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Transtensional deformation at the junction between the Okinawa trough back-arc basin and the SW Japan island arc

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Abstract: The Okinawa trough is a back-arc basin currently forming above the subducting Philippine Sea plate by crustal stretching of the Eurasia lithosphere. Existing geophysical investigations have revealed that the northern part of the Okinawa trough consists of a series of en echelon left-stepping grabens or half-grabens, some of which were formed in Miocene times and are presently inactive. In the Kyushu island, three major zones of extensional deformation are recognized. They are characterized by 20–40 km long sediment-filled basins lying on the hanging-wall side of N60°- to N80°-trending, north- or NW-dipping normal faults. These basins display an en echelon left-stepping arrangement. The ages of faulted rocks, the ages of graben-filling sediments and radiometric ages newly obtained on pseudotachylites associated with normal faulting indicate that extension started at 13 Ma at the southern end of Kyushu and migrated northwards in the middle part of Kyushu (Beppu Bay), where it is still active today.

The continentward-dipping, listric geometry inferred in depth for the fault systems is consistent with that of faults imaged by existing seismic profiles obtained off-shore in the Okinawa trough and across the Beppu Bay. The spatial association between Miocene or younger normal faults and pre-Miocene regional low-angle thrust faults suggests the possibility of a reactivation of some of the thrust faults as low-angle detachment faults merging in depth into a mid-crustal partial attachment zone.

Oblique rifting at divergent plate boundaries or along intracontinental rifts is a common process that has been described in many areas (Illies 1977; Angelier et al. 1981; Withjack & Jamison 1986, and references therein; Boccaletti et al. 1987; Dauteuil & Brun 1993, 1996; Schreurs & Colletta 1998, and references therein; Schumacher 2002). It has also been extensively studied through the means of analogue experiments (Withjack & Jamison 1986; Tron & Brun 1991; Schreurs & Colletta 1998; Acocella et al. 1999; Basile & Brun 1999; Mart & Dauteuil 2000). Oblique rifting within back-arc basins in the upper plate at convergent margins is a less common process. A notable example is provided by the Havre trough, currently opening behind the Kermadec trench and propagating southwards through the New Zealand arc in the Taupo Volcanic Zone (Caress 1991; Wright 1993; Benes & Scott 1996; Parson & Wright 1996; Wright et al. 1996; Delteil et al. 2002). The Okinawa trough, currently opening behind the Ryukyu trench

between SW Japan and Taiwan, is another example of oblique rifting. The aim of this chapter is to analyse the transtensional deformation linked with oblique rifting in the junction area where the rift propagates into the SW Japan arc. We also propose a cross-sectional model for the junction area in which the scattered near-surface extensional systems merge at depth into a hypothetical mid-crustal partial attachment zone as defined by Tikoff et al. (2002).

Geodynamical and geological outline

Present-day plate configuration and recent evolution

The study area is located behind the zone of convergence between the subducting Philippine Sea plate and the overriding Eurasia plate. The direction of relative convergence is about N45°W and the rate of convergence is between 4 and

5 cm a^{-1} (DeMets *et al.* 1990; Seno *et al.* 1993; El-Fiky *et al.* 1999). The Quaternary to present-day volcanic arc associated with the Philippine Sea plate subduction can be traced across Kyushu and the western part of Honshu (Fig. 1; Kamata 1998). Further south, it corresponds to an alignment of volcanic islands located behind the non-volcanic Ryukyu arc (Notsu *et al.* 1987). It can be discontinuously traced to Taiwan (Sibuet *et al.* 1995, 1998). In Kyushu, an east–west alignment of volcanoes, possibly related to back-arc rifting (Nakamura *et al.* 1985; Nakada & Kamata 1991), crosses the middle part of the island and is superimposed on the SW–NE volcanic arc related to the subduction.

The present-day N45°W direction of relative convergence has remained steady for the past 1.5 to 5 Ma. Before 1.5 to 5 Ma, the direction of relative convergence was NNW–SSE, as indicated by various onland shortening structures in central Japan (Matsuda 1980; Seno & Maruyama 1984; Angelier & Huchon 1987) and also in Taiwan (Angelier *et al.* 1986).

The Okinawa trough back-arc basin, which extends from Kyushu to Taiwan, has been forming since Miocene times behind the non-volcanic Ryukyu arc by crustal stretching and thinning of the Eurasia lithosphere (Lee *et al.* 1980; Kimura 1985; Letouzey & Kimura 1985, 1986; Sibuet *et al.* 1987, 1995, 1998; Park *et al.* 1998). The crust underlying the Okinawa trough is everywhere continental in nature and its thickness decreases from 27–30 km in the northeastern part near Kyushu to 15–18 km in the southern part near Taiwan (Iwasaki *et al.* 1990; Hirata *et al.* 1991; Sibuet *et al.* 1995).

Intraplate earthquakes reflecting tensional stresses inside the Eurasia lithosphere are clearly distinguishable from deeper interplate earthquakes distributed along a N45°E-trending, NW-dipping Wadati–Benioff plane (Eguchi & Uyeda 1983; Kao & Chen 1991). Whereas interplate earthquakes mostly show compressional mechanisms with NW–SE-directed *P* axes, intraplate earthquakes in the crust or upper mantle underlying the Okinawa trough display either extensional or strike-slip focal mechanisms (Kao & Chen 1991; Fabbri & Fournier 1999; Fournier *et al.* 2001). The strike-slip type mechanisms are more numerous in the northern Okinawa trough than elsewhere, and most nodal planes strike between north–south and N20°E for one family, and between N90°E and N110°E for the other family.

Global Positioning System (GPS) measurements have shown that the maximum rates of extension across the Okinawa trough are found in the southernmost part, where they reach 4 cm a^{-1} (Imanishi *et al.* 1996). Elsewhere, the rates are 1 cm a^{-1} or less.

