High slip rate for a low seismicity along the Palu-Koro active fault in central Sulawesi (Indonesia)

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ABSTRACT

In eastern Indonesia, the Central Sulawesi fault system consists of complex left-lateral strike-slip fault zones located within the triple junction area between the Pacific, Indo-Australian and Eurasian plates. Seismicity in Central Sulawesi documents low-magnitude shallow earthquakes related, from NW to SE, to the NNW-trending Palu-Koro (PKF) and WNW-trending Matano fault zones. Study of the active fault traces indicates a northward growing complexity in the PKF segmentation. Left-lateral displacement of 370 ± 10 m of streams incised within fans, whose deposition has been dated at 11 000 ± 2300 years, yields a calculated PKF horizontal slip rate of 35 ± 8 mm yr^{-1}. This geologically determined long-term slip rate agrees with the far-field strike-slip rate of 32–45 mm yr^{-1} previously proposed from GPS measurements and confirms that the PKF is a fast slipping fault with a relatively low level of seismicity.

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Introduction

Sulawesi Island, eastern Indonesia, is at the triple junction of the Pacific (through the Philippine plate), Indo-Australian and Eurasian Plates (Fig. 1). Its peculiar shape results from an on-going, complex history of collisions and subsequent rotations of continental slivers, island arcs and oceanic domains with the Sunda Block, i.e. the south-eastern edge of the Eurasian Plate. Presently, Sulawesi is obliquely crossed by one of the main fault systems limiting the Eurasian Plate to the East: the left-lateral Central Sulawesi Fault System (CSFS). This fault system, which comprises two fault zones, the NNW-trending Palu-Koro (PKF) and the WNW-trending Matano (MF) fault zones, connects, from north-west to south-east, the North Sulawesi Subduction zone (NSS) to the Banda Sea domain (Fig. 1). Previous studies have sugges-

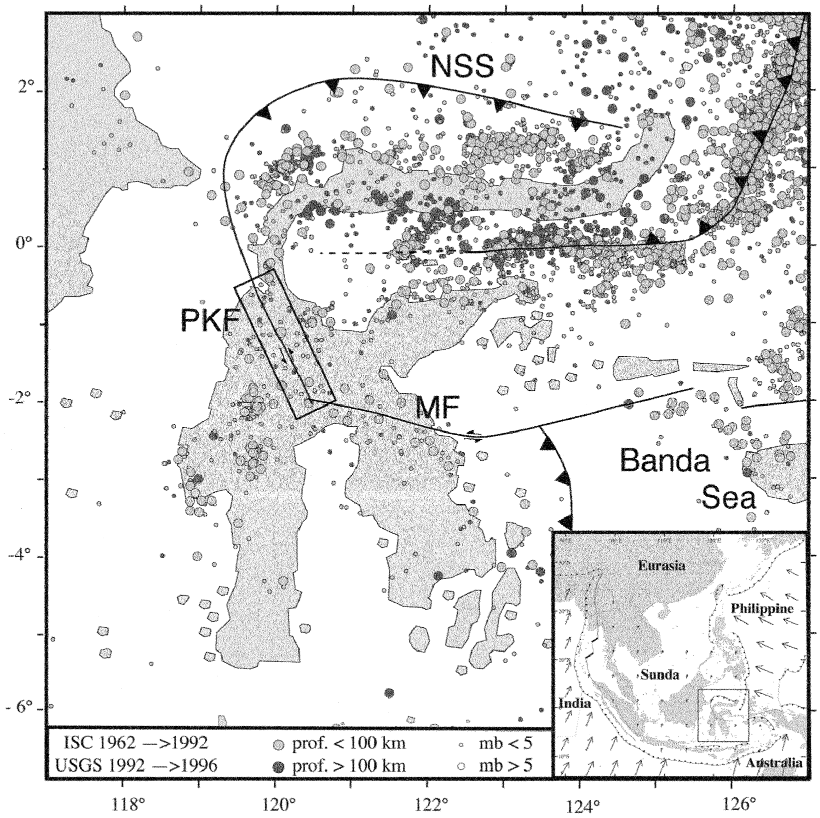

Fig. 1 Seismicity of the Sulawesian region from the ISC and USGS catalogues. PKF and MF represent the Matano Fault and Palu Koro Fault zones, respectively, while NSS is the North Sulawesi Subduction. The box indicates the approximate location of Fig. 2. Inset at bottom right shows the SE Asia geodynamic frame and velocity field (arrows) of the Indo-Australian and Philippine plates relative to Eurasia (after Baroux *et al.*, 1998).

