

4 The Geology and Tectonics of Kyushu. Part 2: Tectonic Evolution of southwest Japan since 15 Ma

The tectonics of southwest Japan has undergone complex and marked changes over the last 15 Ma, but throughout this period it has been dominated by the interaction between the Philippine Sea Plate (PSP) and the Amur, or Amurian Plate (which is considered a “sub-plate” of the Eurasian plate) (Figure 3.1). The major driver of tectonics in southwest Japan over the last 15 Ma is the ever-evolving subduction history of PSP. This contrasts with northern Japan which has been experiencing relatively straightforward, long-lived subduction of the Pacific Plate in a northwest direction beneath northern Japan. The subducting PSP can be spatially split into two parts of significantly different ages separated by the Kyushu Palau Ridge (KPR), with Eocene-Cretaceous PSP crust of the West Philippine Basin subducting at the Ryukyu trench and beneath southern Kyushu, and younger (27-15 Ma) Shikoku basin crust subducting at the Nankai Trough. The age difference of the subducted segments of the PSP has a crucial influence over the angle of subduction achieved by each slab segment, which in turn has an important spatial control on the complexity of the tectonic and volcanic evolution of this region. This will be discussed fully in this Section, and later Sections.

For convenience of discussion, the tectonic development in southwest Japan since 15 Ma can be broken down into periods from 15-10 Ma, from 10-6 Ma, from 6-2 Ma and from 2 Ma - present.

4.1 15 Ma to 10 Ma

A summary of the tectonic configuration during the 15-10 Ma period is shown in Figure 4.1. By 15 Ma, back-arc rifting in the Sea of Japan and spreading in the Shikoku Basin had ceased.

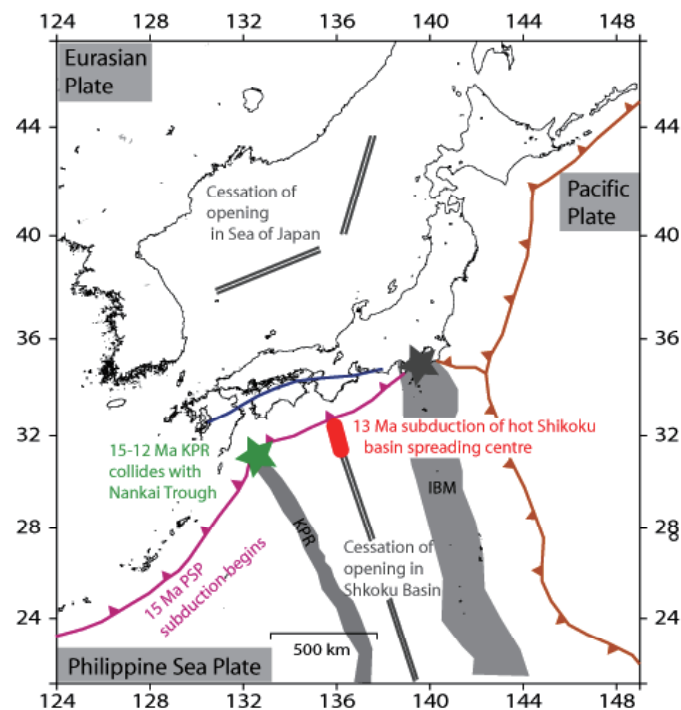


Figure 4.1. Major tectonic events occurring in the time period 15-10 Ma. At 15 Ma the Sea of Japan and Shikoku Basin ceased spreading. Between 15-12 Ma the Kyushu Palau Ridge collides with the Nankai trough (green star shows subduction point). At 13 Ma the hot spreading centre of the Shikoku basin begins to subduct (thick red line shows subduction point). The Median Tectonic Line (blue line) shows normal faulting during the mid Miocene. KPR = Kyushu-Palau ridge; IBM = Izu Bonin Marianas arc; PSP = Philippine Sea Plate