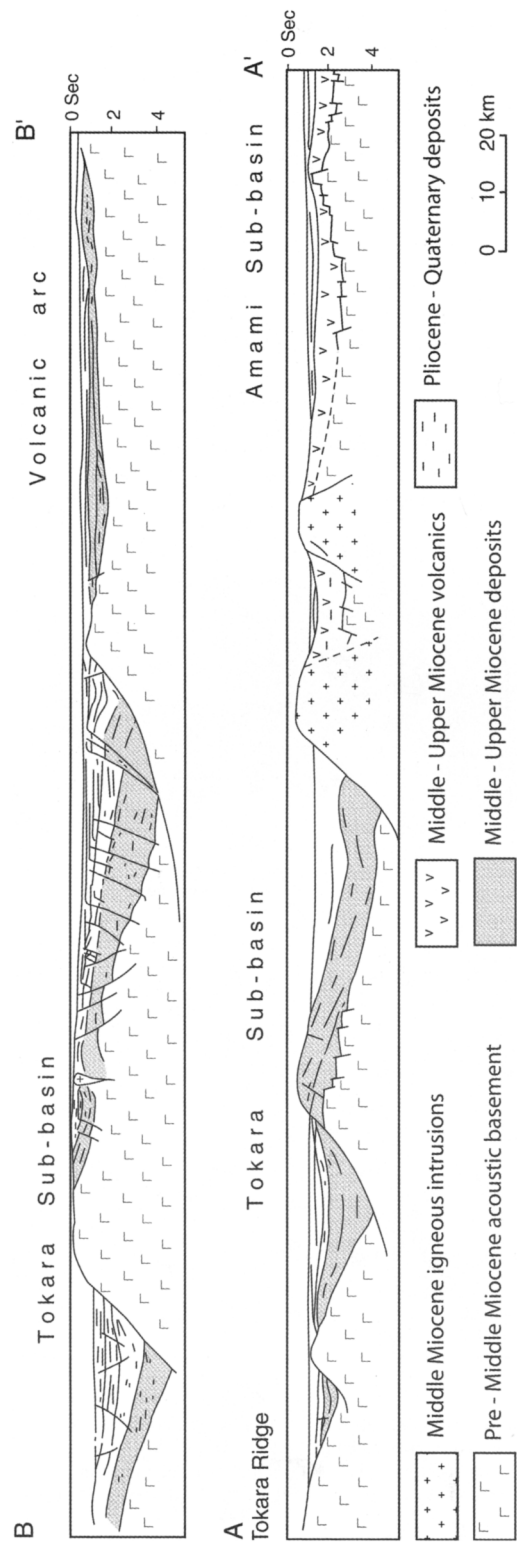## Structure of the northern part of the Okinawa trough

In the northern part of the Okinawa trough, water depths never exceed 1000 m. The geological structure has been studied with the help of seismic refraction and reflection, magnetic and gravity profiles (Aiba & Sekiya 1979; Nash 1979; Sibuet *et al.* 1987, 1995, 1998; Iwasaki *et al.* 1990). Seismic reflection profiles (Nash 1979) reveal that the northern Okinawa trough is not a unique graben but rather is composed of a series of basins and ridges that are hardly recognizable in the present-day bathymetry due to an extensive Quaternary sedimentary cover (Figs 1 & 2). Despite this difficulty, the following features can be mapped from the SE to the NW: (1) the non-volcanic Ryukyu arc represented by the Yakushima and Tanegashima islands; (2) the volcanic arc, a broad zone composed of deformed sedimentary rocks covered or intruded by Plio-Quaternary to present-day volcanic deposits, lava flows and sills; (3) the Tokara sub-basin, a series of half-grabens filled with at least 3000 m of Miocene–Pliocene sedimentary strata; (4) the Tokara ridge, locally emerging in the Koshiki islands; (5) the Goto sub-basin, inside which the thickness of the Miocene–Pliocene sedimentary strata exceeds 5000 m; (6) the Goto ridge; and (7) the East China Sea continental shelf. Southwestwards, the Tokara and Goto sub-basins merge to form a single graben system, the central Okinawa trough.

The basement of the ridges and basins is Middle Miocene in age or older. The basement rocks of the Koshiki islands consist of Cretaceous to Palaeogene sandstones and siltstones intruded by Middle Miocene granodiorite plutons. The basement rocks of the Goto islands consist of Miocene volcano-sedimentary strata intruded by Middle Miocene granodiorites or covered by Quaternary alkaline basalts. The oldest strata filling the various basins is of Pliocene or Miocene age (Nash 1979; Letouzey & Kimura 1985). Inception of normal faulting, subsidence and block tilting in the northern Okinawa trough is not accurately dated but likely took place during the Late Miocene. The youngest tilted strata are Pleistocene in age.

Two regional N20°E-trending zones of west-dipping normal faults can be mapped (Fig. 1). The Tokara Line fault zone, separating the volcanic arc from the Tokara sub-basin, is a major,
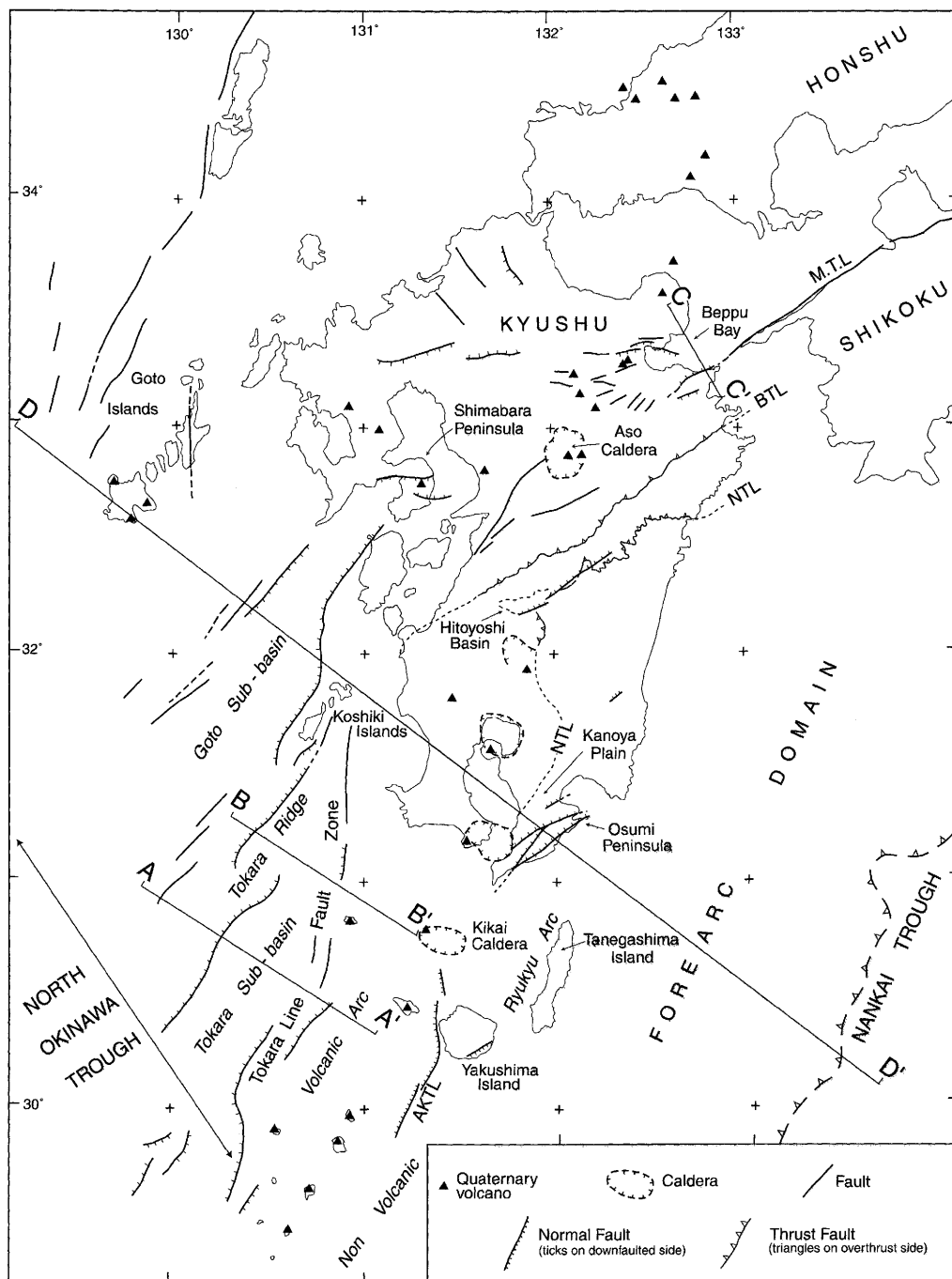
Fig. 1. Simplified structural map of the northern part of the Okinawa trough, northern Ryukyu arc and Kyushu island. Partly after Research Group for Active Faults of Japan (1991). AKTL, Amami–Kagoshima Tectonic Line; BTL, Butsuzo Tectonic Line; MTL, Median Tectonic Line; NTL, Nobeoka Tectonic Line. Cross-sections A–A′ and B–B′ are shown on Figure 2. Cross-section C–C′ is shown on Figure 8. Cross-section D–D′ is shown on Figure 10.