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ted major active tectonics along the CSFS, particularly along the PKF (Tjia, 1969; Katili, 1970). However, the seismicity of Sulawesi, as recorded by global seismic networks (Fig. 1), Indonesian network and historical seismicity indicate a relatively low level of shallow seismic activity in Central Sulawesi (e.g. Beaudouin, 1998). In contrast with this low seismicity, PKF long-term slip rates, as high as 40–50 mm yr^{-1} for the last 5 Myr, have been estimated, on the basis of geodynamic reconstruction models (i.e. plate convergence rate along the NSS; Silver *et al.*, 1983; Walpersdorf *et al.*, 1998a) or from palaeomagnetic studies (Surmont *et al.*, 1994). Based on a 5-Myr time span, these estimates may integrate different tectonic regimes and consequently variations of the slip rate on the PKF. In that case, the estimates are most likely inaccurate, particularly in a rapidly evolving complex area of a triple junction. Recently, the far-field slip rate of the PKF was calculated at ~38 ± 8 mm yr^{-1} from geodetic (GPS) measurements (Walpersdorf *et al.*, 1998b; Stevens *et al.*, 1999). To complement these analyses, it is therefore crucial to estimate the PKF long-term slip rates to interpret GPS results. The aim of the current study was to determine the Holocene slip rate, i.e. on a time-span during which the tectonic regime has been stable.

To constrain the PKF long-term slip rate, detailed mapping of the active fault traces and of the along-strike offsets have been performed using SPOT images. They were further constrained by geomorphic and tectonic field studies and complemented by analyses on topographic and geological maps (GRDC, 1981–93). These permitted us to determine a horizontal long-term slip rate on the PKF, over the Holocene, by observations of stream offsets. The offsets were

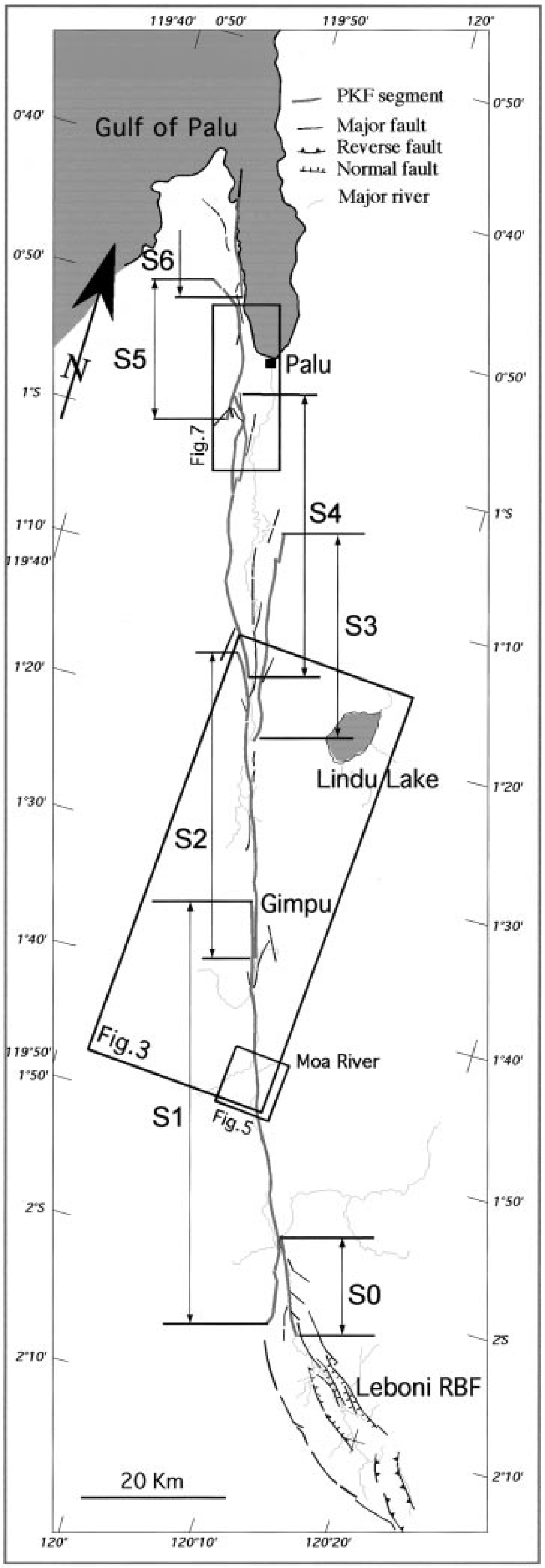

Fig. 2 Active segmentation of the PKF. The boxes indicate the approximate locations of Figs 3, 5 and 7. Leboni RBF, the Leboni fault relay-bend zone that connects the PKF to the MF. Dashed faults are those with a dominant normal component (ticked on the downthrown block) while triangles indicate faults with a reverse component (triangles on the upthrown block).