The northern margin of the Shikoku basin reached southwest Japan at roughly 15 Ma, and PSP/Eurasian relative plate motions were such that the PSP began to subduct northwards beneath the Eurasian Plate (Watanabe, 2005). The basement of this central zone is intruded by a line of mid Miocene (15-10 Ma) I-type felsic granite plutons, providing good evidence for subduction related volcanism occurring at approximately 15-10 Ma in this area (Kimura et al., 2005). The continued northward subduction of the PSP also led to the collision of the Kyushu Palau ridge with the Nankai Trough, at around 15-12 Ma (Kimura et al., 1996). The Shikoku basin crust was still very young when it began subducting beneath Eurasia, with volcanic activity in the Shikoku basin continuing until around 12 Ma, as recorded on the Kinan seamounts (Kobayashi et al., 1995). As such, at around 13 Ma the most recently active spreading centre of the Shikoku basin began subducting beneath southwest Japan. The response to this was distinctive adakitic fore-arc volcanism (Takahashi et al., 1999).

4.2 10 Ma to 6 Ma

Some workers propose that northward subduction of the PSP beneath the Eurasian Plate ceased from 10-6 Ma (Uto, 1989; Kamata, 1992) (Figure 4.2). Conflicting views are held by other authors who either suggest there was no late Miocene halt in subduction of the PSP (e.g. Kimura et al, 2003), or suggest an alternative time period for a 'stagnant' phase in subduction (e.g. Taira, 2001 suggests 14-8 Ma).

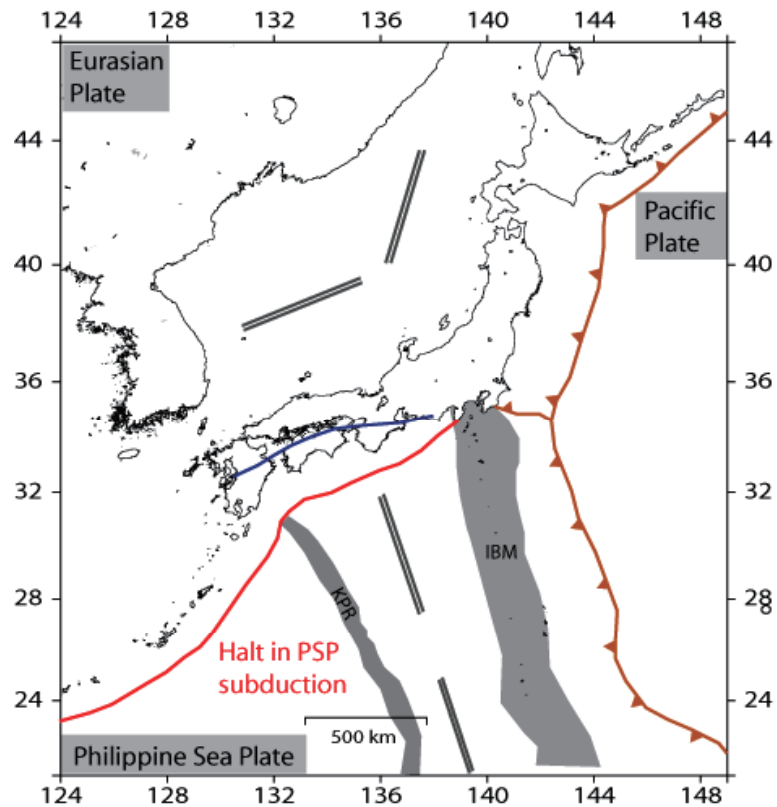


Figure 4.2: Major tectonic changes occurring in the time period 10-6 Ma.

The proposed halt in subduction is summarised by Kamata and Kodama (1994) and mainly supported by volcanic evidence (i.e. lack of a subducted plate signature in erupted lavas during this time). Whether or not there was an actual halt in PSP subduction from 10-6 Ma is inherently difficult to resolve, as it is very challenging to find direct evidence for an actual halt in subduction of the PSP slab, while it is much more straightforward to recognize initiation of subduction-related processes (e.g. arc volcanism, back arc spreading etc).