Fig. 2. Cross-sections across the northern part of the Okinawa trough. Modified from Nash (1979), with permission from the Japanese Association for Petroleum Technology. Location is given on Figure 1. Vertical scale is two-way travel time in seconds.

listric-shaped growth fault, which can be followed downward to more than 6000 m on seismic sections. Its northward extension is not precisely known. According to Nash (1979), it connects with the Butsuzo Tectonic Line (BTL, Fig. 1) in Kyushu. We retained the more north–south trend proposed by the Research Group for Active Faults of Japan (1991). The Amami–Kagoshima Line stretches between the non-volcanic Ryukyu arc and the volcanic arc. To the SW of the study area, it constitutes the eastern boundary of the Amami sub-basin, a small half-graben filled with about 2000 m of Pliocene sediments (Fig. 2, section A–A'). The Amami–Kagoshima Line cannot be imaged at depth on seismic profiles. Its downward geometry is thus unknown. It is still active today, at least at the latitude of Yakushima. Indeed, the anomalously high elevation of the Yakushima island, located immediately to the SE of the Amami–Kagoshima Line and culminating at 1935 m, the highest point in SW Japan, indicates a significant active uplift of the footwall block. According to Nash (1979), the Amami–Kagoshima Line can be traced through the Kikai and Ata calderas until the southern tip of Kyushu. The N60°E-trending normal faults crossing the southern part of the Osumi peninsula likely abut against the more northerly trending Amami–Kagoshima Line between the Ata and Kikai calderas. The faults bounding the Tokara and Goto half-grabens and other minor sub-basins have shorter extents than the Tokara or Amami–Kagoshima lines and are slightly oblique to them (Fig. 1). They strike between N40°E and N50°E, drawing an en echelon pattern that suggests formation under a right-lateral transtensional shear along a N20°E direction.

The asymmetric half-graben structures with master faults dipping away from the trench, which are characteristic of the northern part of the trough, are also recognized in the central part, where a multichannel reflection profile shows a probable detachment fault located between the Okinawa trough and the Ryukyu arc, and dipping northwards (Park et al. 1998).

Outline of the geological structure of Kyushu

The southern half of the Kyushu island, which belongs to the so-called 'Outer Zone' of SW Japan, consists of a stack of imbricate thrust sheets composed predominantly of Jurassic to Palaeogene clastic rocks (Murata 1981, 1987, 1991; Sakai & Kanmera 1981; Taira et al. 1982; Ogawauchi & Iwamatsu 1986; Nishi 1988; Kimura et al. 1991; Saito et al. 1996). The otherwise well-delineated Median Tectonic Line (MTL) of SW Japan disappears in eastern Kyushu, south of the Beppu Bay, beneath widespread Plio-Quaternary continental volcanic deposits. Clastic rocks involved in the thrust sheets get younger when going southwards closer to the Pacific Ocean. Jurassic rocks constitute thrust sheets located to the north of the Butsuzo Tectonic Line (BTL), a major regional thrust. Cretaceous rocks are found between the BTL and the Nobeoka Tectonic Line (NTL), another major regional thrust. Palaeogene to Lower Miocene strata are distributed southwards or eastwards of the NTL. A series of granitic to granodioritic plutons are intruded into the thrust sheets and their ages are well constrained and clustered around 14 Ma (Oba 1977; Shibata 1978). These plutons were considered as 'post-tectonic'. Although they undoubtedly post-date thrust sheet formation, several studies have shown that they are affected by normal faults (Oba 1961; Obata 1961; Nozawa & Ota 1967; Saito et al. 1996; Fabbri et al. 1997).

Diffuse extension across south Kyushu: geometry and kinematics of faults and chronology

In the southern half of Kyushu, post-15 Ma extensional faulting is observed in three key areas, which will be successively described.

Osumi region

The Osumi peninsula is located to the south of the Kyushu island (Fig. 1). Its southernmost tip is occupied by the Middle Miocene Osumi granodioritic pluton intruded in Eocene to Oligocene sandstones and mudstones of the Shimanto Group (Figs 3 & 4). The pluton is cut by a series of N60°E-trending normal faults dipping predominantly northwards (Obata 1961; Fabbri et al. 1997). Fault plane dips are between 45° and 80°. Given the lack of Miocene syntectonic deposits overlapping the faulted granodiorite, it is impossible to know whether normal faulting at Osumi was accompanied or not by block tilting. As mentioned above, the southern Osumi normal faults likely abut against the Amami–Kagoshima Line between the Ata and Kikai calderas.