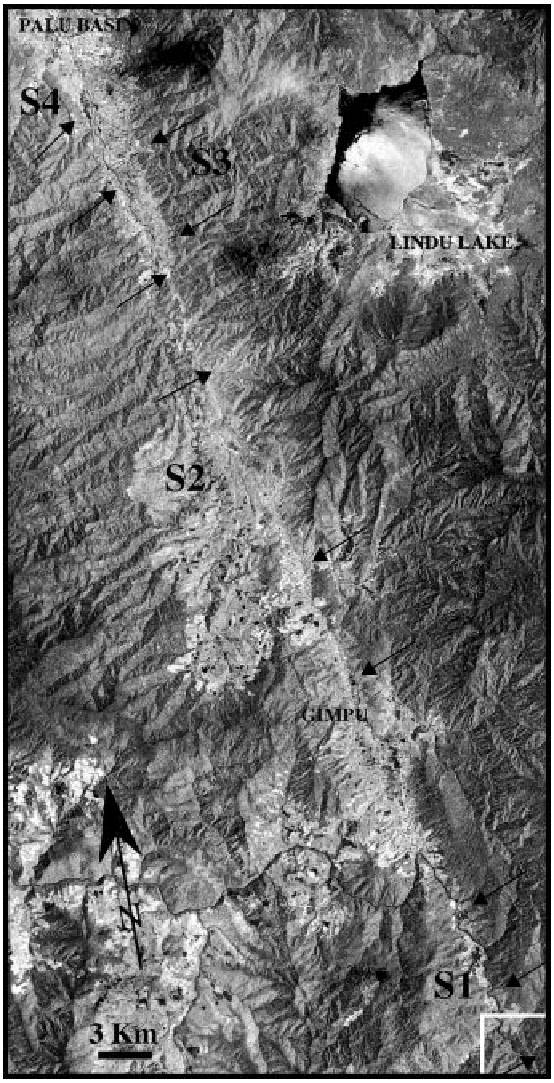

Fig. 3 Detailed view of the SPOT image K/J-309/353 (22 October 1988). Location on Fig. 2. Arrows point to the PKF fault trace. S1, S2, S3, S4 are the PKF fault segments reported on Fig. 2. The box approximately locates the Moa river (Fig. 5).

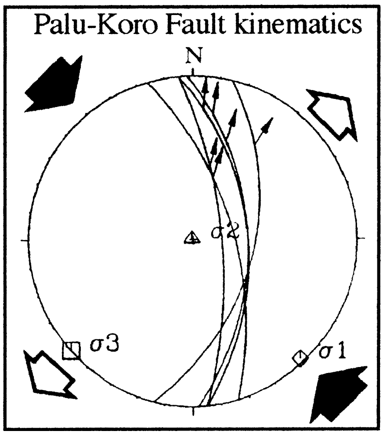

Fig. 4 Present-day fault kinematics of the northern PKF. Examples of strike-slip faulting slip data measured along the major PKF bounding the Palu basin: lower hemisphere stereoplot of fault planes and measured striations, direction arrows point in the horizontal slip azimuth direction. σ_1, σ_2 and σ_3 represent the stress axes of the regionally significant stress regime obtained from the inversion of major fault striations measured around the Palu bassin (Beaudouin, 1998). Large open and black arrows give the azimuths of the computed σ_3 and σ_1, respectively.

correlated to Recent alluvial fan abandonment dated using *in situ* produced ^{10}Be concentrations.

