment.

Kyaukkyan-Indaw segment

In the north the Kyaukkyan-Indaw segment, equivalent to the Myint Nge segment of Wang *et al*. (2014), is expressed by a linear and relatively narrow surface fault zone, including a spectacular west-facing fault scarp 1.2 km high and prominent river offsets (Fig. 2a). This segment originates amidst splaying NW-SE trending thrust faults in the Yadana Theingi mine area immediately south of Mogok. The restraining splay terminates the Kyaukkyan Fault within the Mogok Metamorphic Belt, in a zone of intensely folded and faulted rocks close to the intersection between the Momeik, Kyaukme, Shan Scarp and Sagaing faults (Fig. 1a). East of the termination splay, and considered to be a normal fault on the basis of its straight, steep scarp, the southwest-facing Goteik Fault shows little evidence of neotectonic activity. To the west, the N-S trending Sedawgyi Fault (La Touche 1913) immediately south of the splay is parallel to the main fault system. From the northern splay to Indaw village in the south, the mainly NNW-SSE trending Kyaukkyan-Indaw segment is about 145 km long, and south of the termination splay it is uniformly narrow, composed of few closely-spaced strands and rarely greater than 1 km wide. The localised strike-slip zone is bounded by a wider system of associated normal and strike-slip faults (e.g. the Goteik Fault) up to 40 km wide.

The Kyaukkyan-Indaw segment cuts mainly through the poorly dated and largely unfossiliferous Permo-Carboniferous Plateau Limestone Group and low-grade metasediments of the presumed Precambrian Chaung Magyi Group (e.g. Mitchell *et al*. 2012; Win Swe 2012; Myanmar Geosciences Society 2014). These rocks have experienced significant folding, faulting (Fig. 3a, b), low grade metamorphism and shearing (Fig. 3c), much of which may have occurred prior to Cenozoic Kyaukkyan Fault activity. Therefore exhumed fault rocks in the region must be analysed with caution. Nonetheless, a number of faults exposed along the Kyaukkyan-Indaw segment display kinematic indicators consistent with the neotectonic regime of NNW-trending dextral shear. All observed structures indicate upper crustal brittle shearing – the absence of mylonitic rocks may simply be a result of insufficient exhumation, or may indicate that the Kyaukkyan Fault is an entirely thin-skinned structure.

In the region of Kyaukkyan village the fault is expressed by a line of low hills (Fig. 3d), where fault breccia is developed in Ordovician limestones, together with slickenfibre lineations showing top-to-the-NW oblique thrusts and folded strata, which may pre-date Cenozoic Kyaukkyan Fault activity. The Mandalay-Lashio railway curves ~2 m to the right where the line orthogonally crosses the Kyaukkyan fault near the eastern foot of the linear hills (Fig. 3e). This curvature was first described by Coggin Brown (1917) and attributed to the 1912 Maymyo earthquake (described below). It remains unclear whether the railway was straight prior to 1912, so the offset must be treated with caution. Between Kyaukkyan village and the deep Myitnge River gorge there are prominent west-facing fault scarps, best developed in Gelaung valley, which is bounded to the east by a 1.2 km high scarp below Nyawnghkio Plateau (Fig. 2a). The scarp preserves a number of geomorphic features characteristic of active strike-slip faults, including drainage consistently offset to the right, beheaded streams, shutter ridges, linear valleys, landslides and rock falls, springs and stacked triangular facets (Fig. 4a).

Significant down-to-the-west extension across the fault bounding the Gelaung valley is indicated by the scarp's 900 m modern topographic relief, and migration of the valley's axial drainage (Paungaw stream) towards the basin-bounding fault (Fig. 4a). To estimate the minimum total dip-slip displacement across the fault a pre-kinematic palaeotopographic datum was assumed to be defined by an enveloping surface bounded by modern topographic highs, after the method of Ufimtsev (1990) and Dawers *et al*. (1993). Projection of this enveloping surface towards an upward projected fault eliminates compromising effects such as footwall crest erosion. Domino-style fault block rotation is assumed in construction of the enveloping surfaces. Three such profiles were drawn across the Gelaung valley and another three across the Kyaukkyan Fault immediately to the south (Fig. 5). Although subject to large uncertainties, the profiles show a maximum of 1.2 ± 0.2 km dip-slip displacement. Profiles 2 to 5 show a crudely elliptical displacement profile across the fault, while profiles 1 and 6, characterised by down-to-the-east extension, show the rapid along-strike changes in geometry characteristic of a transtensional strike-slip fault.

South of Gelaung valley, the deeply incised (and hence laterally confined) Myitnge river is offset 5.3 ± 0.8 km to the right from the apex of a 180° hairpin bend (Fig. 6a). It is interesting to note that restoration of 5.3 ± 0.8 km dextral offset leaves a distinct 10.2 ± 1.3 km offset to the left along a valley immediately west of the modern Kyaukkyan Fault (Fig. 6b), hinting at an earlier phase of sinistral shear. If the antecedent river was entrenched enough to have been offset to the left during an earlier phase of sinistral shear, then any subsequent dextral offset of the same river must represent total fault displacement during the younger dextral phase of activity. The possibility of a pre-dextral phase of sinistral shear is discussed further below. When interpreted as representing lateral fault displacement, both sinistral and dextral offsets rely on the assumption that the antecedent river traversed the plateau in a straight line before becoming incised during a pre-kinematic episode of uplift or base-level fall, and has not avulsed since then.

South of Myitnge River, a gentle restraining bend takes the fault trace through meta-sedimentary rocks of the Chaung Magyi Group. A simple topographic lineament is absent in this area, perhaps because the fault is expressed more by low-angle thrusts within the restraining system. Immediately to the south, Indaw valley is bounded in the west by a NNW-trending linear fault scarp that rises up to 500 m above the valley floor; despite this the valley's drainage exits westwards across the scarp via the deeply incised Zawgyi River valley (Fig. 2a). Along Zawgyi River the Kyaukkyan Fault is marked by faulted brecciated limestone, polished shear planes and sub-horizontal slickenside lineations showing both dextral and sinistral shear senses (Fig. 3 f). The Zawgyi River is offset to the right by 7.2 ± 0.5 km along the basin-bounding fault (Fig. 6c). If this offset is taken as recording right-lateral fault displacement, it is the largest such offset observed along the Kyaukkyan Fault. However, development and subsidence of the prominent central depocentre in the Indaw Basin (now occupied by Zawgyi Reservoir) may also have caused southward migration of the river upstream of the Kyaukkyan Fault, distorting the apparent fault displacement and making the offset uncertainty difficult to quantify.

The Kyaukkyan-Indaw segment is famously considered responsible for the 1912 Maymyo earthquake, largely based on the seismic intensity map and interpretations of Coggin Brown (1917), which placed the epicentre close to Kyaukkyan village. Isoseismals of the Rossi-Forel scale peaked at intensity XI in a narrow zone along the Kyaukkyan Fault, while intensity VIII extended from Yamethin almost to Bhamo, and extended west to Mandalay and Sagaing. Based on the likely earthquake size (M 8.0 (Gutenberg & Richter 1954); or M_s 7.6-7.7 (e.g. Abe & Noguchi 1983; Pacheco & Sykes 1992; Wang *et al*. 2009)), the fresh geomorphic appearance of the fault segment and the isoseismals of Coggin Brown (1917), it is likely that the entire Kyaukkyan-Indaw segment ruptured during the 1912 Maymyo earthquake (Wang *et al.* 2009, 2014).

Seismicity records (Fig. 1b) show more recent earthquakes of M_w 3.4 to 4.9 distributed around the periphery of the shear zone and a M_w 5-5.9 event close to the Kyaukkyan Fault itself (NEIC and IRIS catalogues 1972-2010). Historical records from Myinpyu Pagoda (10 km south of Kyaukkyan village) describe collapse of the top part of the pagoda during the 1912 earthquake. The pagoda was restored in 1953, but in July 1959 it was damaged again and there was a large landslide west of the pagoda's hill as a result of another earthquake. Oral accounts from local people suggest 3 to 10 small earthquakes each year are felt in this area.

Yaksawk-Inle Segment

About 10 km south of Zawgyi reservoir the clearly defined linear trace of the Kyaukkyan Fault is lost as the fault enters the broad Yaksawk Basin. This transition defines the boundary between the Kyaukkyan-Indaw and Yaksawk-Inle segments (Figs. 1b & 2b). The Yaksawk-Inle segment, equivalent to the Taunggyi segment of Wang *et al*. (2014), continues 135 km south to the southern termination of the Inle basin at about 20.25° N. It is characterised by a broad transtensional system of releasing bends and steps that forms a rhomboidal zone of subsidence and linear ranges up to 55 km wide (Fig. 2b), bounded in the west by the Pindaya normal fault and in the east by the Taunggyi listric normal fault. Observed bedrock faults within the segment are variably orientated, dominantly strike-slip or normal, locally overprinting older fault fabrics and folded bedding (Fig. 7a, b, c), supporting a long-lived strike-slip tectonic setting. Fault systems range from dispersed arrays of en-echelon tension gashes (Fig. 7d) to thick zones of foliated gouge and regions of bedding transposition into parallelism with major fault strands (Fig. 7e).

The segment originates where the Kyaukkyan Fault branches into three splays at the northern tip of the Yaksawk basin. The eastern splay trends NNW and is the focus of considerable instrumental seismicity (Fig. 1a). The western splay trends NNE, parallel to the major basin-bounding Pindaya east-facing oblique normal fault in the west. In this region Ordovician limestones contain reactivated shear planes showing both normal and strike-slip lineations (Fig. 7c) and thrust faults reactivated as dextral-normal faults. The central splay is the through-going strike-slip Kyaukkyan Fault. Although its surface trace forms a more discontinuous, wider and less clearly expressed fault zone than the Kyaukkyan-Indaw segment, the strike-slip element of the Yaksawk-Inle segment clearly follows a more pronounced N-S trend, consistent with its overall releasing geometry. Steeply dipping fault planes recording sub-horizontal lineations with evidence of dextral (Fig. 7f) and sinistral (Fig. 7g) strike-slip are common. The fault passes through young sedimentary basins and so some portions are obscured by alluvium and lacustrine deposits. Elsewhere it can be readily identified by morphologic features such as small pressure ridges, sag ponds formed in alluvial soil, sub-recent fault scarps, terraces and offset stream channels. Brick-cored embankments representing the remains of the ancient Pawritha (Kawthanbi) city wall between Shwenyaung and Nyaungshwe appear to be offset to the right by 12.2 ± 1.2 m, and vertically offset ~2 m down-to-the-east (Fig. 8a-c). The line of offset is marked by darkly mottled surface deposits and localisation of the Nam Latt stream, supporting fault activity in the surficial deposits.

In the Taunggyi area there is pronounced partitioning between the main strike-slip Kyaukkyan Fault strand and a series of structurally controlled terraces that climb vertically 500 m from the valley floor to the plateau top at Taunggyi city, via an intermediate terrace at Ayethayar. Field observations suggest a series of down-to-the-west synthetic listric normal faults plus antithetic structures. Outcrop-scale listric faults and bedding-parallel extension within limestones are exposed within the Taunggyi scarp (Fig. 7h). The west-dipping faults may root into the Kyaukkyan Fault below the basin, forming an asymmetric negative flower structure.