Three fault zones can be distinguished. The northern fault zone separates the Osumi pluton from Palaeogene country rocks exposed to the south of the Kanoya plain, a flat-lying depression covered by Quaternary volcanic deposits of
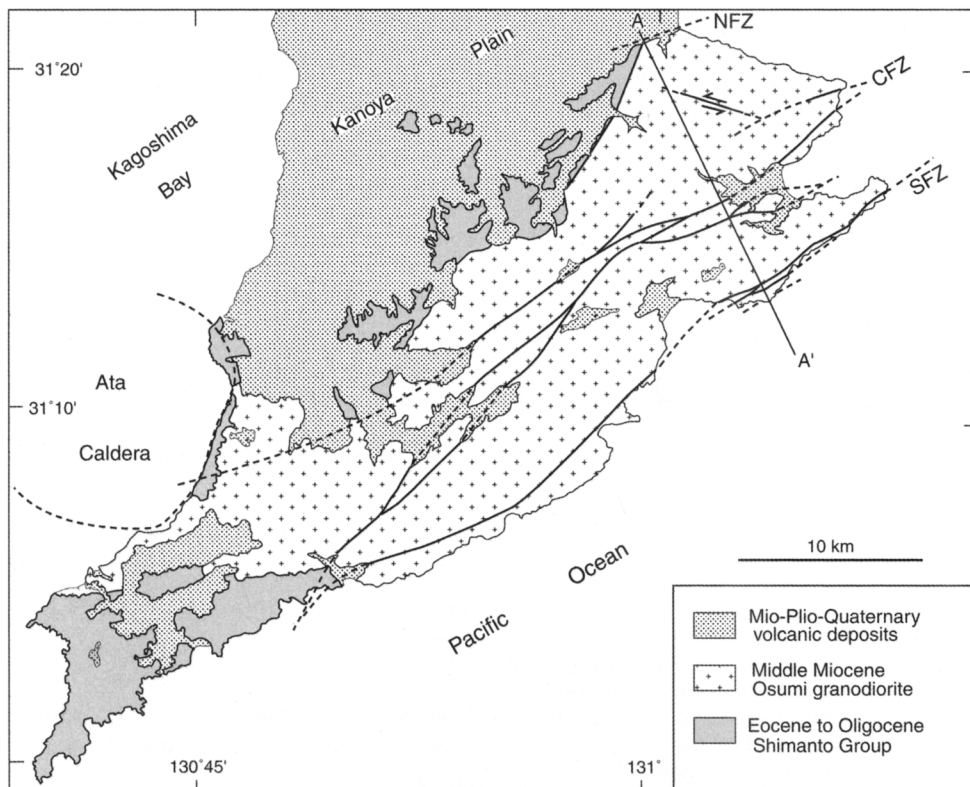
Fig. 3. Simplified geological map of the southern part of the Osumi peninsula.

unknown thickness. At least two faulting stages are recognized: a N30°E-trending, NW-dipping fault of unknown kinematics (Oba 1961) is displaced by a N65°E-trending, north-dipping normal fault (Fig. 3). The central and southern fault zones are well exposed and can be mapped across the entire length of the pluton. Along the central and southern fault zones, striations borne by fault planes indicate predominant dip-slip (Fabbri *et al.* 1997). Slip-sense indicators testify
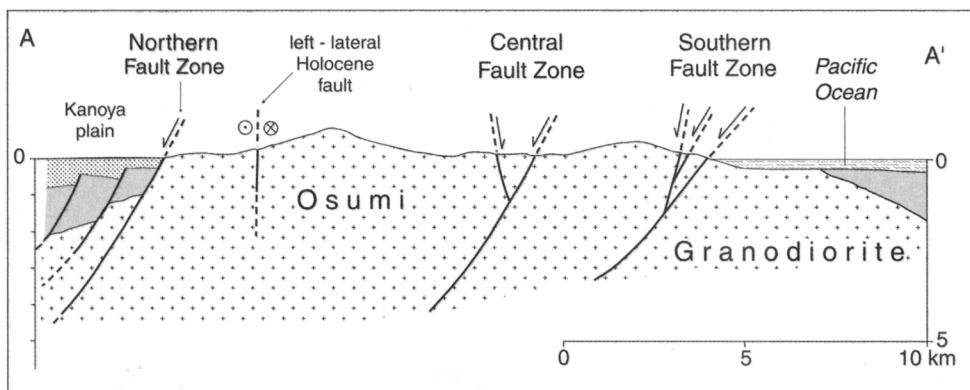

Fig. 4. Interpretative cross-section across the Osumi pluton and associated fault system (no vertical exaggeration).

to a normal slip component on all planes. The strike-slip component, which remains minor, is equally distributed between dextral and sinistral senses. In a few localities along the central fault zone, pseudotachylite veins are injected along or obliquely to the fault planes (Fabbri *et al.* 2000). The sense of shear indicated by the arrangement of these veins is always a normal one.

During the course of the present study, $^{40}Ar/^{39}Ar$ laser probe ages were determined both on biotite from the host granodiorite and on a pseudotachylite vein in the central fault zone (Table 1; for details on experimental procedure, see Monié *et al.* 1997). A single biotite grain from the granodiorite was progressively degassed using a defocused laser beam. It produces a partially discordant age spectrum (Fig. 5a) for which ages progressively increase from about 10 Ma until a plateau date of 14.1 ± 0.4 Ma calculated for 58% of the argon released. In the isotope correlation plot (Fig. 5b), the data display a good linear trend with an intercept age of 14.5 ± 0.4 Ma and an initial $^{40}Ar/^{36}Ar$ ratio that is lower than the present-day air value and results from the partial resetting of the biotite evidenced by the first heating steps. It is noticeable that this new $^{40}Ar/^{39}Ar$ biotite age is fully consistent with a K–Ar age of 14.5 ± 0.3 Ma obtained on a nearby rhyolite (Fabbri, unpublished data; Table 1). It is interpreted to record cooling of the Osumi pluton through 300 °C.

Pseudotachylite has been investigated in two ways. First, a small glass fragment optically free of any inclusions was progressively degassed. The corresponding age spectrum (Fig. 5c) shows apparent ages ranging from 10.0 ± 3.1 Ma to 18.6 ± 3.7 Ma and a plateau age of 13.0 ± 0.4 Ma for the less discordant portion of the spectrum. The isotope correlation plot gives

an intercept age of 13.2 ± 0.4 Ma with an atmospheric initial $^{40}Ar/^{36}Ar$ ratio (Fig. 5d). In a second experiment, a series of *in situ* laser ablations was performed across a 1 cm wide pseudotachylite vein using a focused laser beam. In the host granite, biotite in contact with the vein gives ages scattering from 12.9 ± 0.4 Ma to 19.8 ± 0.8 Ma (Fig. 5e). In the vein, 11 analyses yield ages ranging from 13.1 ± 0.3 Ma to 15.3 ± 0.4 Ma. This distribution is interpreted to result from the presence of numerous clasts (mainly quartz and feldspar) in the glassy matrix that has trapped a minor amount of excess argon during the formation of the vein. In the isotope correlation plot (Fig. 5f), the data are scattered along a line giving an intercept age of 13.2 ± 0.4 Ma and an initial $^{40}Ar/^{36}Ar$ ratio of 362 ± 26 that is indicative of excess argon contamination. The presence of excess argon in pseudotachylite veins is a common feature (e.g. Kelley *et al.* 1994) due to the fact that their injection along cracks occurs nearly instantaneously, allowing isotopic exchanges only at a very small scale. Excess argon released from the vein has also been trapped by host rock biotite immediately in contact with the vein. More than 1 mm from this contact, biotite displays an age of 12.9 ± 0.4 Ma, which is consistent with the minimum age of the vein, with the intercept age in the isotope correlation plot and with the data reported above concerning the analysed pseudotachylite glass fragment.