Historical and instrumental seismicity in Central Sulawesi

According to the seismicity catalogues (USGS, ISC, CMT, etc.), Central Sulawesi seismicity is diffuse and characterized by few shallow events located around both the PKF and the MF zones (Fig. 1). Although poorly documented, historical seismicity in Central Sulawesi has been recorded since the 19th century. However, even if some damaging earthquakes have been reported within Central Sulawesi, few major earthquakes (Mw > 4.5) have occurred on the PKF and MF zones over at least the 100 years. Katili (1970) mentioned three earthquakes near the trace of the PKF in the Gimpu (1905), Kulawi (1907) and Kantewoe (1934) basins, respectively. A damaging earthquake on the PKF in 1909 was reported by Hamilton (1979). In addition, a recent reappraisal study (Beaudouin, 1998) of the seismic history based on several catalogues (Rothé, 1969; Kertapati *et al.*, 1991; PPPG, 1995; Pelinovsky *et al.*, 1996) reported 28 major earthquakes around Sulawesi between 1845 and 1998. This study did not report events in 1905, 1907, 1909 and 1934 but reported two destructive earthquakes in 1927 and 1985 that could have occurred along the PKF and two other major events in 1968 (Ms ~ 6.7) and 1993 (Mw ~ 5.7) that probably correspond to PKF reactivations.

Fault geometry in Central Sulawesi

A large-scale map covering the CSFS was compiled by investigation of detailed geomorphological fault characteristics. It provides evidence for a broad geometric discontinuity arranged in a complex crustal-scale fault relay-bend zone located at around 2°15′S (Leboni RBF, Fig. 2). This zone connects the PKF to the MF (Fig. 1) that accounts for the major active deformation in Central Sulawesi.

The Palu-Koro Fault segmentation

To examine potential partitioning of the deformation across the Palu-Koro region, detailed mapping of the surface fault traces was conducted. This provides evidence for discontinuities such as stepovers, relays and bends and allowed us to compile a segmen-

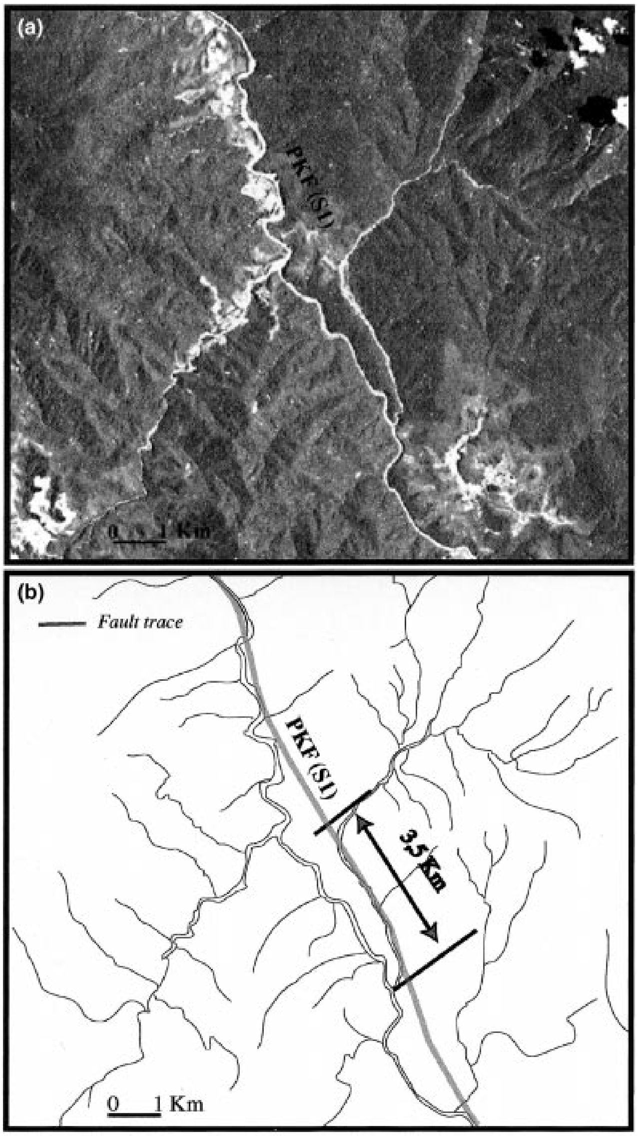

Fig. 5 (a) Detailed views of SPOT image K/J-309/353 showing the Moa river stream offset. (b) Interpretation sketch of the SPOT view reported on (a). PKF (S1) represents the fault trace of PKF segment S1.

tation map (Fig. 2). The map documents seven geometric fault segments whose lengths range from 15 to 59 km (segment S0 to S6). Segment S0 is related to the northern segment comprised within the Leboni relay-bend marking the PKF southern termination. S6 is the northernmost onshore PKF segment, its northern termination being offshore. The PKF segment lengths are: S0: 15 km, S1: 59 km, S2: 43 km, S3: 29 km S4: 40 km, S5: 20 km, S6: $\sim$ 12 km (onshore). Based on this analysis, distinct domains may be distinguished. The northern domain is characterized by segments smaller than the southern one. Indeed, the southern PKF deformation is localized along the linear and long segments, S1 and S2 (Fig. 3). The northernmost PKF domain comprises several segments arranged in an *en echelon* pattern or in relay. In the northernmost zone the deformation is distributed over a broad zone and extends into the Palu Gulf. Thus, this large-scale segmentation study provides evidence for a northward-growing complexity in the segmentation.