The rhomboidal zone of transtensional subsidence defined by the Yaksawk-Inle segment is strongly asymmetric overall, with the through-going Kyaukkyan Fault consistently close to or lying along its eastern margin (Fig. 2b), where there are also strong geomorphic signals of neotectonic activity. The western margin is dominated by a series of east-dipping normal faults and nested pull-apart basins such as the Heho basin, separated by linear mountain ranges (Fig. 1b). The outer-most normal fault is the down-to-the-ESE Pindaya Fault, expressed by an eroded scarp marked by well developed triangular facets.

The Pindaya scarp is flanked by a wide alluvial fan-bajada complex, obscuring the true throw of the fault. To estimate throw along the fault a similar method was applied as described above for the Gelaung valley, after Ufimtsev (1990) and Dawers *et al*. (1993). In the Pindaya Fault case, topography of the pre-kinematic hangingwall blocks was also projected below the bajada to an intersection with a planar fault projected to depth, to account for thicker sedimentation against the Pindaya scarp than against the Gelaung scarp (Fig. 9). Maximum apparent throw along the Pindaya Fault determined by this method was 1.2 ± 0.22 km. Displacement along the fault length is broadly symmetric about a maximum at its midpoint declining to zero at its tips (Fig. 9) as observed in other empirical studies (e.g. Dawers *et al*. 1993). Maximum normal displacement is also similar to a maximum value calculated in the same way for the Taunggyi Fault on the east side of the basin, although the listric nature of that fault reduces the reliability of the method.

South of Taunggyi and along the western shore of Inle Lake, a strand of the Taunggyi Fault develops a prominent linear scarp marked by spectacular triangular facets as it approaches the southern closure of the Inle pull-apart system (Fig. 7i). Alluvial fans crossing southern fault strands are offset to the right from their source streams (Fig. 4b), indicating active strike-slip tectonics. At the southern end of Inle Lake the western, eastern and any residual cross-basin fault systems converge into a narrow fault zone that marks the southern boundary of the Yaksawk-Inle segment (Figs. 1b & 2b).

The USGS earthquake catalogue positions the May 1912 earthquake on the Yaksawk-Inle segment; however, as described above, contemporary accounts (e.g. Coggin Brown 1917) and geomorphic evidence suggest that only the Kyaukkyan-Indaw segment ruptured (e.g. Wang *et al.* 2009), and that the major faults of the Yaksawk-Inle segment, though likely active in the Late Holocene, do not display evidence of very recent activity. Oral reports from local people recount large ground cracks forming during the 1912 earthquake west of Inyar village, on the west shore of Inle Lake, though it is conceivable that these were related to landslips. A number of smaller instrumental events (M_w 4-5.9) from the NEIC and IRIS earthquake catalogues are located throughout the pull-apart system (Fig. 1b), but these are unlikely to have been surface-rupturing.

Mobye-Hpansang segment

The Mobye-Hpansang segment, equivalent to the Salween segment of Wang *et al.* (2014), passes 220 km south from the southern end of Inle Lake to south of Hpansang, where it is crossed by the Thanlwin River several times and links with the Mae Ping Fault along the Myanmar/Thai border (Fig. 1a, b). Much of the Mobye-Hpansang segment lies within inaccessible terrain and in parts of Kayah State where the security situation remains unstable, so observations of this segment come solely from satellite image interpretation. The segment has a distinctive kinked geometry (Fig. 2c). A NNE-SSW-trending fault system in the north passes through the broad rhomboidal basin containing Mobye reservoir. A complex restraining bend marks a more pronounced change in trend to a long N-S section in the south. Features such as triangular facets, offset streams and alluvial fans (Fig. 4c), asymmetric basins and drainage reversals indicate that this segment is tectonically active. Several shallow focus earthquakes have occurred along the fault trace, including three of Mw>5 at the restraining bend (NEIC 1972-2010) (Fig. 1b).

In the Mobye basin the fault is expressed by hot springs, linear ridges and streams and a series of small modern and dry linear lakes, likely sag ponds. A number of prominent low ridges occur within and adjacent to Mobye reservoir, parallel to the trace of the Kyaukkyan Fault. Apparent dextral offset of a linear ridge by 4.6 ± 0.2 km (Fig. 10a) supports dextral slip along the cross-basin fault strand, but it is also possible that the two ridges are separate elements of a pop-up system and not a bisected single uplift. Further south at Hpansang the Thanlwin River shows a possible 6.4 ± 1.0 km dextral offset where the river passes west into the Kyaukkyan Fault valley at the intersection between the Kyaukkyan and Nampun faults (Fig. 10b). The river either side of the bend is deeply incised and laterally constrained, though in the area of the bend itself there is the possibility that the river may have previously followed a more southerly route before a forced avulsion.

Southern parts of the Mobye-Hpansang segment converge with the dextral Nampun and Shan Scarp faults south of Hpansang to define a series of branching splays, part of what Morley (2004) termed a nested strike-slip duplex. Close to its convergence with the Taungoo Fault, the Mobye-Hpansang segment occupies a 26 km long narrow, linear and steep-sided V-shaped valley flanked on its eastern side by triangular facets and wine glass canyons, indicating active down-to-the-west normal faulting in addition to strike-slip. Indications of tectonic activity on adjacent fault strands and distributed seismicity indicates that deformation along this segment is accommodated along a shear zone approximately 11 km wide.

Discussion

Based on its prominent geologic and geomorphic expression, the Kyaukkyan Fault is clearly a long-lived structure. Modern seismicity and the notable 1912 Maymyo earthquake show that it is still active, and represents a significant seismic hazard to Myanmar and northern Thailand despite its apparently small geodetic slip rate. In order to understand the seismic hazard posed by the Kyaukkyan Fault it is necessary to place bounds on its age of onset, finite displacement and Late Neogene slip rate.

Fault displacement and rate of displacement

Finite displacement across the Kyaukkyan Fault is poorly known – there are few demonstrably offset pre-kinematic markers, though the contact between Ordovician and Permo-Triassic carbonates has been mapped with an ~8 km right-lateral offset across the fault near Pyin Oo Lwin (Myanmar Geosciences Society, 2014). Along strike to the south, the Mae Ping Fault is known to have a pre-

Neogene sinistral displacement of at least 40-50 km, based on boudinage restoration (Lacassin *et al*. 1993), and probably up to 150-300 km, based on offset magmatic-metamorphic belts (Tapponnier *et al*. 1986; Lacassin *et al*. 1997). Its subsequent dextral offset is as poorly known as that of the Kyaukkyan Fault, and has been reported as 'a few kilometres' (Morley *et al*. 2007) up to a few tens of kilometres (Morley *et al*. 2011) based on opening of the Mae Sot dextral pull-apart basin (Fig. 1a). To what extent post-Late Oligocene dextral displacements along the Mae Ping Fault can be extrapolated to the Kyaukkyan fault is unclear.

Dextral geomorphic offsets are well developed along the Kyaukkyan Fault. The largest is the possible 7.2 ± 0.5 km offset of the Zawgyi River along the Kyaukkyan-Indaw segment, although as discussed above, the dip-slip component of this segment may have exaggerated any tectonic displacement. More robust offsets of rivers that are laterally constrained by their incised valleys include the Myitnge River (5.3 ± 0.8 km) and Thanlwin River (6.4 ± 1.0 km). Since the Myitnge River preserves an apparent older sinistral offset, it can be assumed that its incised valley is antecedent to onset of dextral shear – it is effectively a pre-kinematic marker with respect to the dextral phase and thus records the full dextral slip offset. Fault-parallel topographic ridges within the Mobye reservoir display a similar offset (4.6 ± 0.2 km), which may be a genuine fault displacement of an originally wide ridge, or may simply represent separate elements of a pop-up system. Numerous smaller stream and fan offsets support continued right-lateral faulting into the Holocene. Minimum apparent dip-slip across the Kyaukkyan fault is ~ 1.2 km, measured in the Gelaung valley, Pindaya and Taunggyi normal fault scarps and separately also in Nampun valley.

As yet no displaced natural features along the Kyaukkyan Fault have been dated to determine a Late Neogene slip rate. However, the ancient city wall of Pawritha (Kawthanbi), which straddles the fault between Swenyaung and Naungshwe (Fig. 8) and is known from historical records to be 800-1200 years old, has been offset by 12.2 ± 1.8 m, yielding a range of modern slip rates from 9-18 mm/yr. These are surprisingly high given the very small geodetic rate predicted from GPS measurements (e.g. Socquet *et al*. 2006). If the 1912 earthquake is typical, it may be that the Kyaukkyan Fault slips in infrequent large earthquakes, such that an 800-1200 year average is not representative of the long-term slip rate.

An Early Cenozoic phase of sinistral shear

A key offset marker along the Kyaukkyan Fault, Myitnge River, has a hairpin geometry that could suggest 10.2 ± 1.3 km of sinistral offset prior to 5.3 ± 0.8 km of dextral offset across the active fault trace (Fig. 6a, b). This pattern is similar to examples of hairpin bends identified from the NE-SW trending faults of the Shan Plateau, including the remarkable 12 ± 2 km sinistral offset and ~30 km residual dextral offset of the Mekong River across the Nam Ma Fault along the Lao-Myanmar border (Lacassin *et al*. 1998) (Fig. 1a). Many other major strike-slip faults of the Shan Plateau and elsewhere in Indochina are considered to have experienced such a late shear sense reversal, generally dextral to sinistral for NE-SW trending faults like the Nam Ma, Momeik (Nanting), Dien Bien Phu, Khlong Marui and Ranong, and sinistral to dextral for NW-SE trending faults like the Mae Ping, Three Pagodas and Ailao Shan-Red River (e.g. Le Dain *et al*. 1984; Tapponnier *et al*. 1986; Polachan *et al*. 1991; Huchon *et al*. 1994). It therefore seems reasonable to propose an early sinistral history for the broadly NNW-trending Kyaukkyan Fault, along strike from the Mae Ping, as well.

In many of the fault examples outlined above, the early phase of shear is associated with large displacements, up to tens to hundreds of kilometres for the Mae Ping and Ailao Shan-Red River faults, and is recorded by exhumed metamorphic rocks that are either developed synchronously with or are overprinted by ductile mylonitic fabrics (e.g. Tapponnier *et al*. 1990; Lacassin *et al*. 1993;

Leloup *et al*. 2001; Akciz *et al*. 2008; Watkinson *et al*. 2008; Morley *et al*. 2011). These rocks provide excellent opportunities to unravel the earlier shear history, and have facilitated attempts to place absolute constraints on the timing of shear sense reversal (e.g. Lacassin *et al*. 1997; Zhang & Schärer 1999; Searle 2006; Morley *et al*. 2007; Watkinson *et al*. 2011; Palin *et al*. 2013).