4.3 6 Ma to 2 Ma

In Kyushu, characteristics of the modern-day subduction regime began around 6 Ma, as shown in Figure 4.3. Re-initiation of subduction was accompanied by a change in subduction direction, with the PSP subducting in a NNW direction (Seno, 1989). The NNW direction of PSP subduction meant that the intersection point of the Kyushu Palau ridge with the trench migrated north east along the Nankai Trough. Subduction of the PSP beneath the Ryukyu arc at this time was coincident with the commencement of back arc rifting in the Okinawa Trough (e.g., Sibuet et al., 1987). NNW subduction of the PSP at the Nankai trough during this time period was nearly perpendicular to the plate boundary (e.g., Kamata and Kodama 1994) (compared with the present day, where there is currently dextral obliquity).

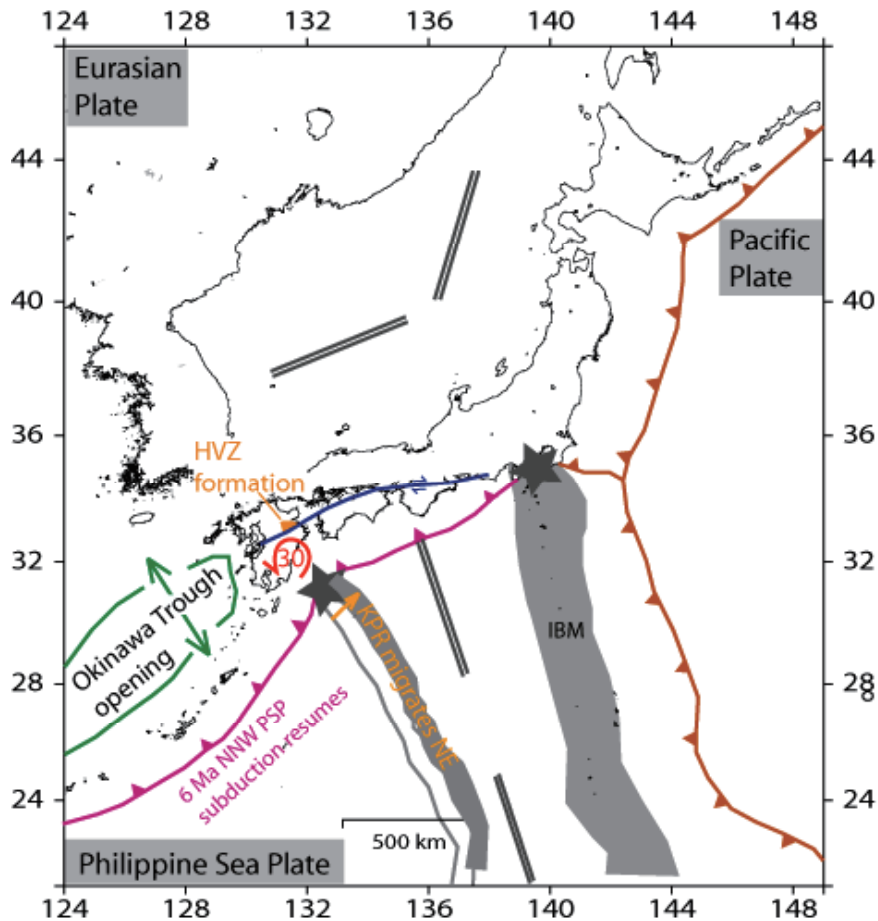


Figure 4.3: Major tectonic changes occurring in the time period 6-2 Ma. The Philippine Sea Plate (PSP) began subducting once again, in a NNW direction. The Kyushu Palau ridge (KPR) subduction point began migrating NE up along the Nankai Trough due to relative plate motions. The Okinawa Trough began opening. The MTL began dextral motion, and there was clockwise rotation of the forearc sliver in south Kyushu. The Hohi volcanic zone (HVZ) formed on the edge of the Median Tectonic Line (MTL). IBM = Izu Bonin Mariana arc.