Palu-Koro Fault kinematics

The PKF exhibits left-lateral offsets of geomorphic features, i.e. streams, late Quaternary alluvial fans, etc. Faceted spurs with 300–400-m-high triangular facets also characterize the northern PKF trace. The western Palu basin boundary front is controlled by a N- to NNW-trending, 2300–2500-m-high escarpment. This escarpment as well as Quaternary coral reef terraces that have been uplifted by 210 m indicate that a dip-slip component characterizes the PKF present-day faulting. These observations show that both strike-slip and normal-slip faulting presently occur along the northern PKF. This implies a transtensional tectonic regime confirmed by analysis of the slip-vector measured on the major fault planes related to recent faulting (Fig. 4) and by GPS measurements (Walpersdorf *et al.*, 1998b). However, both methods yield a dominant lateral component for the PKF present-day faulting (rake of $\sim$ 15°) that agrees with a NW-trending σ_1 strike-slip stress regime (Fig. 4). Fault kinematics as well as fission track analyses provide evidence for a change in the tectonic regime since 6 Ma (Beaudouin, 1998; Bellier *et al.*, 1998). They demonstrate that the 2500-m-high northern PKF escarpment is partly inherited from an older extensional (normal slip faulting) tectonic regime.

Geomorphic feature offsets along the Palu-Koro Fault

Along the PKF trace, morphological features are left-laterally offset and might thus be used to calculate the fault strike-slip rate. For along-strike PKF segments S1 and S2, left-lateral stream offsets ranging from 210 ± 20 m to 3530 ± 20 m have been observed on SPOT images (usually, the stream offset uncertainties ranged between ± 10 m and ± 20 m, e.g. Bellier and Sébrier, 1995). The longer offset of 3530 ± 20 m is related to the major Moa river (at lat. $\sim$ 1°45′S; Fig. 5) that incised Pleistocene magmatic rocks, 1.62 Ma in age (Sukamto, 1975). However, it is difficult to estimate the age of this river emplacement except to say that it is related to major recent climatic events.