Therefore, we consider that these ages close to 13 Ma represent the best estimate for the pseudotachylite formation. Compared with published cooling ages obtained on the Osumi pluton (K–Ar on biotite, Shibata 1978; fission tracks on zircon and apatite, Miyachi 1985) and with the new $^{40}Ar/^{39}Ar$ biotite age on this pluton (this study), the $^{40}Ar/^{39}Ar$ dates of the

Table 1. *Synthesis of ages obtained on pseudotachylite veins and host granodiorite at Osumi*

Method	Sample number	Rock type	Dated material	Age $\pm 2\sigma$ (Ma)
K–Ar*	OF-1	rhyolite	whole rock	14.54 ± 0.33
$^{40}Ar/^{39}Ar$	96080303	granodiorite	biotite	14.1 ± 0.4
$^{40}Ar/^{39}Ar$	Q13	pseudotachylite vein	glassy matrix	plateau age: 13.0 ± 0.4 isochron: 13.2 ± 0.4
$^{40}Ar/^{39}Ar$ (localized fusions)	Q14	pseudotachylite vein	profile across the vein	minimum ages: 12.9 ± 0.4 & 13.1 ± 0.3 isochron: 13.2 ± 0.4

*K–Ar whole-rock age of a rhyolite is an unpublished datum.
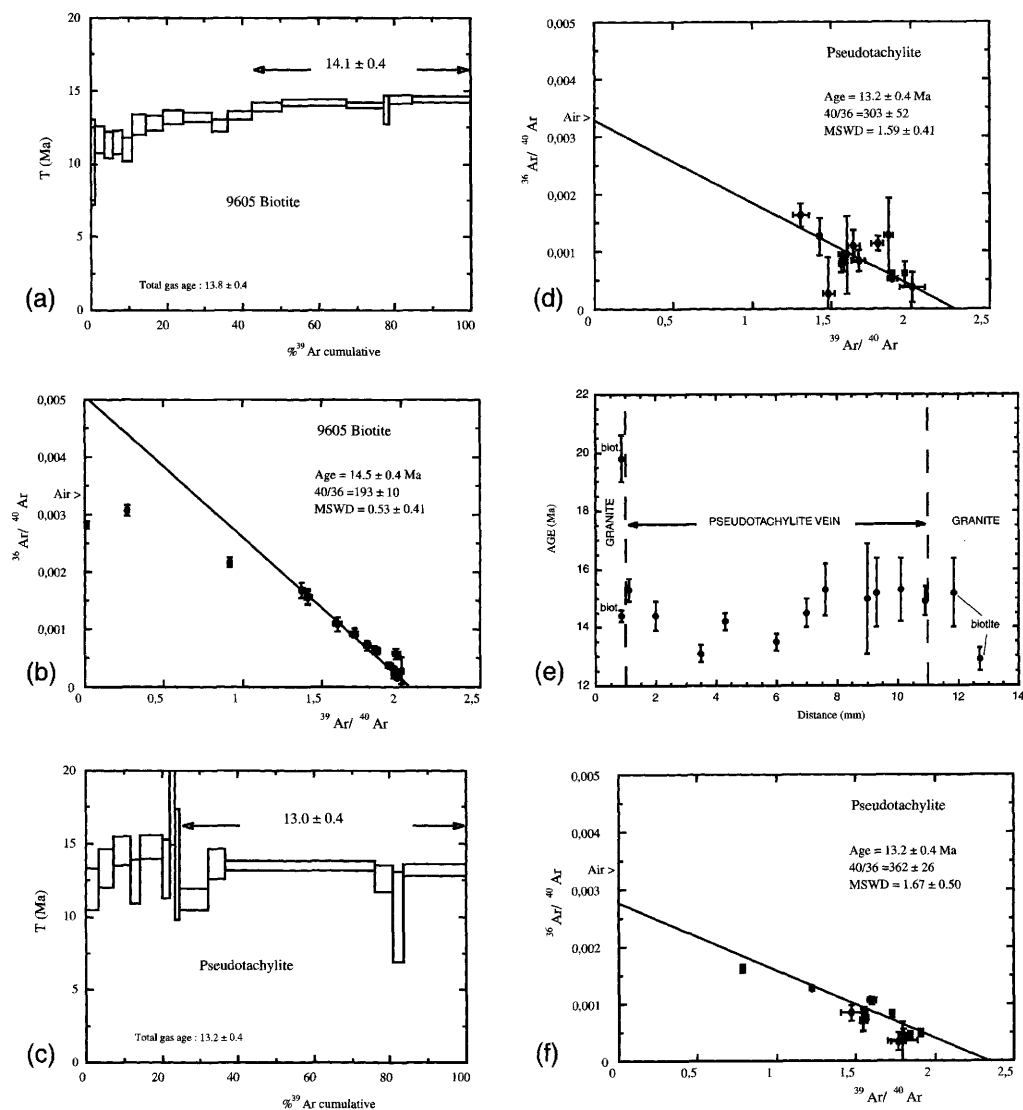
Fig. 5. Results of $^{40}Ar/^{39}Ar$ laser probe dating of Osumi granodiorite and pseudotachylite. (**a**) Age spectrum of a single biotite grain from the host granodiorite. (**b**) Isotope correlation plot corresponding to (**a**). (**c**) Age spectrum of a small glassy, clast-free, pseudotachylite fragment from the central fault zone. (**d**) Isotope correlation plot corresponding to (**c**). (**e**) *In situ* laser ablations carried out with a focused laser beam across a 1 cm thick pseudotachylite vein. Partially discordant ages reflect the influence of clasts in the glassy matrix. Minimum values of 12.9–13.1 Ma are likely the less influenced ages. (**f**) Isotope correlation plot corresponding to (**e**).

pseudotachylites indicate that the deformation took place coevally with the cooling of the pluton (Fig. 6). According to the Research Group for Active Faults of Japan (1991) and our own observations, with the exception of a single isolated left-lateral strike-slip fault located in the northeastern part of the pluton

(Fig. 3), the faults at Osumi are currently inactive. Quaternary sediments of the Kanoya plain seal faults of the northern zone (Fig. 3). The precise age of such unfaulted sediments remains unknown but can be estimated at 2 Ma (Research Group for Active Tectonics in Kyushu 1989). If this age is confirmed, it
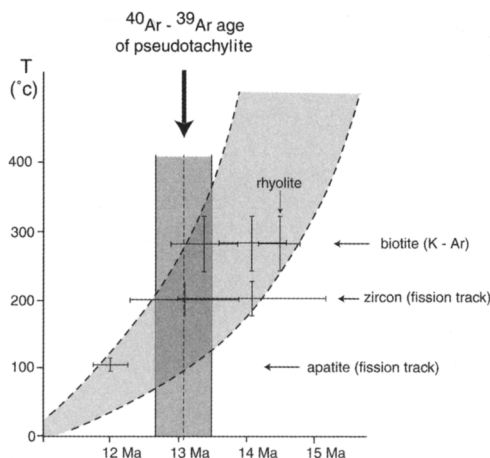
Fig. 6. Cooling ages of the Osumi granodiorite versus formation ages of Osumi pseudotachylites. K–Ar ages on biotites from the granodiorite are from Shibata (1978). Zircon and apatite fission track ages are from Miyachi (1985).

means that the faults at Osumi have been inactive for the past two million years.