Palaeomagnetic data led Kodama and Nakayama (1993) to conclude that southern Kyushu underwent about 30 degrees of anticlockwise rotation after the latest Miocene. Anticlockwise rotation of southern Kyushu also facilitated rifting in the Beppu-Shimabara Graben (BSG) region. Evidence for extensional deformation in southern Kyushu for the past 5 Ma (Tada, 1985; Yamaji, 2003), and slab rollback of the PSP after 5 Ma (Yamaji, 2003), is also consistent with the anticlockwise rotation of southern Kyushu since ~6 Ma. Wallace et al. (2009) suggest that anti-clockwise rotation of southern Kyushu occurs in response to the along-strike change in buoyancy properties of the subducting PSP (e.g., along-strike change from young Shikoku Basin subduction to subduction of the Eocene-Cretaceous crust of the West Philippine Basin).

North of the MTL in northeastern Kyushu, a rectangular volcano-tectonic depression 70 km long and 40 km wide (the Hohi volcanic zone and associated Beppu Graben), began forming at ~6 Ma (Kamata & Kodama, 1994). Temporal evolution of volcanism in the Hohi Volcanic Zone suggests that volcanism subsequently migrated inwards towards the central part of the current Beppu graben (Kamata, 1989; Kamata & Kodama, 1994; Figure 4.4).

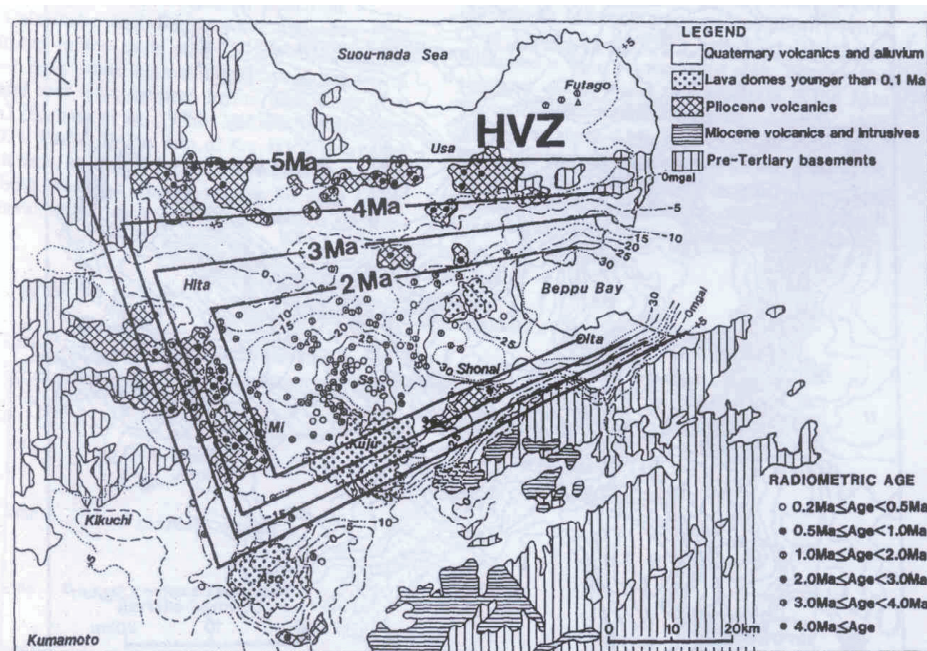


Figure 4.4: Evolution of volcanism in the Hohi Volcanic Zone after Kamata and Kodama (1994). Radiometric ages of volcanic rocks are shown. This map demonstrates that older volcanics occur on the outer boundaries of the graben, while younger deposits concentrate in the centre of the Graben.

Extensional faulting also migrated in the same fashion, from a 45-km-wide zone in 5-6 Ma to a 11 km-wide zone around 1 Ma (Katama, 1989). Presence of lineations (old faults?; see Figure 6.1) parallel to and outside (north and south) the current graben boundaries from analysis of gravity and magnetism maps support the inward migration of faulting. This inward migration of faulting is common in rifts worldwide, as the crust gets thinner along the rift axis, the boundary faults become inactive and activity shifts to the axial faults (Ethiopian Rift: Hayward and Ebinger, 1996; Taupo Rift, New Zealand: Villamor & Berryman, 2006). This also agrees with the presence of thinner seismogenic crust in the Beppu graben area than that outside the graben (Figure 4.5).