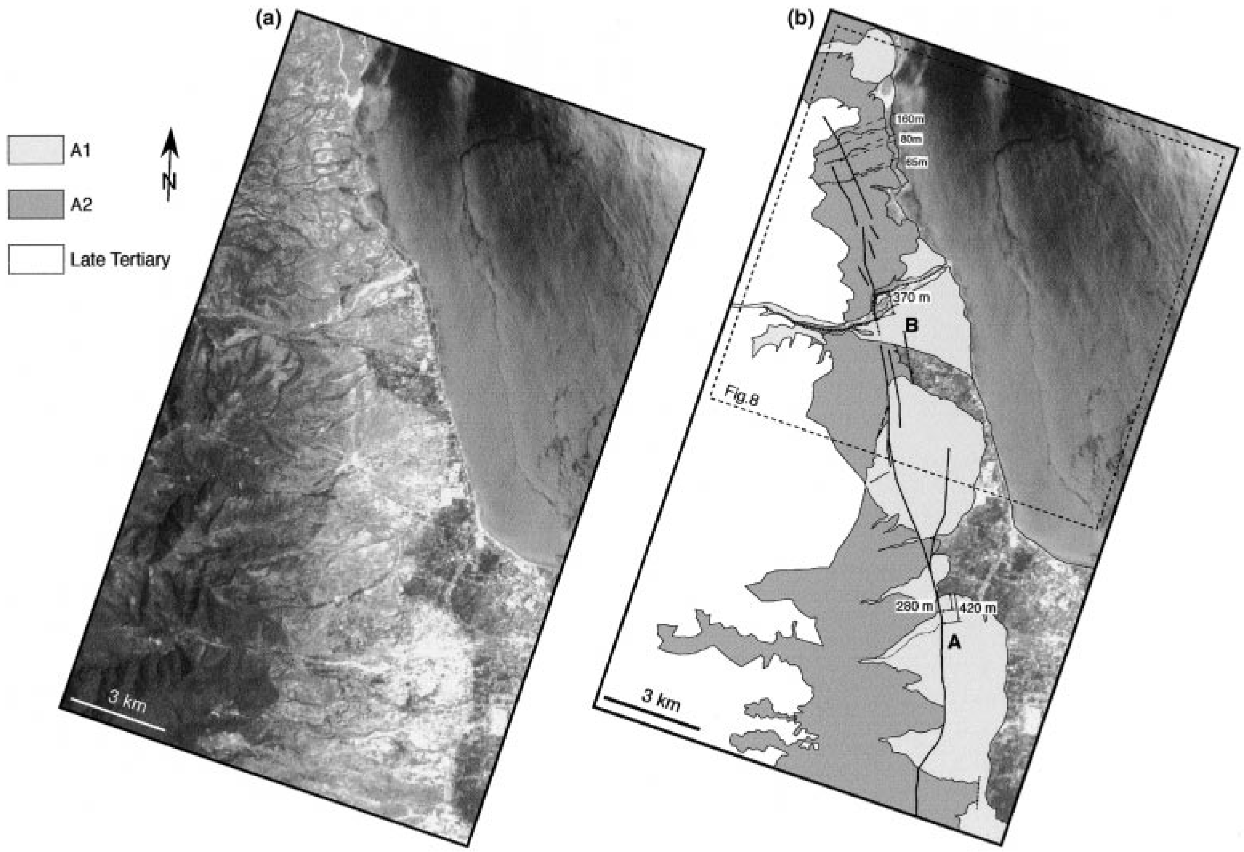

Fig. 6 (a) Detailed view of panchromatic SPOT image K/J-309/352 showing examples of stream and fan boundary offsets. (b) Interpretation sketch of the SPOT view reported on (a). Arrows point to the horizontal offsets. Location on Fig. 7.

From analysis of SPOT images covering the PKF zone, we selected to study the Palu basin region where the morphological characteristics of the fault indicate high current tectonic activity. It was selected for three main reasons: (1) several geomorphic features offsets are observed; (2) contrary to most locations along the PKF, field accessibility to this zone is less limited by a dense forest; (3) it also offers the opportunity, through analysis of the termination of the PKF major segment, to estimate the seismic risk close to Palu city, the largest city in Central Sulawesi. Fan edges and streams incising Quaternary deposits along the western border of the Palu basin exhibit left-lateral offsets ranging from 65 ± 20 m to 420 ± 20 m (Fig. 6). The average long-term slip rate along the PKF has thus been determined through the dating of Late Quaternary alluvial fan abandonment. Indeed, the observed cut and fill-in process of emplacement strongly suggests that the offset channel networks of the different fan units have been formed just after their abandonment. In that case, alluvial fans, which are indicators of climatic change, may be used not only as markers allowing identification of cumulative tectonic displacements through their offset streams, but also to estimate directly the PKF horizontal displacement slip rate through the dating of the alluvial fan surface abandonment using *in situ* produced ^{10}Be (e.g. Siame *et al.*, 1997, 2001).

Quaternary alluvial fans located on the north-western border of the Palu basin

Late Quaternary alluvial fans analysed in this study are located in the western front of the Palu basin, at latitudes ranging between ~ 0°50′ and ~ 1°10′S (Fig. 7). They have been studied using combined cartography, geomorphic (SPOT and field) analyses, and ^{10}Be exposure age approaches. Observation of the relative spatial relationships between the alluvial fans, and thus their relative chronology, leads us to subdivide the alluvial fans into two units. Indeed, east of the fault scarp there are two generations of incised alluvial fans; the younger, A1, is cone shaped in plan view. During deposition, the A1 fans truncated a part of older fans, A2, which are presently mainly observed as relics (Fig. 7) (Bellier *et al.*, 1999a).

Ages of the fan systems

The minimum exposure ages have already been extensively discussed in Bellier *et al.* (1999a). Measurements of *in situ* produced ^{10}Be concentrations in quartz boulders exposed on top fan surfaces show that they have been emplaced during the last two successive major climatic events, at the initiation of deglaciation ending the