Exhumed mylonitic rocks recording an earlier kinematic history have not been identified along the Kyaukkyan Fault. This may indicate either that the fault is a thin-skinned feature that does not penetrate to mid/lower-crustal depths, or that vertical motions have been insufficient to exhume rocks from such levels. However, 250 km along strike from the southern Kyaukkyan Fault, gneisses exposed within and adjacent to the Mae Ping Fault record a long history of deformation. The Umphang gneiss adjacent to the Mae Ping Fault-bounded Chainat duplex in NW Thailand (Fig. 1a) was exhumed between ~50-40 Ma, and cooling ages appear to increase towards the west, hinting at an Early Paleogene phase of shearing (Morley *et al*. 2007). The Thabsila gneisses within the parallel Three Pagodas Fault, to the south of the Mae Ping Fault, have yielded zircon U-Pb ages of 57 ± 1 to 51 ± 7 Ma (Nantasin *et al*. 2012). Further south, zircon rim U-Pb ages from deformed granitoids within the Ranong Fault (80.5 ± 0.6 to 47.6 ± 0.8 Ma) and Khlong Marui Fault (55 ± 3 to 45.6 ± 0.7 Ma) also support Early Paleogene and even older metamorphism and shearing (Watkinson *et al*. 2011; Kanjanapayont *et al*. 2012). All these fault systems probably formed part of a pre-escape tectonics Paleogene transpressional/metamorphic belt along the western margin of Sundaland (e.g. Morley 2004, 2012; Watkinson *et al*. 2008; Searle & Morley 2011; Palin *et al*. 2013) that could have included a proto-Kyaukkyan Fault.

The Lansang gneisses (Fig. 1a) include a 5-6 km wide belt of metamorphic and igneous rocks overprinted by well developed sinistral mylonitic fabrics within the Mae Ping fault zone (e.g. Lacassin *et al*. 1993; Morley *et al*. 2011). Monazite Th-Pb ages of 44.5 ± 6.1 to 37.1 ± 1.5 Ma from protolith gneisses indicate Mid Eocene metamorphism (Palin *et al*. 2013). Sub-horizontal stretching lineations and evidence of simple shear under greenschist facies conditions (e.g. Lacassin *et al*. 1993) is commonly attributed to northward-migrating escape tectonics related to India-Asia collision, coinciding with 33.1 ± 0.4 to 30.6 ± 0.3 Ma (Early Oligocene) mica ^{39}Ar-^{40}Ar plateau ages (e.g. Lacassin *et al*. 1997). Slightly older mica ^{39}Ar-^{40}Ar and K-Ar cooling ages of 36 ± 1 to 33.4 ± 0.4 Ma have been determined from the Three Pagodas Fault (Lacassin *et al*. 1997), and still older mica ^{39}Ar-^{40}Ar ages of 47.6 ± 0.8 to 40.33 ± 0.47 Ma from the Ranong Fault and Khlong Marui Fault further south (Watkinson *et al*. 2011).

Peak high temperature metamorphism from ~37.4 to ~29.3 Ma (Late Eocene-Early Oligocene) in the Mogok Metamorphic Belt near Mandalay (Searle *et al*. 2007) may record the northwesternmost effects of the same phase of escape tectonics-driven deformation (Morley 2004; Searle & Morley 2011), where sinistral shear along the Ailao Shan-Red River/Chong Shan/Mae Ping/Three Pagodas fault systems in the east became transferred into the broad N-S trending belt of dextral shear along the Mogok trend (Fig. 11a. Also see discussion in Soe Thura Tun & Watkinson, *this volume*, and Morley & Searle *In Press*). It remains unclear whether N-S faults in the position of the Kyaukkyan Fault, near the intersection of these Eo-Oligocene sinistral and dextral domains, would have experienced sinistral shear at all.

Late Cenozoic dextral shear

Unlike any poorly preserved sinistral offset, there is abundant geologic and geomorphic evidence for Late Cenozoic dextral shear along the Kyaukkyan Fault (e.g. Fig. 4), but there is no direct timing of its onset. However, three regional events form the basis of a first-pass estimate. Oligocene to Mid Miocene ductile dextral shear within the Mogok Metamorphic Belt gneisses along the western margin of the Shan Plateau is recorded by ^{39}Ar-^{40}Ar cooling ages of 26.9 ± 0.9 to 15.8 ± 1.1 Ma (Bertrand *et al*. 2001; Bertrand & Rangin 2003; Socquet & Pubellier, 2005). The Kyaukkyan Fault, parallel to the Mogok belt, may have been a thin-skin expression of this event on the Shan Plateau. Further east, the timing of Mae Ping Fault slip sense reversal and dextral shear onset may be constrained by rapid cooling of the Bhumibol Dam metamorphics at ~23.5 Ma (latest Oligocene) adjacent to normal faults north of the Lansang Gneiss in Thailand (Lacassin *et al*. 1997) (Fig. 11b).

Finally, a reduction in dextral activity further east in Thailand (Morley 2004; Morley *et al.* 2011) led to relaxation-driven metamorphic core complex exhumation in northern Thailand during the Early-Mid-Miocene and intermittent dextral slip along the Mae Ping Fault (Smith *et al*. 2007; Searle & Morley 2011). This westward migration of a wave of dextral transpression that was initially distributed across the Shan Plateau, but ultimately became focused further west along the Sagaing Fault during the Mid to Late Miocene (e.g. Socquet & Pubellier 2005; Soe Thura Tun & Watkinson, *this volume*) presumably involved the Kyaukkyan Fault. These regional events show that there was widespread dextral shear along structures parallel to and related to the Kyaukkyan Fault starting from ~26.9 Ma (Late Oligocene) to ~15.8 Ma (Mid Miocene). Dextral shear became localised along the onshore Sagaing Fault during the Mid to Late Miocene (e.g. Bertrand & Rangin 2003, Soe Thura Tun & Watkinson *this volume*), intermittent dextral shear continued along the Mae Ping Fault (e.g. Smith *et al*. 2007; Morley *et al*. 2011) and dextral shear apparently clearly continues along the Kyaukkyan Fault to the present day (Fig. 11c).

River incision and kinematic evolution of the Kyaukkyan Fault

Although a correlation between the Cenozoic kinematics of the Kyaukkyan Fault and the more well-studied Mae Ping Fault along strike is appealing, as discussed above there remains little evidence or necessity for Cenozoic sinistral shear along N-S faults in the western Shan Plateau. The only evidence of sinistral shear along the Kyaukkyan Fault is localised kinematic indicators on minor faults within Paleozoic carbonates, and the apparent 10.2 ± 1.3 km sinistral offset preserved when dextral offset across the deeply incised Myitnge River is restored.

When interpreted as preserved sinistral fault displacement, the Myitnge River residual offset relies on the assumption that a straight antecedent river became incised before or during sinistral shear and before dextral shear. Both the Myitnge and similarly offset Thanlwin rivers occupy gorges characterised by spectacularly steep sides and narrow floors, typically indicative of geomorphic youthfulness (e.g. Bull & McFadden 1977). Quantifying this youthfulness is complicated by poorly constrained controlling parameters during the Neogene such as tectonic uplift, relative base level changes, lithology, sediment load and local climate (e.g. Clauzon 1978; Stock & Montgomery 1999; Garcia-Castellanos *et al*. 2003). Further north, the SE Tibetan Plateau, like the Shan Plateau, is deeply incised by rivers such as the upper Thanlwin, Yangtze and Yalong, all of which occupy similarly steep-sided canyons cut into a plateau uplifted during the Late Miocene (~13 Ma to ~9 Ma) (Clark & Royden 2000; Clark *et al*. 2005). Similar geomorphology in the Myitnge River valley could therefore have been maintained for several million years, perhaps long enough to record all or part of the inferred pre-Late Oligocene to Mid Miocene sinistral shear phase.

However, if the post-sinistral phase dextral offset of 5.3 ± 0.8 km described above is taken as finite dextral displacement, then the slip rate since the Oligocene/Mid Miocene becomes extremely small, less than the 1 mm/yr proposed by Wang *et al*. (2014), and far less than the 9-18 mm/yr indicated by the offset Pawritha city wall. There are four possibilities to explain this disparity:

1) The Kyaukkyan Fault has indeed slipped at <<1 mm/yr since the Late Oligocene/Mid Miocene, and the Pawritha wall offset is false or due to several anomalously large Late Holocene coseismic offsets;

2) The fault has slipped at a higher rate than <<1 mm/yr since the Late Oligocene/Mid Miocene, but it has experienced geologically significant periods of inactivity during its Neogene dextral shear phase, like the Mae Ping Fault;

3) The dextral fault is much younger than the dextral Mae Ping Fault, and younger than regional correlations appear to indicate – it became dextral since the end of the Miocene, and has slipped at ~1 mm/yr since then. The 10.2 ± 1.3 km sinistral Myitnge River offset was preserved during the entire Miocene period of fault inactivity;

4) River offsets of 5.3 ± 0.8 km, 6.4 ± 1.0 km and 7.2 ± 0.5 km are not finite dextral offsets –the rivers were incised during continued dextral shear. The total Neogene dextral displacement is larger – implying that the apparent earlier sinistral offset preserved by the Myitnge River is false. Late Holocene slip rates could be as high as 9-18 mm/yr.

Determining which of these models is correct will require further structural study of the Kyaukkyan Fault, and robust dating of deformation, uplift and river incision events.

Concluding remarks

The Early Cenozoic history of the Kyaukkyan Fault remains poorly constrained. However, given the fault's position, considerable length, width and connection to important structures such as the Mae Ping Fault, it is likely that it can be counted amongst other structures involved in the Early Paleogene transpressional deformation event proposed for western Sibumasu (e.g. (Morley 2004, 2012; Morley *et al*. 2007; Watkinson *et al*. 2011; Palin *et al*. 2013) as well as subsequent Late Paleogene escape tectonics (e.g. Tapponnier *et al*. 1986; Lacassin *et al*. 1997). Whether this early kinematic history involved sinistral shear along the Kyaukkyan Fault, and whether it is preserved by river offsets cannot yet be confirmed.

Regional correlations support a Late Oligocene to Mid Miocene dextral shear onset, at about the same time as the Mae Ping Fault and Mogok Metamorphic Belt experienced dextral shear, and overlapping with post-dextral relaxation and metamorphic core complex exhumation in northern Thailand (e.g. Lacassin *et al*. 1997; Bertrand *et al*. 2001; Bertrand & Rangin 2003; Socquet & Pubellier, 2005. Searle & Morley 2011). Geomorphic offsets show that dextral shear likely continues to the present day.

Important questions about Late Neogene/Holocene slip rates follow from the discussion of offset markers such as the Myitnge River and the ancient city wall of Pawritha (Kawthanbi). If the fault slips at the lower rate (<<1 mm/yr) indicated if the Myitnge River preserves sinistral shear, then only << 10 cm of displacement has accumulated since the 1912 Maymyo earthquake, and the seismic hazard must be low. If the city wall offset is representative of the Late Holocene slip rate (9-18 mm/yr) then 0.94-1.87 m of displacement has already been accumulated across the fault, having the potential to yield a highly damaging M6.6-M6.9 earthquake according to the empirical relationships of Wells & Coppersmith (1994).