4.4 2 Ma to Present

Since the beginning of the Quaternary, Kyushu has entered its latest tectonic phase (see Figure 4.6). At this time the PSP shifted its subduction direction from NNW to NW (Matsuda, 1980; Nakamura et al., 1984; Okamura, 1988). This resulted in an increased dextral component of subduction, leading to intensified dextral motion along the Median Tectonic Line (MTL) (Kamata and Kodama, 1994; Kamata, 1998; Itoh et al., 1998a). Okada (1980), Ichikawa (1980) and Sangawa (1986) suggest that the MTL was a thrust/reverse fault in the early Quaternary and then became a dextral strike-slip fault during the second half of the Quaternary.

The change in PSP subduction direction also heralded a change in migration direction of KPR along the PSP-Eurasian margin. Since 2 Ma the position of the KPR subduction has been migrating southwestward, opposite to the previous direction (Figure 4.7). There may have also been a decreasing rate of extensional deformation in the Hohi area (Beppu Graben) with time (Kamata and Kodama, 1999), which could be related to encroachment of the KPR and subduction of the buoyant Shikoku Basin beneath northeast Kyushu (thus lessening the extensional stress in the region with time). Between 1-0.7 Ma, a north-south extensional stress

field was present in the Hoho volcanic zone (Kamata et al., 1988). By 0.7 Ma, a compressional stress regime was active within the Hoho volcanic zone, in particular in the area of the Shishimuta caldera (Kamata et al., 1988).