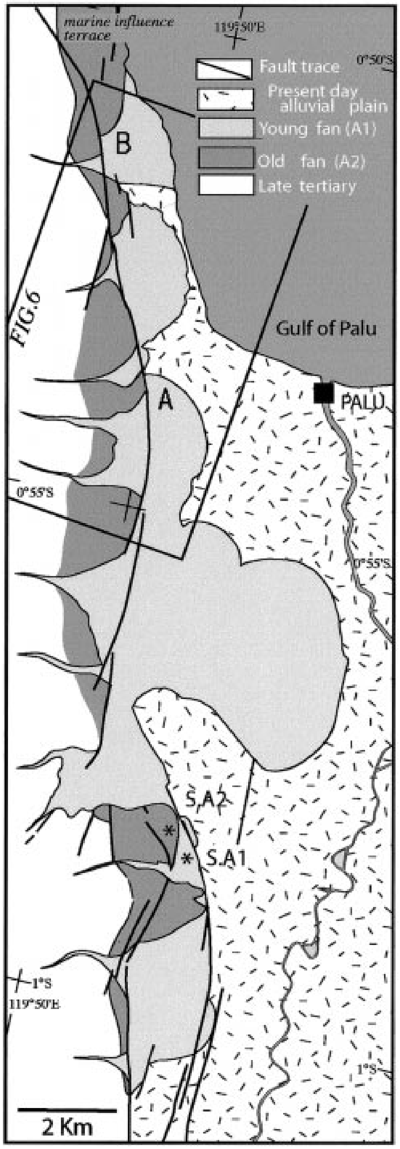

Fig. 7 Map of the Quaternary alluvial fan deposits from field observations and Panchromatic SPOT image (KJ 309-352) interpretations (simplified after Bellier *et al.*, 1999a). It shows the geometrical relationships of the alluvial fan units along the PKF (see Fig. 2), from younger (A1, dated at ~ 11 ka) to older (A2, dated at ~ 125 ka). The fault trace represents the northern PKF. The box shows the fan (A) and stream (B) offsets presented on Fig. 6. SA.2 and SA.1 are the sampling sites for A2 and A1, respectively (see Bellier *et al.*, 1999a). Location: see Fig. 2.

last two glacial cycles. For the stratigraphically determined younger alluvial deposit (A1), the measured ^{10}Be concentration yields a minimum exposure age of 11 000 ± 2300 years. The interpretation of this age is that the younger fan surface was stabilized at the initiation of the deglaciation ending the Last Glacial Maximum (i.e. end of stage 2). The minimum exposure age calculated for the older fan surface A2 leads us to propose that the event that induced this surface emplacement may have been deglaciation ending isotopic stage 6, before commencement of the last interglacial conditions (~ 125 ± 20 ka).

Long-term slip rate along the Palu-Koro Fault

Displacements of fan edges by the PKF have been observed. However, fan boundaries are often difficult to map precisely and likely observation misfits induce large uncertainties. Along the northern PKF, the observed fan offset ranges from 280 ± 20 m to 420 ± 20 m (A, Fig. 6). The younger fan age of 11 000 ± 2300 years yields a slip rate ranging between 20 and 51 mm yr^{-1}. Since the last major regional climate change is contemporaneous with the deglaciation of the Last Glacial Maximum, the stream incision most likely results from enhanced stream power associated with interglacial conditions. In addition, owing to the high erosion rate under a tropical climate, the assumption that the minor stream network within the Palu basin boundary was installed just after the fan emplacement implies that the fan envelope was incised by distinct stream channel networks 11 000 ± 2300 years ago. These stream networks reveal left-lateral offsets ranging between 65 ± 20 m and 370 ± 20 m along the PKF (Figs 6 and 8). The maximum stream offset of 370 ± 20 m (B, Fig. 6) is related to a drainage in capture process (see below) and reflects in fact an A1 fan edge offset (presently eroded and preserved as a relic outcrop, see Fig. 6). This offset allows us to calculate a horizontal displacement rate of 36 ± 9 mm yr^{-1}. North of this, a minor drainage network provides evidence for systematic stream offsets ranging from 65 m to 160 m. Different amounts of incision characterize the analysed upstream and downstream channels, and thus reflect stream capture (e.g. Bellier *et al.*, 1999b). Taking this into account, the 'true' cumulative river offset deduced from the drainage network restoration (Fig. 8) is 370 ± 10 m. This yields a slip rate of 35 ± 8 mm yr^{-1} that better constrains the slip rate deduced from the imprecise fan and stream offsets.

In addition, the assumption that the mountain belt major stream network affected by the PKF segments S1 and S2 could have been installed coeval with the A2 older fan emplacement, at ~ 125 ± 20 ka, allows us to calculate a slip-rate using the Moa river stream offset of 3530 ± 20 m. This offset yields a slip rate of ~ 29 ± 5 mm yr^{-1}. Even if speculative, it is consistent with the slip-rate determined using offsets affecting Recent features.