This study shows that there are three clearly defined geomorphic domains along the Kyaukkyan Fault, but that structural domains – i.e. segments bounded by distinct structural discontinuities, are less clear. The more youthful geomorphic expression of the northern domain has previously been related to more recent tectonic activity along the Kyaukkyan-Indaw segment compared to the other segments (e.g. Wang *et al*. 2014), supported by the apparent location of the 1912 earthquake near this segment. Additionally the basin-bounding faults of the Inle and associated basins in the central domain lack evidence of recent rupture and are in places rather poorly defined, suggesting reduced activity of the

Yaksawk-Inle segment. However, we caution against this conclusion, in the light of evidence that through-going fault strands underlie the central part of the basin. Analogue models and natural examples show that transtensional basins such as the Inle Basin commonly develop a cross-basin fault as they evolve, and sidewall faults can become abandoned (e.g. Mann *et al*. 1995, Mann 2007; Wu *et al*. 2009). It is likely that, although the segmented basin bounding faults are presently becoming inactive, the through-going fault may be highly active, but because it experiences pure strike-slip, there is little coseismic vertical offset and it is rapidly buried following rupture.

Therefore, factors to consider in any seismic hazard assessment of the Kyaukkyan Fault include: the great uncertainty in slip rate and interseismic strain accumulation; poorly consolidated and water saturated basin fill; the presence of a linear, shallow buried cross-basin fault system which may be continuous with fault segments to the north and south; the long time elapsed since a previous rupture south of the 1912 event; and intensive human development within the Inle Basin. The booming towns of Shwenyaung and Nyaungshwe lie squarely on the projected trace of this cross basin fault system, and are especially vulnerable. Paleoseismic investigations along this section are essential to identify the timing and size of historical seismicity.

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Figure captions

Fig. 1: Kyaukkyan Fault location and overview. a) Tectonic setting of the Kyaukkyan Fault. Modified after Morley *et al.* (2011); Soe Thura Tun & Maung Thein (2012); Wang *et al.* (2014); Morley & Alvey (2015) and Soe Thura Tun & Watkinson (*this volume*). b) Main faults making up the Kyaukkyan Fault. Solid line: confident interpretation; dashed line: uncertain interpretation; dotted line: other related faults. Earthquake locations from the NEIC and IRIS catalogues 1972-2010. Map location shown in Fig. 1a.

Fig. 2: Detail of Kyaukkyan Fault structural segments. a) Kyaukkyan-Indaw segment. b) Yakswak-Inle segment. c) Mobye-Hpansang segment. GF: Goteik Fault; SF: Sedawgyi Fault; TF: Taunggyi Fault. Map locations shown in Fig. 1b.

Fig. 3: Field observations of the Kyaukkyan-Indaw segment. a) Bedding and tectonic foliation measured in rocks exposed along the fault zone. Great circles, lower hemisphere equal area projection. b) Measured fault planes (great circles) and slickenside lineations (red: sinistral; green: dextral; black: unknown). Lower hemisphere equal area projection. c) Weakly metamorphosed sheared Plateau Limestone (?) near Yaksawk, showing prominent north-dipping foliation. d) View of linear uplifted ridge along the Kyaukkyan Fault. Inferred fault trace marked by break of slope (white arrows). View to SW from Kyaukkyan village. e) View to ENE along the Mandalay-Lashio railway just west of Kyaukkyan village, showing prominent dextral bend where the line crosses the Kyaukkyan Fault. f) Brecciated dolomite of the Plateau Limestone Group near Zawgyi Reservoir, showing a steeply east-dipping fault plane, sub-horizontal slickenside lineations and dextral steps. Photo locations shown in Fig. 2a.

Fig. 4: 3-D perspective Google Earth images showing geomorphic characteristics along the Kyaukkyan Fault. a) Tectonic geomorphology of the Gelaung Valley, view to SE. b) Two-stage alluvial fan offset along from its source valley along the Yaksawk-Inle segment. View to W. c) Triangular facets, drainage and alluvial fan offset along the Mobye-Hpansang segment. View to E. View locations shown in Fig. 2a.

Fig. 5: Topographic profiles across the Kyaukkyan-Indaw segment, showing variation in vertical offset. Profile locations shown in inset map. Green lines show upper (dotted) and lower (dashed) limits on inferred palaeotopography. Graph shows total offsets down to west (positive) and east (negative) plotted along the fault's length. Map location shown in Fig. 2b.

Fig. 6: Major river offsets along the Kyaukkyan-Indaw segment. a) Myitnge River dextral offset of 5.3 ± 0.8 km. b) Apparent residual sinistral offset of 10.2 ± 1.3 km after restoration of 5.3 km along the main fault strand. c) Zawgyi River offset of 7.2 ± 0.5 km, highlighting the potential impact of low ground to the east of the fault on this measurement. Base maps are 90 m Shuttle Radar Topography Mission data. Map locations shown in Fig. 2a.

Fig. 7: Field observations of the Yaksawk-Inle segment. a) Bedding and tectonic foliation measured in rocks exposed along the fault zone. Great circles, lower hemisphere equal area projection. b) Measured fault planes (great circles) and slickenside lineations (red: sinistral; green: dextral; blue: normal; black: unknown). Lower hemisphere equal area projection. c) Fault plane showing both normal and strike-slip slickenside lineations, in argillaceous limestone of the Wunbye Fm. near

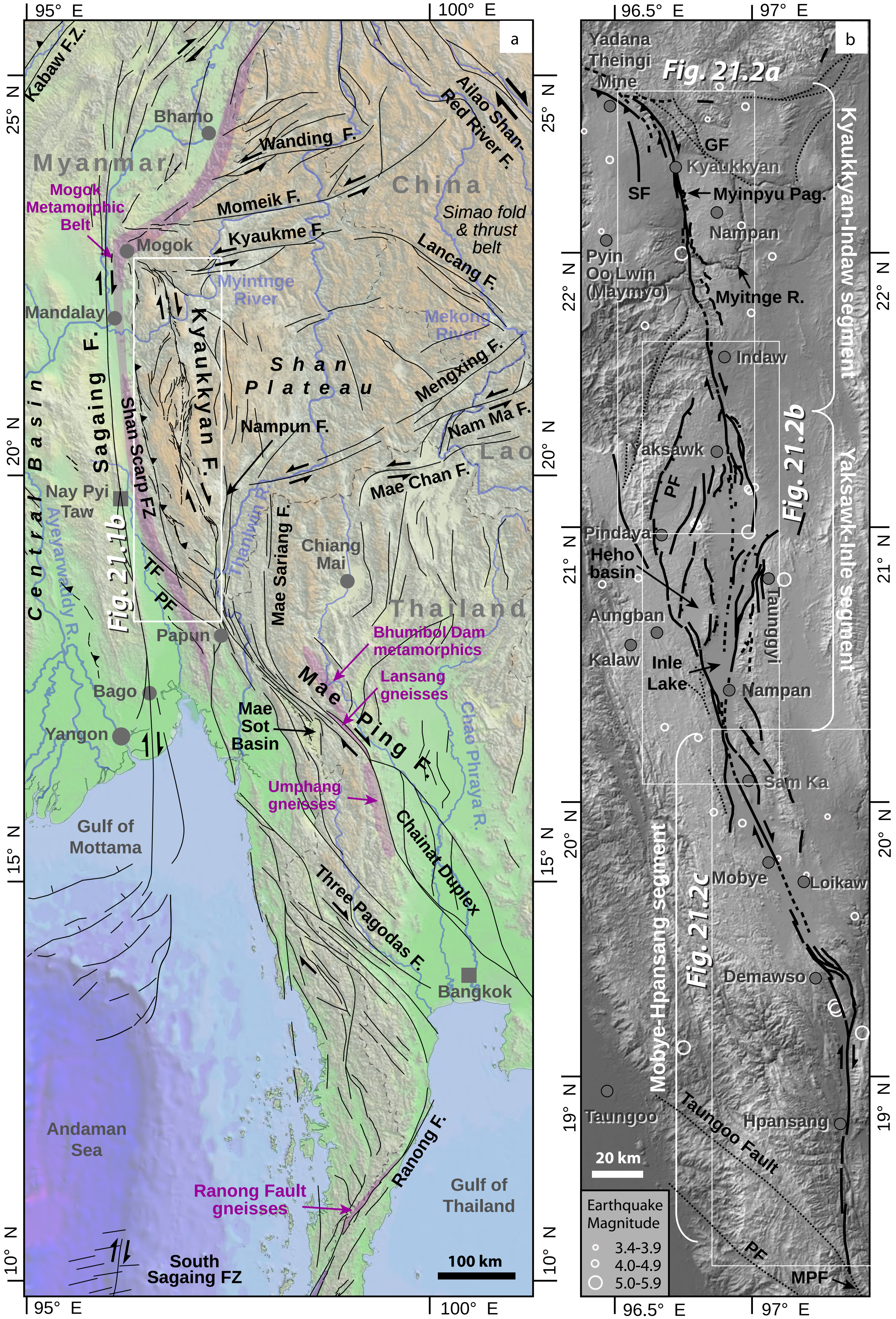
Yaksawk. d) Calcite-filled veins, including en-echelon tension gashes in Plateau Limestone, near Heho. e) Bedding transposition into parallelism with major fault. Linwe Fm., near Taunggyi. f) Dextral fault plane in argillaceous limestone of the Wunbye Fm. near Yaksawk. g) Calcite slickenfibre-covered sinistral fault plane in argillaceous limestone of the Wunbye Fm. near Yaksawk. h) NW-dipping listric normal faults within the Taunggyi fault zone exposed on the scarp west of Taunggyi city. i) Triangular facets developed along the prominent section of the main Kyaukkyan Fault strand where it marks the western shore of Inle Lake. White arrows delineate the approximate break of slope and inferred position of the fault. Photo locations shown in Fig. 2b.

Fig. 8: Apparent lateral offset of brick-cored embankments (highlighted in red) representing the remains of the ancient Pawritha (Kawthanbi) city wall between Shwenyaung and Nyaungshwe. Base maps from ESRI World Imagery compilation, which includes <1 m DigitalGlobe imagery. a) A shallow buried Kyaukkyan Fault strand is revealed by linear zones of darkly mottled surface deposits, and coincides with the Nam Latt stream and loci of wall offsets. Dextral offset is 12.2 ± 1.2 m, and vertical offset is ~2 m down-to-the-east. b) Detail of the offset northern wall. c) Detail of the offset southern wall. Map location shown in Fig. 2b.

Fig. 9: Topographic profiles across the Pindaya Fault, showing variation in vertical offset. Profile locations shown in inset map. Green lines show upper (dotted) and lower (dashed) limits on inferred footwall palaeotopography. Red lines show inferred hangingwall palaeotopography, projected (dashed line) below alluvial fans where they are present. Graph shows total offsets down to east plotted along the fault's length. Map location shown in Fig. 2b.