Hitoyoshi–Ichifusa region

Like the Osumi peninsula, the northeastern part of the Ichifusa area is occupied by a 14 Ma pluton intruded into Cretaceous to Oligocene sandstones and mudstones of the Shimanto Group (Fig. 7). The strata of the Shimanto Group are arranged in kilometre-scale thrust sheets bound by N60°E-trending reverse faults (Saito et al. 1996; for simplicity, the reverse faults are not represented on Fig. 7). Thrust planes dip weakly to moderately (0–55°) northwestwards. Emplacement of the Ichifusa pluton clearly post-dates reverse faulting and thrust sheet formation. Both the pluton and the Shimanto rocks are cut by numerous normal faults trending N60°E and dipping 40–75° northwestwards (Saito et al. 1996). The largest dips (70–75°) are observed for faults inside the pluton whereas the smallest ones (40–50°) are found for faults in the Shimanto Group. Age of normal faulting is post-14 Ma but cannot be determined more precisely.

Normal faulting also affects the southwestern part of the Hitoyoshi–Ichifusa area. A conspicuous N50°E-trending, NW-dipping normal fault separates uplifted strata of the Shimanto Group at the footwall from Pliocene to Quaternary volcanic, lacustrine or fluviatile deposits of the Hitoyoshi basin at the hanging wall. To the

north or NW, the Plio-Quaternary deposits unconformably overlap the Shimanto Group. The Hitoyoshi basin thus appears as a half-graben. Plio-Quaternary deposits are not accurately dated. The age of the oldest strata in the graben is estimated at 3 Ma (Kano et al. 1991). According to the Research Group for Active Faults of Japan (1991), faults bounding the graben have displaced Holocene terrace deposits and thus are currently active.

Because of poor exposure quality, fault-slip data from the Hitoyoshi basin or from the Ichifusa pluton area are very scarce. At only two localities, Pliocene deposits show steeply dipping faults trending N45°E ± 20° (Tokushige & Fabbri 1996). Slip indicators testify to either normal slip (NW–SE extension) or oblique slip with a right-lateral component (NW–SE extension combined with NE–SW shortening).

Beppu region

The Beppu area is almost entirely covered by Pliocene to Quaternary lava flows, pyroclastic deposits and subordinate lacustrine or fluviatile deposits (Kamata 1989; Mizuno 1992). These strata are cut by a series of east–west normal faults defining a graben (Kamata 1989; Chida 1992). Outside the graben, pre-Miocene basement rocks are locally exposed, whereas, inside the graben, they have subsided to about 3000 m below the surface, as shown by Bouguer gravity anomaly, seismic reflection profiling and drilling. Based on seismic reflection profiles, Yusa et al. (1992), Yamakita et al. (1995) and Ito et al. (1996) interpreted the Beppu graben as a half-graben developed above the northward-dipping MTL reactivated as a master detachment fault during Plio-Quaternary times (Fig. 8). Timing is not accurately known, but the oldest rocks drilled in the Beppu graben are 6 Ma old, thus providing a maximum age for the inception of the subsidence in the half-graben.

Geodetic measurements (Tada 1993; Nishimura et al. 1999), faulting of Holocene volcanic deposits and historical seismicity (Research Group for Active Tectonics in Kyushu 1989; Research Group for Active Faults of Japan 1991) show that extension is still active and is directed north–south.

Summary

Extension-related structures in the three studied areas show the following characteristics:

1   most normal faults, especially the laterally consistent ones, strike N50° to N90°E and
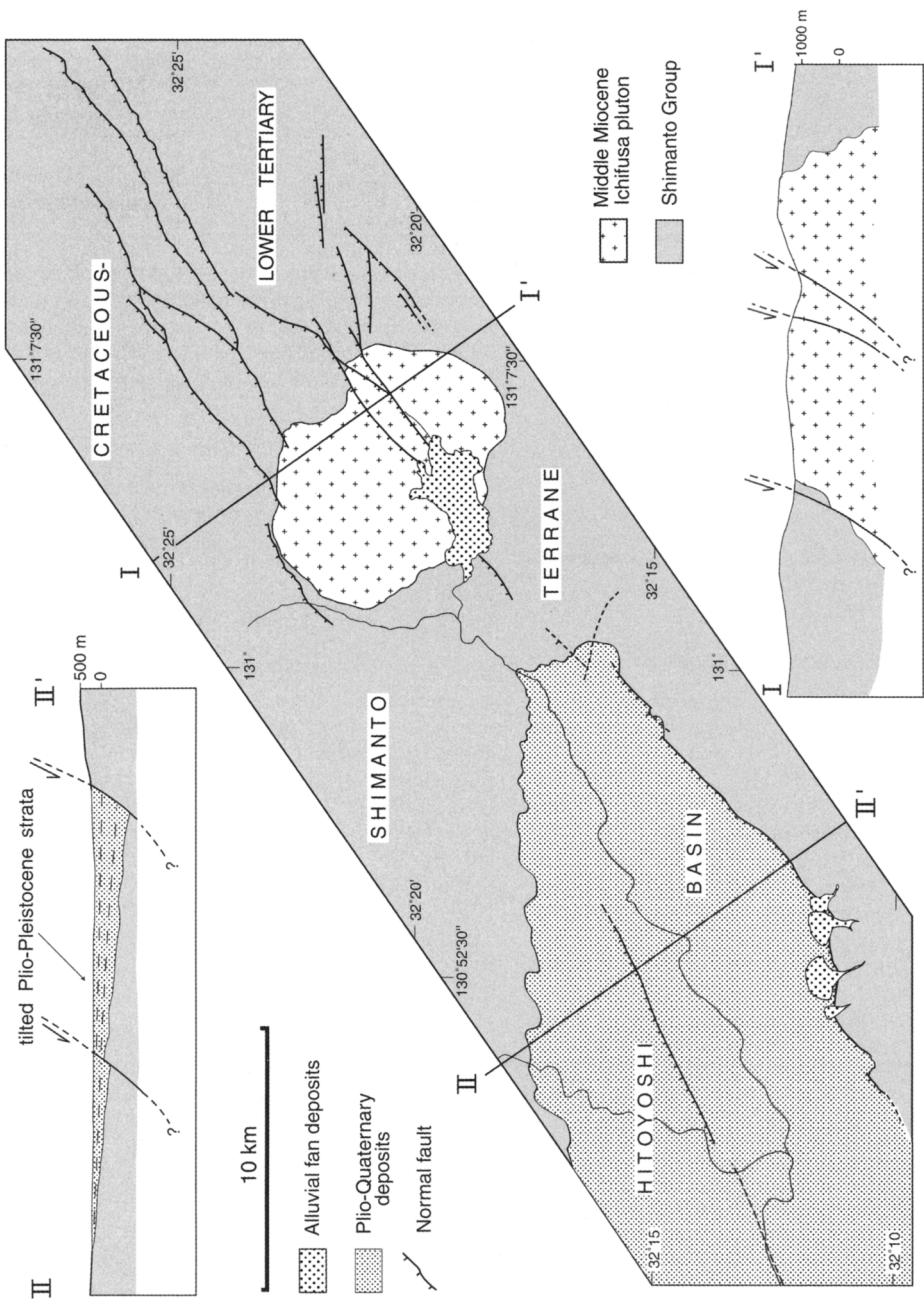
Fig. 7. Simplified geological map and cross-sections of the Hitoyoshi–Ichifusa area and associated fault system. Partly after Saito *et al.* (1996). For simplicity, traces of thrust faults are omitted. No vertical exaggeration on cross-sections.
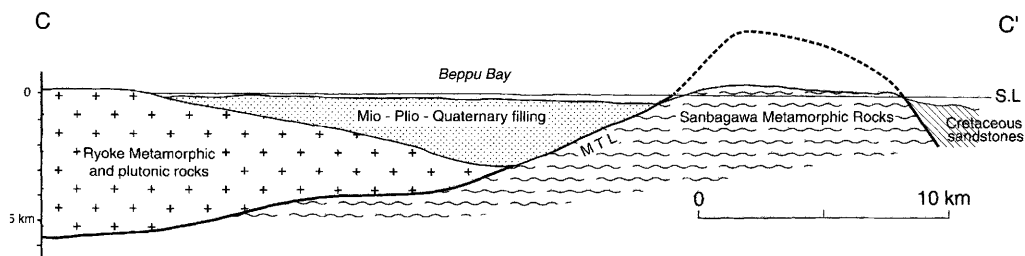
Fig. 8. Section across the Beppu Bay (section C–C′ on Fig. 1). Modified after Yamakita *et al.* (1995). SL, sea level.