Conclusion

The aim of this geological survey was to identify and quantify the active deformation of the northern part of the PKF over the period of the Holocene. The determined long-term slip of ~ 35 ± 8 mm yr^{-1} is in fairly close agreement with the GPS determined slip rate (Walpersdorf *et al.*, 1998b; Stevens *et al.*, 1999). It confirms that the PKF is a fast slipping fault with a relatively low level of seismicity. This suggests that either: (1) the fault is mechanically locked or (2) part of the fault displacement is aseismic. Hypothesis 1 would imply that the fault displacement is purely coseismic, produced by major earthquakes. Preliminary palaeoseismicity results (Beaudouin, 1998; Bellier *et al.*, 1998) do not support such an interpretation because they provide evidence for three 6.8 < Mw < 8 earthquakes along the PKF segment during the last 2000 years, implying a recurrence interval of about 700 years for Mw ~ 7–8 earthquakes. Even if the upper bound magnitude is chosen with a horizontal displacement per event of about 10 m (e.g. Wells and Coppersmith, 1994), those three events would have produced a cumulative offset of ~ 30 m whereas the ~ 35 ± 8 mm yr^{-1} long-term lateral slip rate yields an offset ranging between 54 and 86 m within 2000 years. Hypothesis 2 would imply that the preliminary palaeoseismicity results are consistent with a coseismic slip deficit. In such a case, a significant part of the fault displacement would be accom-

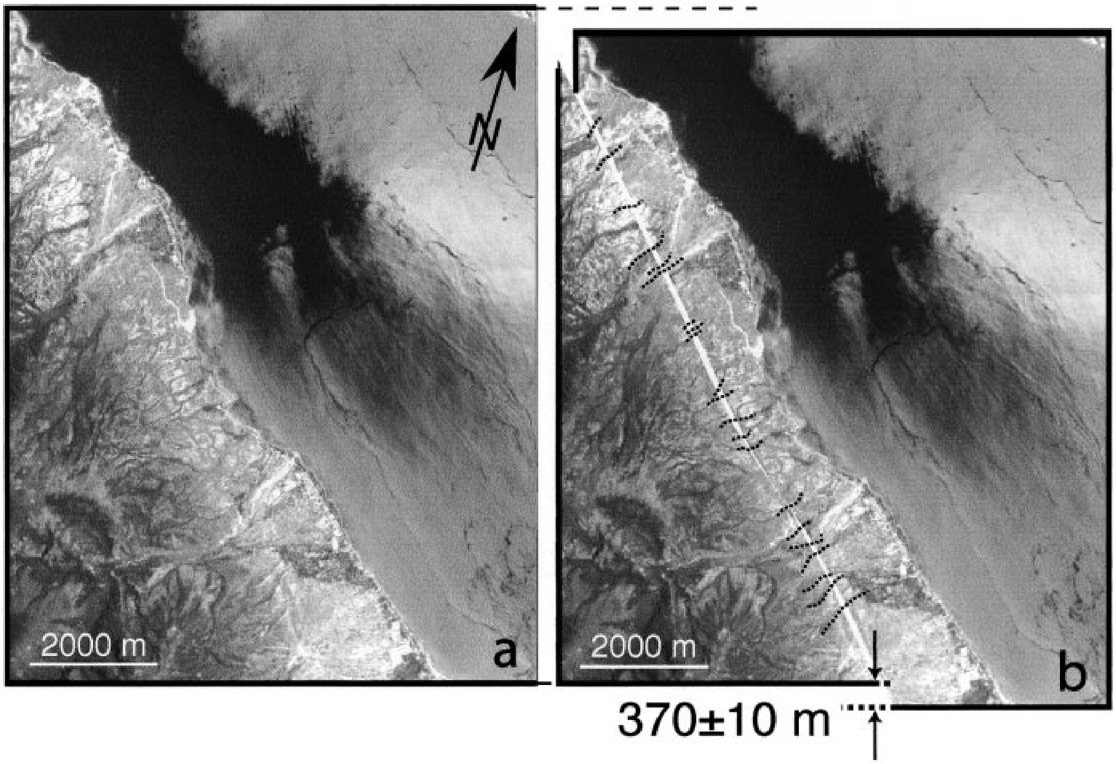

Fig. 8 Present-day (a) and restored (b) drainage along-strike PKF segments, shown on a detailed SPOT view. The restoration involves an offset of 370 ± 10 m. Location: see Fig. 6.

modated by creep, which is not presently evidenced by available GPS data (Walpersdorf *et al.*, 1998b; Stevens *et al.*, 1999).

Acknowledgments

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