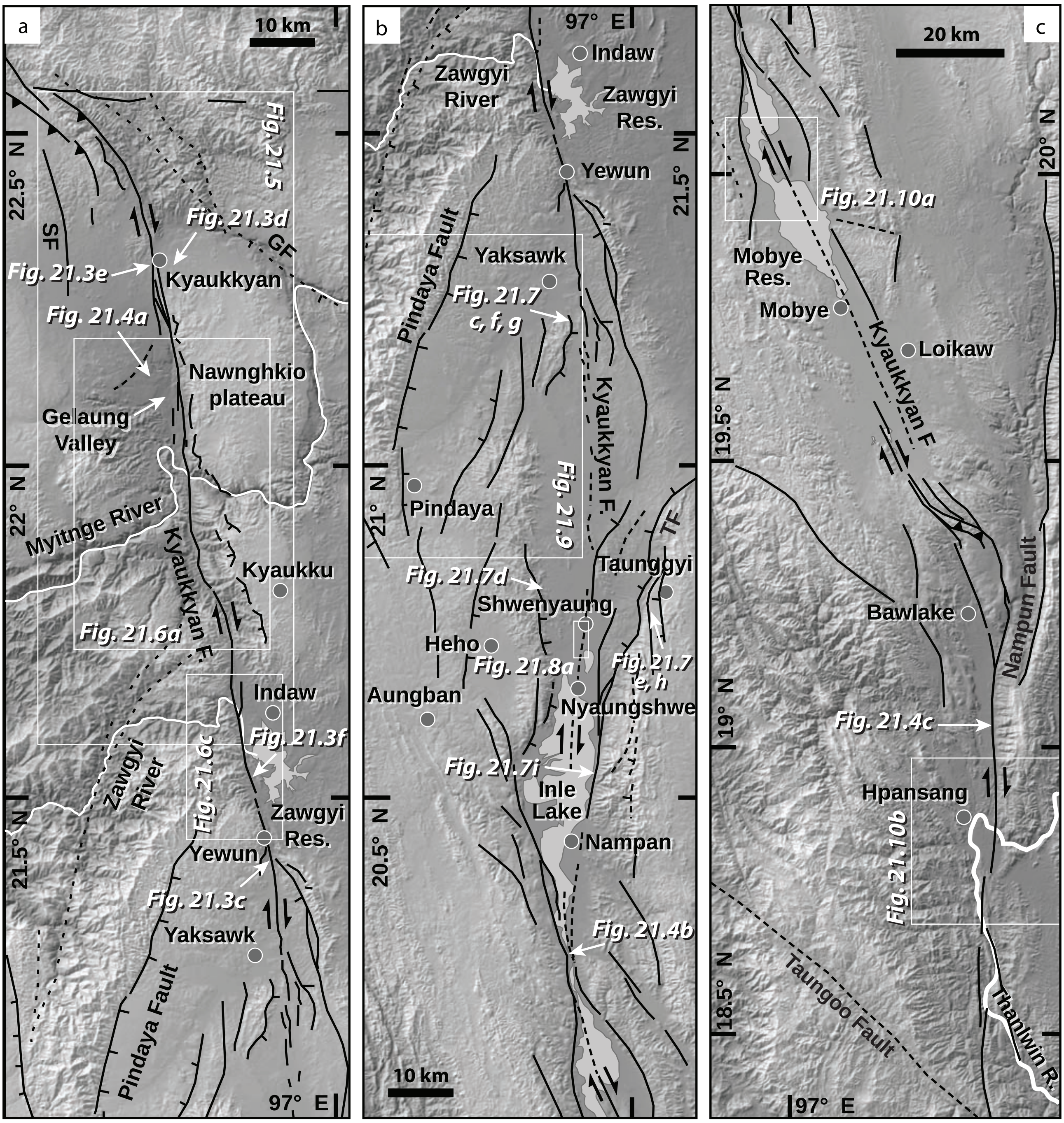
Fig. 10: Major river offsets along the Mobye-Hpansang segment. a) Apparent lateral offset of prominent low ridges (highlighted in red) adjacent to Mobye reservoir, parallel to the trace of the Kyaukkyan Fault. Apparent dextral offset is 4.6 ± 0.2 km. Base map from Google Earth. b) Apparent lateral offset of the Thanlwin River at Hpansang by 6.4 ± 1.0 km. Base map is 90 m Shuttle Radar Topography Mission data. Map locations shown in Fig. 2c.

Fig. 11: Schematic evolutionary maps showing the development of the Kyaukkyan Fault since Late Eocene times, modified after Soe Thura Tun and Watkinson (*this volume*) and synthesised largely from ideas presented in Bertrand & Rangin (2003); Socquet & Pubellier (2005); Morley *et al.* (2011); Searle & Morley (2011); Morley & Alvey (2015). See text for explanation and additional references. No attempt is made to show finite displacement across the fault systems because of the large uncertainty involved. The modern coastline is for reference only.



a
b
95° E
100° E
25° N
20° N
15° N
10° N
Kabaw F.Z.
Bhamo
Myanmar
Mogok Metamorphic Belt
Mogok
Mandalay
Wanding F.
Momeik F.
Kyaukme F.
China
Ailao Shan-Red River F.
Simao fold & thrust belt
Lancang F.
Myintnge River
Mekong River
Shan Plateau
Mengxing F.
Nam Ma F.
Lao
Nampun F.
Kyaukkyan F.
Sagaing F.
Central Basin
Shan Scarp FZ
Nay Pyi Taw
Ayeyarwaddy R.
Fig. 21.1b
TF
PF
Papun
Thanlwin R.
Mae Sariang F.
Mae Chan F.
Chiang Mai
Thailand
Bhumibol Dam metamorphics
Lansang gneisses
Mae Ping F.
Bago
Yangon
Mae Sot Basin
Umphang gneisses
Chao Phraya R.
Gulf of Mottama
Chainat Duplex
Three Pagodas F.
Bangkok
Andaman Sea
Ranong F.
Ranong Fault gneisses
Gulf of Thailand
South Sagaing FZ
100 km
96.5° E
97° E
22° N
21° N
19° N
Yadana Theingi Mine
Fig. 21.2a
GF
Kyaukkyan
SF
Myinpyu Pag.
Nampan
Pyin Oo Lwin (Maymyo)
Myitnge R.
Kyaukkyan-Indaw segment
Indaw
Fig. 21.2b
Yaksawk
PF
Yaksawk-Inle segment
Pindaya
Heho basin
Aungban
Taunggyi
Kalaw
Inle Lake
Nampan
Sam Ka
Mobye
Loikaw
Mobye-Hpansang segment
Fig. 21.2c
Demawso
Taungoo
Taungoo Fault
Hpansang
20 km
Earthquake Magnitude
3.4-3.9
4.0-4.9
5.0-5.9
PF
MPF

Fig. 21.1



a
10 km
Fig. 21.5
22.5° N
SF
GF
Fig. 21.3d
Fig. 21.3e
Kyaukkyan
Fig. 21.4a
Nawnghkio plateau
Gelaung Valley
22° N
Myitnge River
Kyaukkyan F.
Kyaukku
Fig. 21.6a
Indaw
Fig. 21.3f
Zawgyi River
Fig. 21.6c
Zawgyi Res.
Yewun
21.5° N
Fig. 21.3c
Yaksawk
Pindaya Fault
97° E
b
97° E
Indaw
Zawgyi River
Zawgyi Res.
Yewun
21.5° N
Pindaya Fault
Yaksawk
Fig. 21.7 c, f, g
Kyaukkyan F.
Fig. 21.9
21° N
Pindaya
TF
Taunggyi
Fig. 21.7d
Shwenyaung
Heho
Fig. 21.8a
Fig. 21.7 e, h
Aungban
Nyaungshwe
Fig. 21.7i
Inle Lake
20.5° N
Nampan
Fig. 21.4b
10 km
c
20 km
20° N
Fig. 21.10a
Mobye Res.
Mobye
Kyaukkyan F
Loikaw
19.5° N
Bawlake
Nampun Fault
19° N
Fig. 21.4c
Hpansang
Fig. 21.10b
18.5° N
Taungoo Fault
Thanlwin R.
97° E

Fig. 21.2

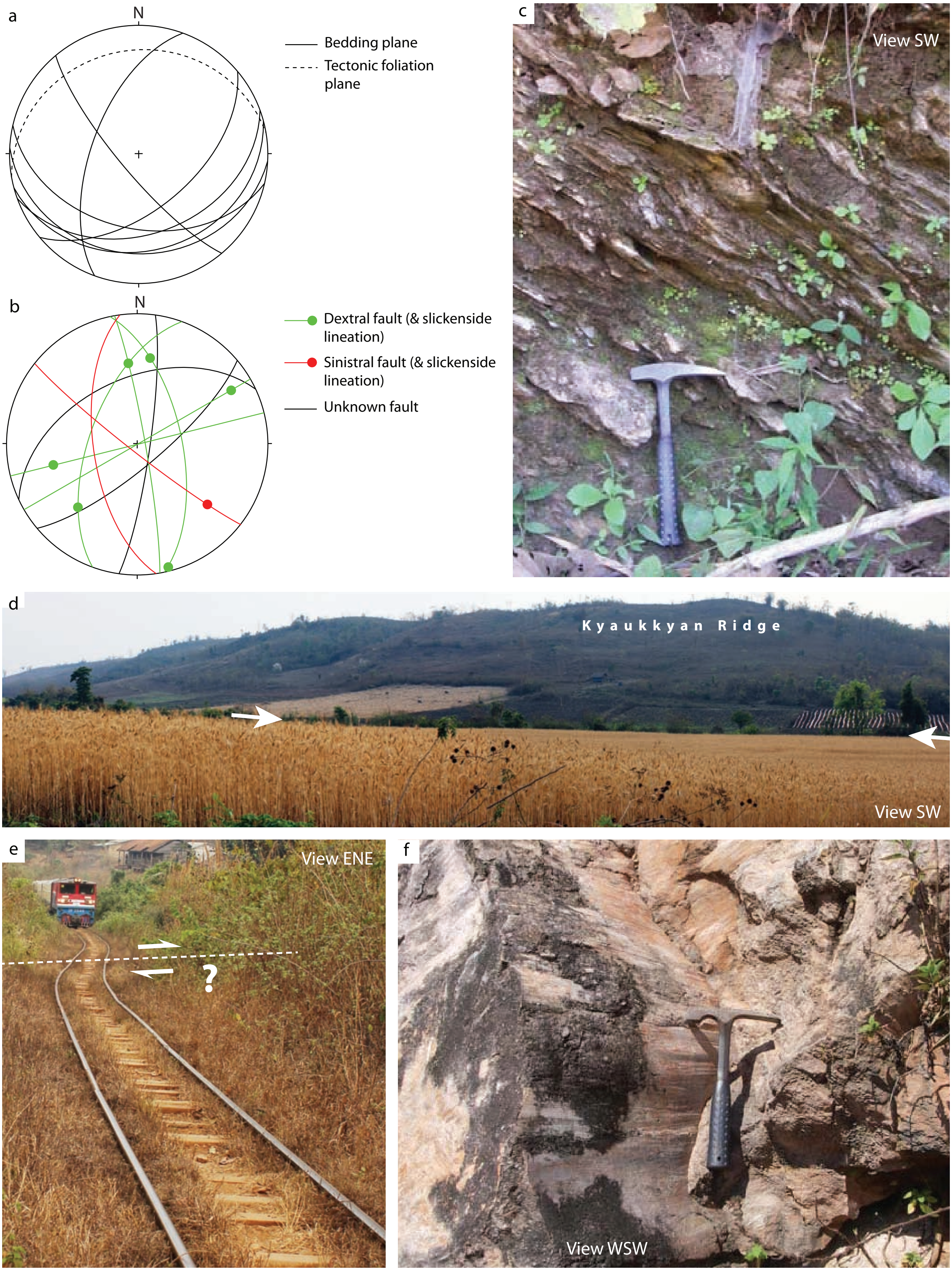

a
N
Bedding plane
Tectonic foliation plane
b
N
Dextral fault (& slickenside lineation)
Sinistral fault (& slickenside lineation)
Unknown fault
c
View SW
d
Kyaukkyan Ridge
View SW
e
View ENE
?
f
View WSW