dip moderately to steeply towards the north or the NW;

2 in the two areas of Hitoyoshi–Ichifusa and Beppu, a half-graben developed upon a master northward-dipping normal fault, suggesting block tilting;

3 activity of normal faults has a maximum age of 14 Ma, and took place at 13 Ma at Osumi;

4 normal faults are still active at Beppu and at Hitoyoshi, but have been inactive since about 2 Ma at Osumi.

Proposed model of evolution of the Okinawa–Kyushu junction area

Transtension in the northern Okinawa trough–Kyushu region

At the junction between the Okinawa trough back-arc basin and the SW Japan arc, the extension-related structures are characterized in cross-section by an asymmetric half-graben structure and, in map view, by a left-stepping en echelon arrangement. This distinctive geometry requires a combination of extension and right-lateral shear along a N10° to N30°E direction (Fig. 9). The right-lateral shear implies that the oceanward side of the arc has been moving south to SW relative to the back-arc domain (continent). Such a right-lateral motion has already been proposed in the northern and central parts of the Okinawa trough by Fournier *et al.* (2001) to account for the present-day kinematics and more precisely to explain the right-lateral motion along north–south- to N20°E-trending nodal planes of focal mechanisms for earthquakes in the region. This general motion also accounts for Quaternary right-lateral motion along the MTL in western Shikoku and eastern Kyushu, and along N20° to N30°E-trending faults in central Kyushu (SW of Aso caldera, Fig. 1). The scenario proposed by Fournier *et al.*

(2001) associates a perpendicular opening in the southern part of the Okinawa trough and an oblique transtensional opening in the northern part of the trough (Fig. 9).

Accommodation of extension through reactivation of thrust faults

The spatial association between Miocene or post-Miocene extensional structures and pre-Miocene shortening structures is obvious in the Beppu Bay and Hitoyoshi–Ichifusa areas. As already noted by Yusa *et al.* (1992), Yamakita *et al.* (1995) and Ito *et al.* (1996), the Beppu graben is in the hanging wall of the MTL, which was reactivated as a normal fault in Plio-Quaternary times. Reverse motion along the MTL near Beppu dates back to the Oligocene or earlier (Yamakita *et al.* 1995). Normal faults also developed in the vicinity of the NTL (Fig. 1), a major fault whose reverse motion accumulated before the Middle Miocene (as attested by the cross-cutting Ichifusa pluton). Though still to be ascertained by field or subsurface evidence, reactivation of the NTL as a detachment fault could explain the development of normal faults in the pre-Miocene Shimanto Group as well as in the Ichifusa pluton. In the Osumi area, the spatial link between Miocene or younger normal faults and the pre-Miocene thrust faults is less obvious than in the two other areas because of the widespread Quaternary cover of the Kanoya plain and of the sea. Geophysical investigations are obviously needed to allow a better understanding of the possible spatial or genetic links between the two kinds of faults in the Osumi area.
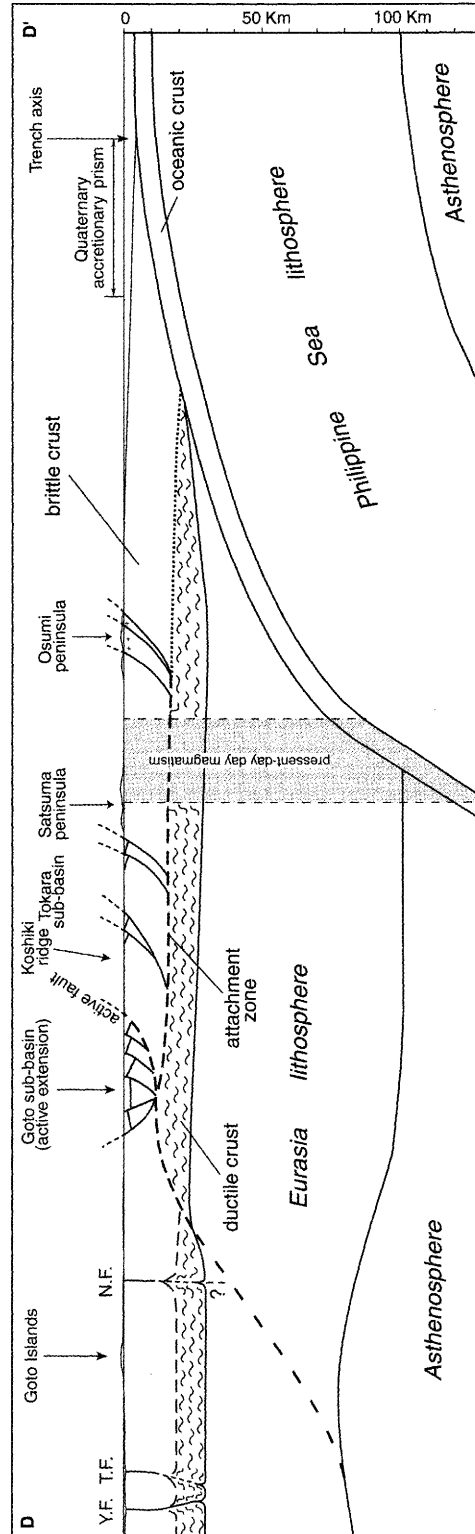
Cross-section model