Fig. 21.3

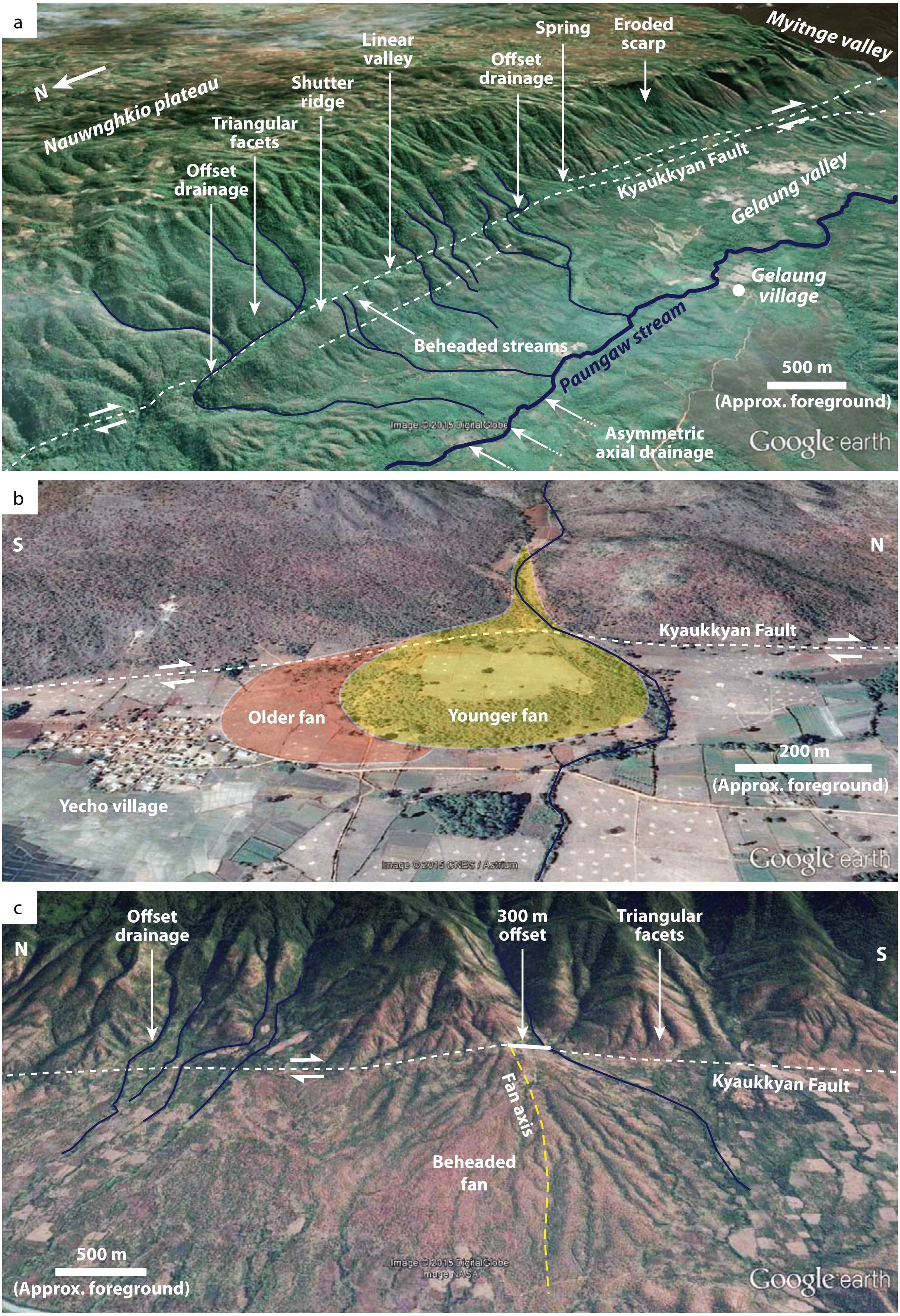

a
N
Nauwnghkio plateau
Triangular facets
Offset drainage
Shutter ridge
Linear valley
Offset drainage
Spring
Eroded scarp
Myitnge valley
Kyaukkyan Fault
Gelaung valley
Gelaung village
Beheaded streams
Paungaw stream
500 m
(Approx. foreground)
Asymmetric axial drainage
b
S
N
Kyaukkyan Fault
Older fan
Younger fan
200 m
(Approx. foreground)
Yecho village
c
N
S
Offset drainage
300 m offset
Triangular facets
Kyaukkyan Fault
Fan axis
Beheaded fan
500 m
(Approx. foreground)

Fig. 21-4

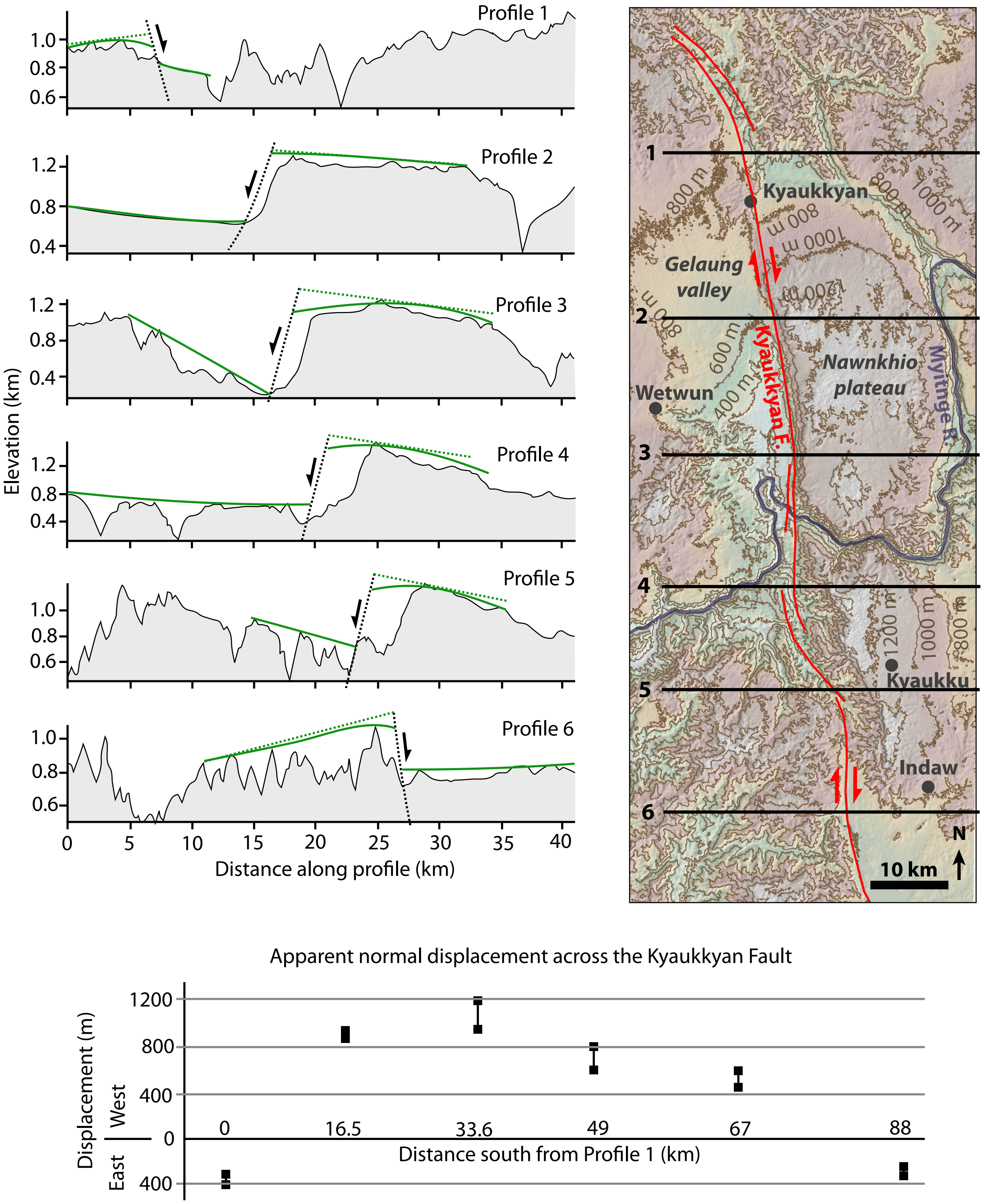
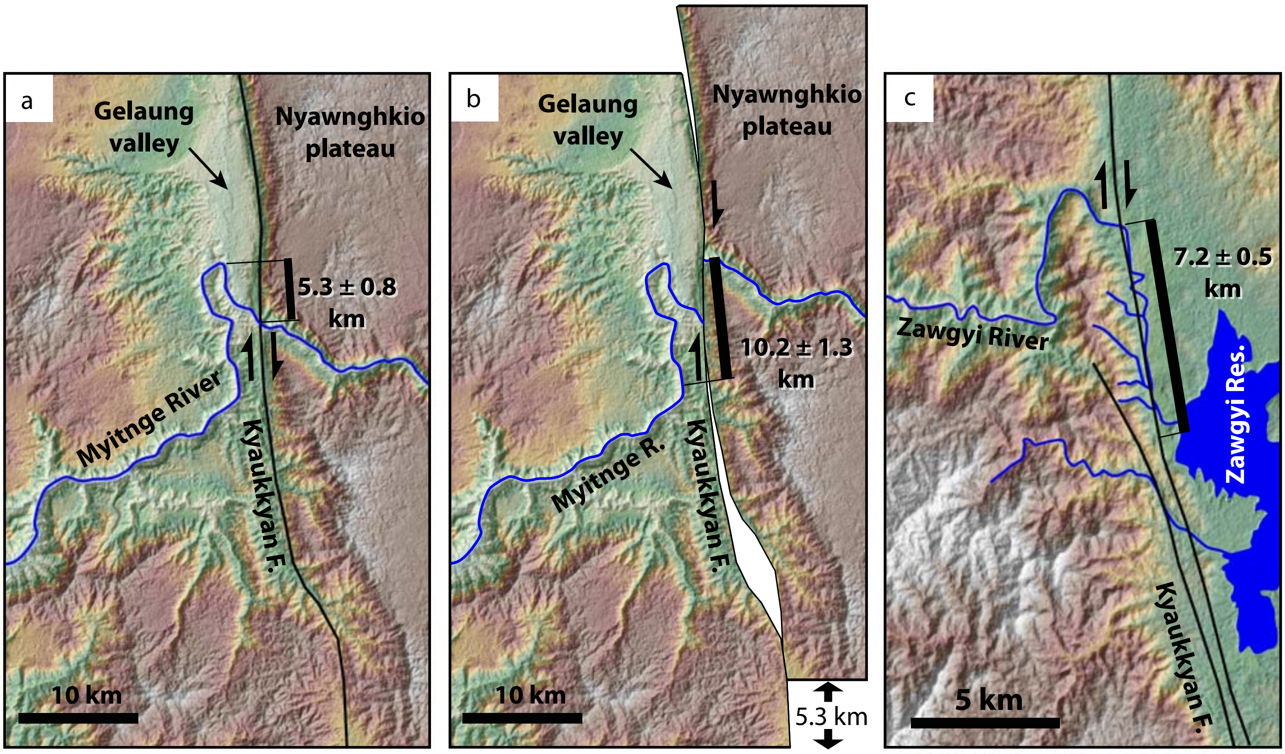