Figure 10 depicts a schematic cross-section of the present-day convergence between the Philippine
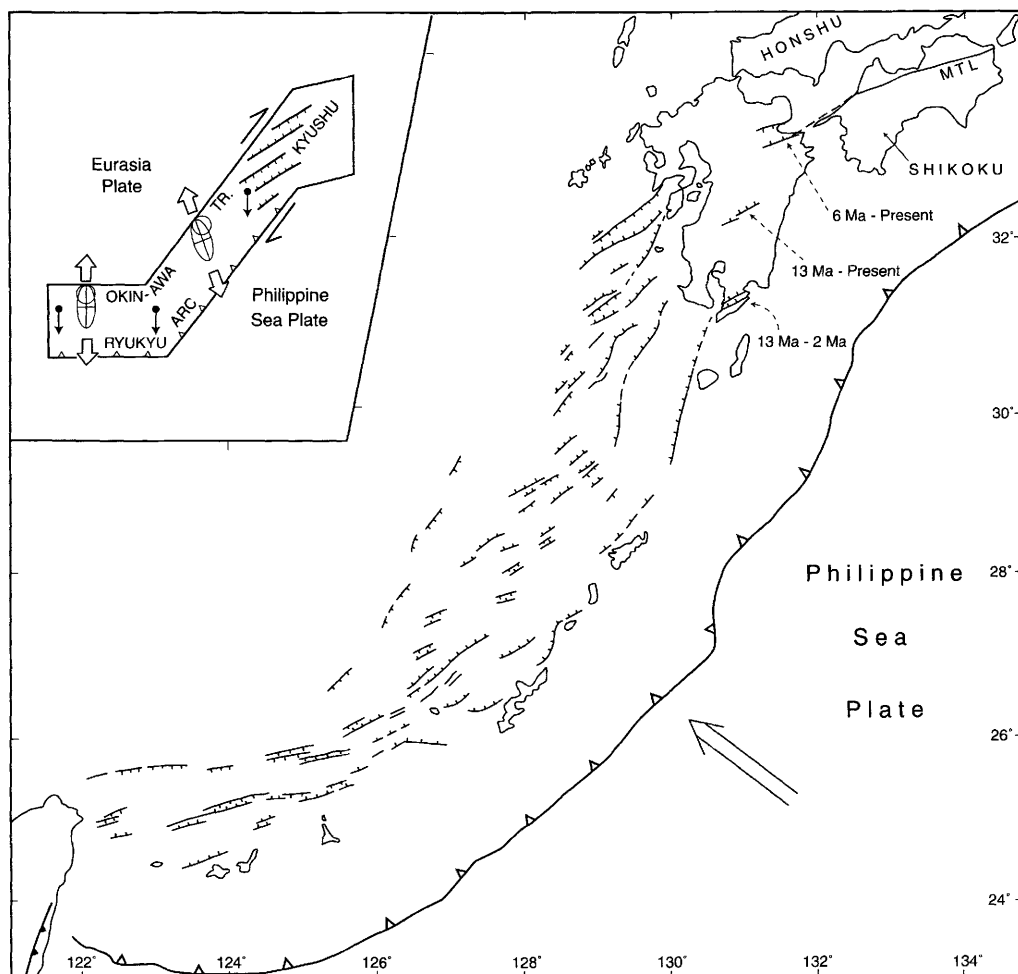
Fig. 9. Perpendicular extension in the southern part of the Okinawa trough versus oblique opening in the northern part of the trough and in Kyushu. Modified after Sibuet *et al.* (1987) and Fournier *et al.* (2001). The arrow represents the relative direction of convergence between the Philippine Sea and Eurasia plates. Absolute ages are the estimates for the periods of extension in the three areas of Osumi (13–2 Ma), Hitoyoshi–Ichifusa (13 Ma to present) and Beppu (6 Ma to Present). Inset: Geometric relationship between the direction of extension (large divergent arrows) and the direction of relative displacement of the Ryukyu arc relative to Eurasia. In the southern Okinawa trough, the direction of extension is parallel to that of relative displacement, whereas it trends halfway between the direction of relative displacement and the perpendicular to the rift, as shown by Withjack & Jamison (1986) and Tron & Brun (1991).

Sea and Eurasia plates. We propose that the normal faults in southern Kyushu (Osumi on the section) and those bounding the half-grabens in the northern Okinawa trough extend downwards through the entire brittle upper crust and merge into a partial attachment or coupling zone at the transition between the ductile lower crust and the upper brittle crust (Tikoff *et al.* 2002). The attachment zone could explain present-day and past extension in

apparently scattered individual basins in the junction area, in a way similar to that described in eastern Greenland by Larsen (1988), with the difference that, in the present case, a strike-slip component is also recorded. Furthermore, it could provide kinematic linkage between the upper crust undergoing heterogeneously distributed brittle deformation and the lower crust characterized by distributed ductile deformation. Toward the continent, the attachment zone could

Fig. 10. Idealized cross-section showing partial attachment/coupling (in the sense of Tikoff *et al.* 2002) at the transition zone between the brittle upper crust and ductile lower crust of the Eurasia lithosphere (section D–D' on Fig. 1; no vertical exaggeration). The crustal thickness of the arc (26–30 km) is after Iwasaki *et al.* (1990). The dip of the Wadati–Benioff plane is after Nagamune & Tashiro (1989). Yangsan fault (YF), Tsushima fault (TF) and Nakadori fault (NF) are regional strike-slip faults.

either cross the Eurasia lithosphere, in accordance with the lithosphere-scale simple shear model (Wernicke 1985), or merge with a lithosphere-scale vertical strike-slip zone, following the model of Teyssier & Tikoff (1998). In this last model, the lithospheric strike-slip zone could lie beneath the noth–south to NE–SW strike-slip faults known in the vicinity of the Goto islands and further north (Figs 1 & 10). Alkaline basalts exposed in NW Kyushu and in the Goto islands and radiometrically dated between 12 and 1 Ma (Nakamura *et al.* 1985; Kano *et al.* 1991), which could reflect the upwelling of the asthenospheric mantle beneath the Goto sub-basin where the extension is active, would favour the lithosphere-scale simple shear model. Additional data, especially geophysical, are needed to help make precise the geometry of the attachment zone toward the continent.

Conclusion

Mapping of normal faults in the Kyushu–Okinawa trough junction area, along with the dating of the fault motion, leads to the following results. Firstly, it shows that extension started in the junction area as early as Middle Miocene times (*c.* 13 Ma), as already suggested off-shore by Letouzey & Kimura (1985, 1986). Secondly, it confirms that extension was combined with dextral strike-slip shear. Thirdly, it demonstrates that crustal stretching is not restricted to a narrow graben, but encompasses a wide area inside which localization of extension has evolved through time. The distributed transtensional deformation at the junction between a nascent back-arc rift and an arc, which appears to be a characteristic of the study area, was likely favoured by the normal-slip reactivation of low-angle thrust faults, which are widespread in the fore-arc and arc domains.

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