Profile 1
Profile 2
Profile 3
Profile 4
Profile 5
Profile 6
Elevation (km)
Distance along profile (km)
0
5
10
15
20
25
30
35
40
1.0
0.8
0.6
1.2
0.4
1
2
3
4
5
6
Kyaukkyan
Gelaung valley
Kyaukkyan F.
Nawnkhio plateau
Myitnge R.
Wetwun
Kyaukku
Indaw
800 m
1000 m
1200 m
600 m
400 m
N
10 km
Apparent normal displacement across the Kyaukkyan Fault
Displacement (m)
West
East
1200
800
400
0
16.5
33.6
49
67
88
Distance south from Profile 1 (km)

Fig. 21-5



a
Gelaung valley
Nyawnghkio plateau
5.3 ± 0.8 km
Myitnge River
Kyaukkyan F.
10 km
b
Gelaung valley
Nyawnghkio plateau
10.2 ± 1.3 km
Myitnge R.
Kyaukkyan F.
10 km
5.3 km
c
7.2 ± 0.5 km
Zawgyi River
Zawgyi Res.
Kyaukkyan F.
5 km

Fig. 21.6

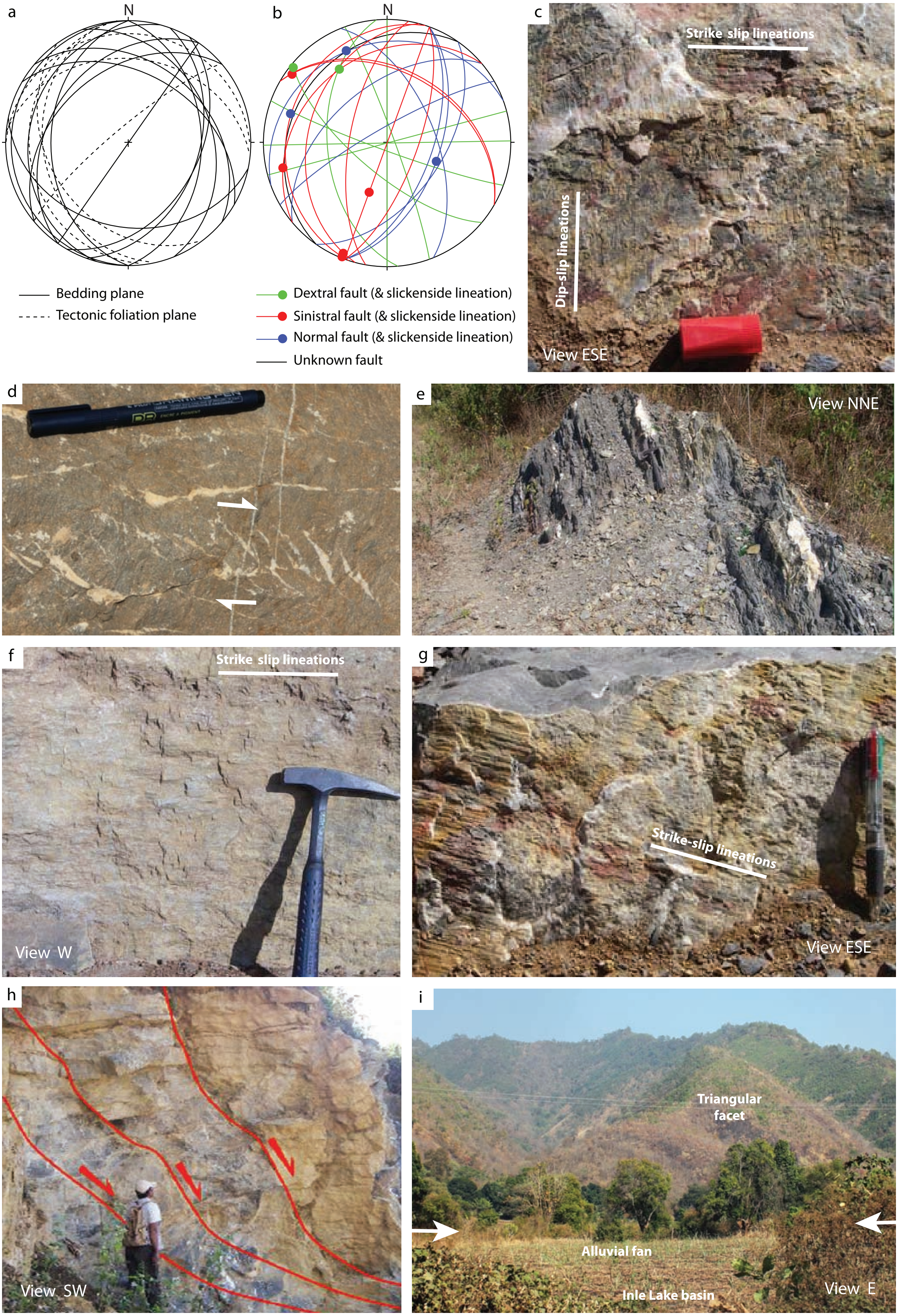

a
N
b
N
Bedding plane
Tectonic foliation plane
Dextral fault (& slickenside lineation)
Sinistral fault (& slickenside lineation)
Normal fault (& slickenside lineation)
Unknown fault
c
Strike slip lineations
Dip-slip lineations
View ESE
d
e
View NNE
f
Strike slip lineations
View W
g
Strike-slip lineations
View ESE
h
View SW
i
Triangular facet
Alluvial fan
Inle Lake basin
View E

Fig. 21-7

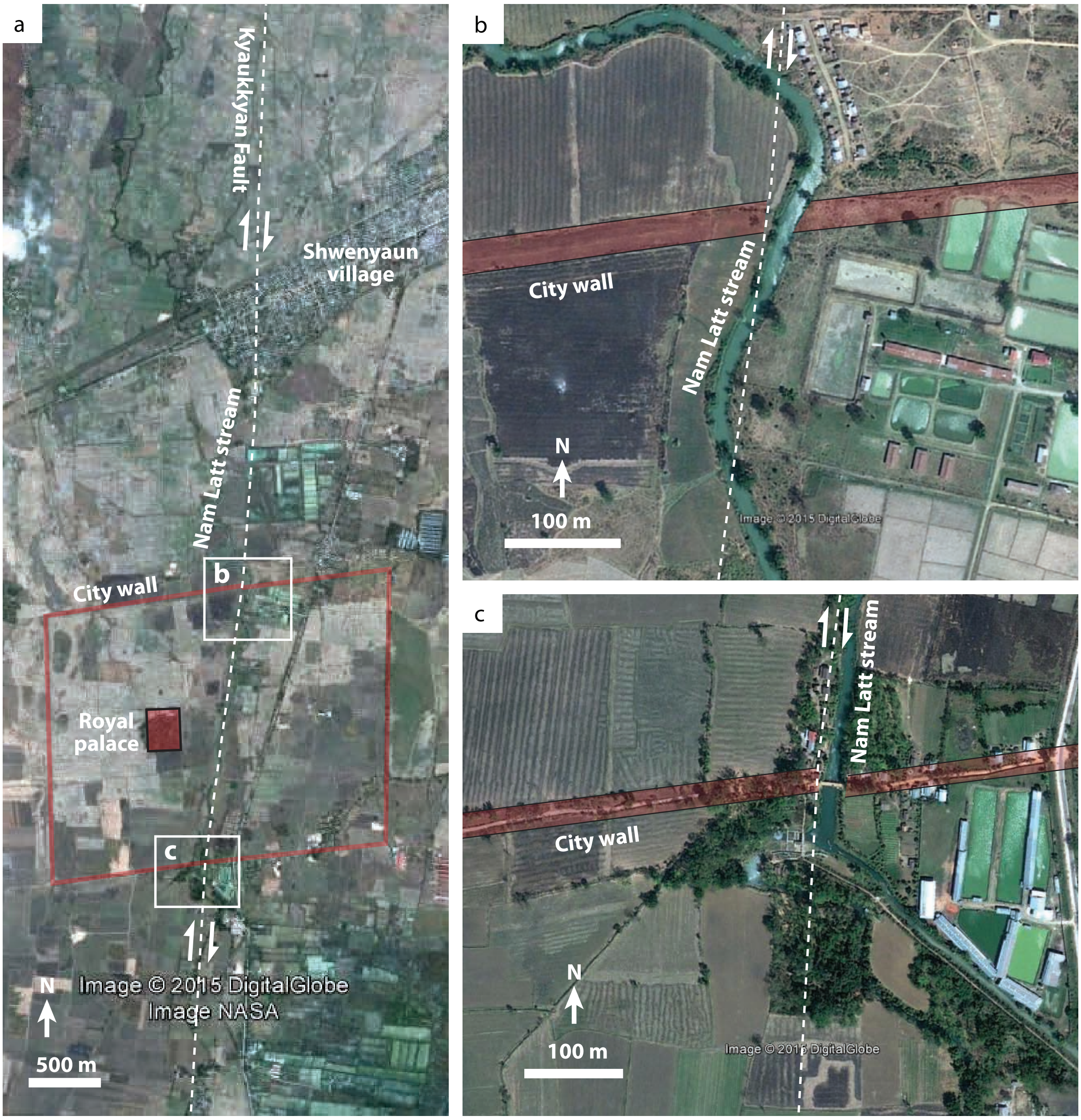
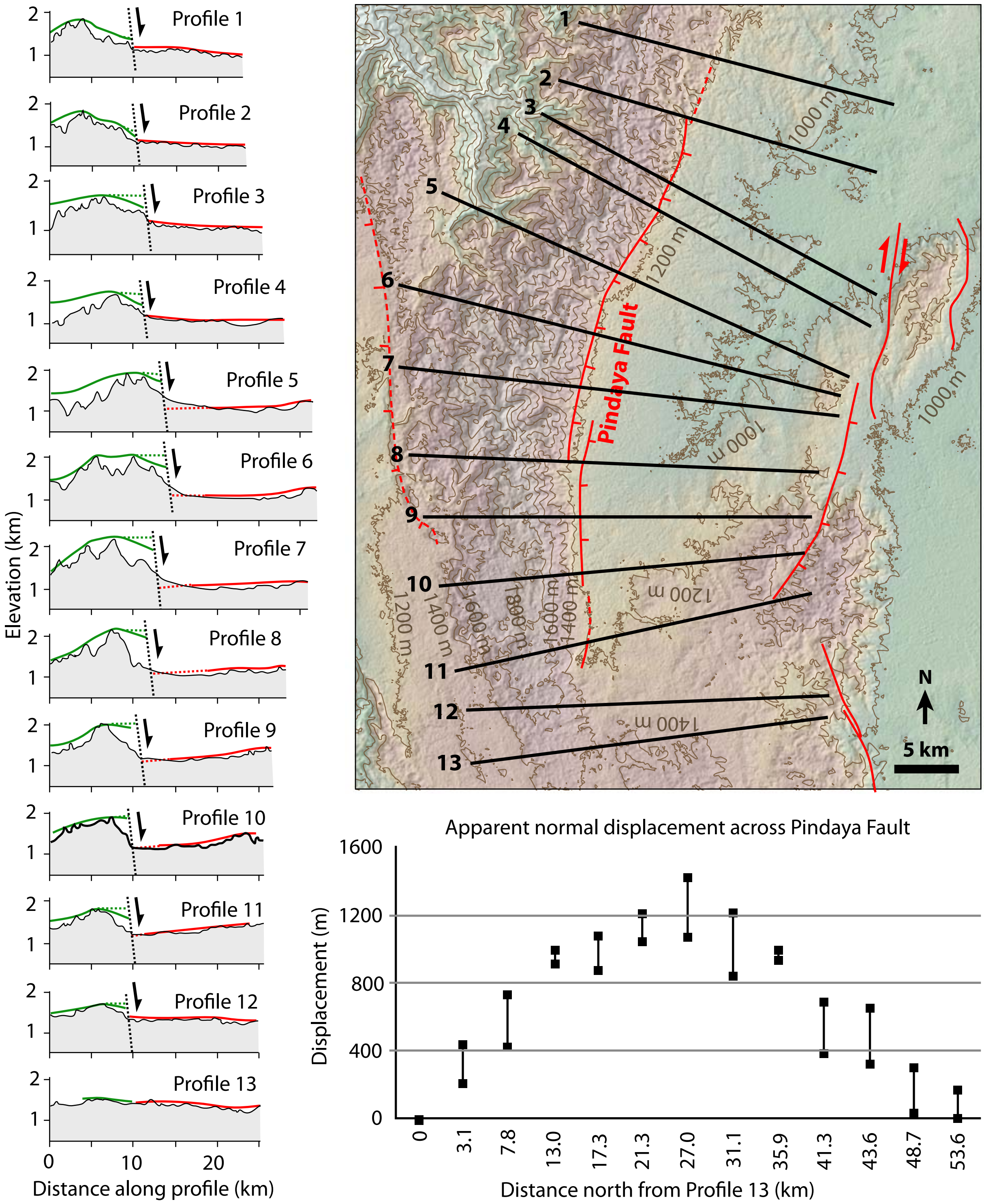

a
Kyaukkyan Fault
Shwenyaun village
Nam Latt stream
City wall
b
Royal palace
c
N
Image © 2015 DigitalGlobe
Image NASA
500 m
b
City wall
Nam Latt stream
N
100 m
Image © 2015 DigitalGlobe
c
Nam Latt stream
City wall
N
100 m

Fig. 21-8



Profile 1
Profile 2
Profile 3
Profile 4
Profile 5
Profile 6
Profile 7
Profile 8
Profile 9
Profile 10
Profile 11
Profile 12
Profile 13
Elevation (km)
Distance along profile (km)
Pindaya Fault
1000 m
1200 m
1400 m
1600 m
1800 m
N
5 km
Apparent normal displacement across Pindaya Fault
Displacement (m)
Distance north from Profile 13 (km)

Fig. 21.9

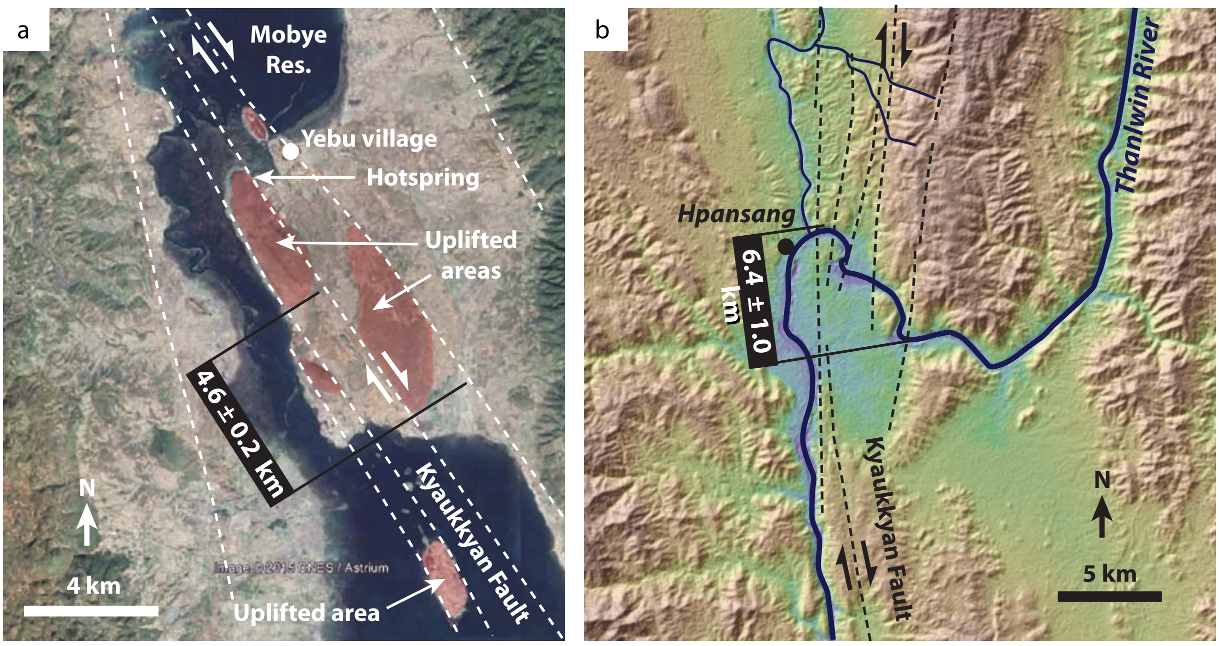
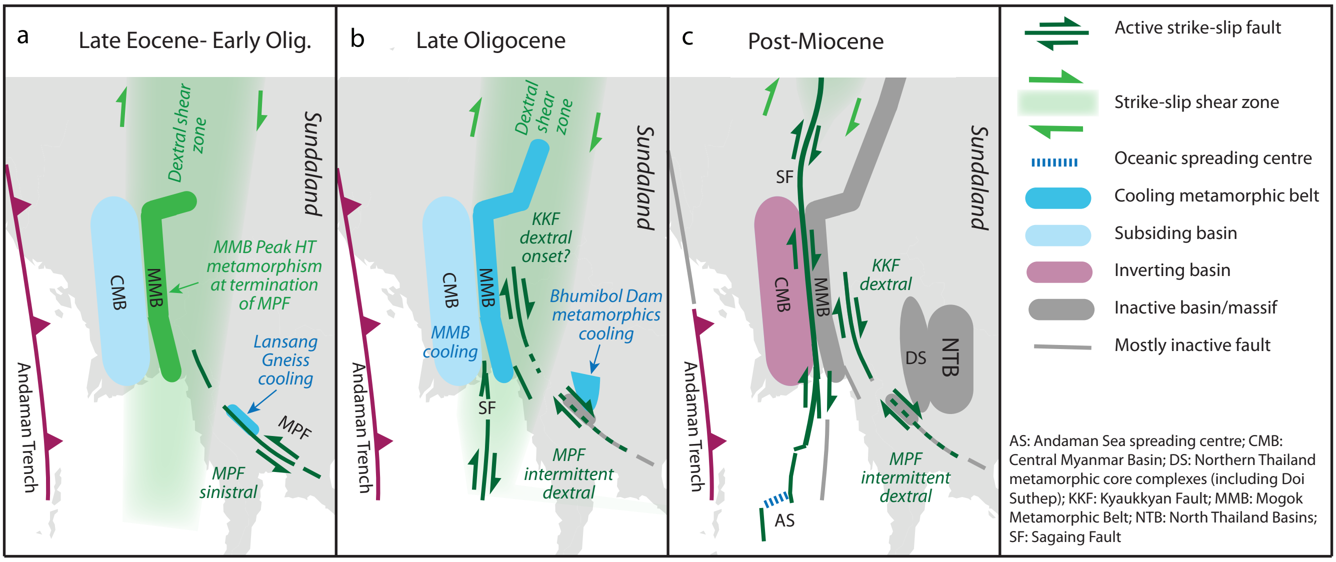

a
Mobye
Res.
Yebu village
Hotspring
Uplifted
areas
4.6 ± 0.2 km
Kyaukkyan Fault
N
4 km
Image © 2015 CNES / Astrium
Uplifted area
b
Hpansang
6.4 ± 1.0
km
Thanlwin River
Kyaukkyan Fault
N
5 km

Fig. 21.10



a
Late Eocene- Early Olig.
Dextral shear zone
Sundaland
CMB
MMB
MMB Peak HT metamorphism at termination of MPF
Lansang Gneiss cooling
MPF
MPF sinistral
Andaman Trench
b
Late Oligocene
Dextral shear zone
Sundaland
KKF dextral onset?
CMB
MMB
MMB cooling
Bhumibol Dam metamorphics cooling
SF
MPF intermittent dextral
Andaman Trench
c
Post-Miocene
SF
Sundaland
CMB
MMB
KKF dextral
DS
NTB
MPF intermittent dextral
AS
Andaman Trench
Active strike-slip fault
Strike-slip shear zone
Oceanic spreading centre
Cooling metamorphic belt
Subsiding basin
Inverting basin
Inactive basin/massif
Mostly inactive fault
AS: Andaman Sea spreading centre; CMB: Central Myanmar Basin; DS: Northern Thailand metamorphic core complexes (including Doi Suthep); KKF: Kyaukkyan Fault; MMB: Mogok Metamorphic Belt; NTB: North Thailand Basins; SF: Sagaing Fault

Fig. 21.11