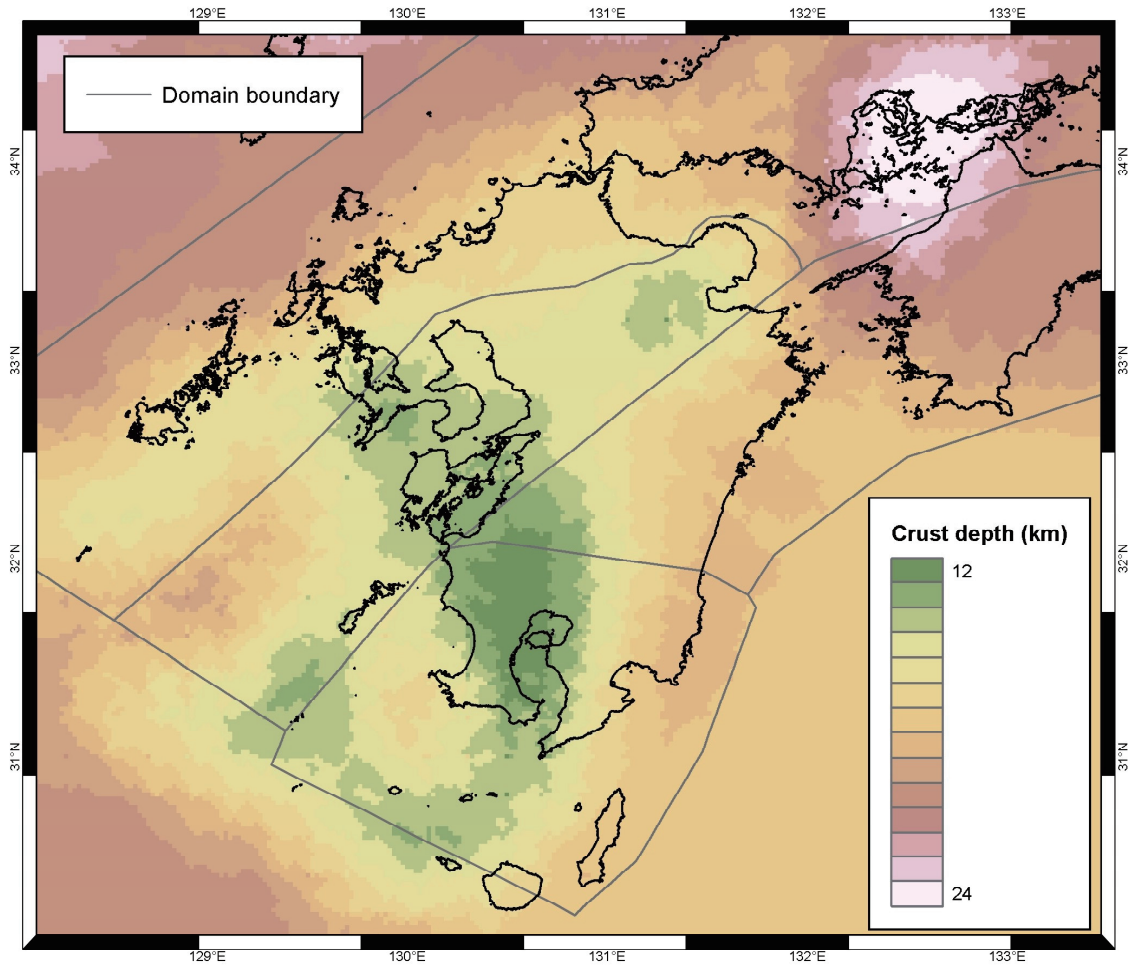


Figure 4.5: Map of the depth of the seismogenic crust from earthquake depth distribution data

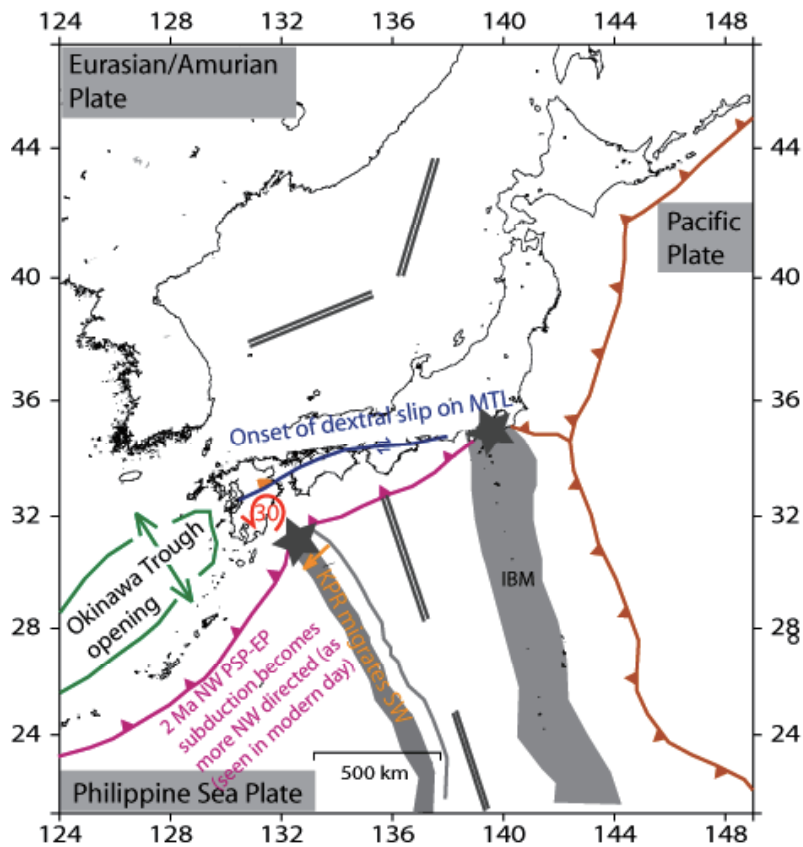


Figure 4.6: Major tectonic changes occurring in the time period 2-0 Ma. The Philippine Sea Plate (PSP) changed subduction direction to NW, which caused an onset of dextral motion on the Median Tectonic Line (MTL). The KPR began migrating SW along the Nankai Trough due to the change in plate motion direction. This may have caused a change from extensional to compressional regime in the HVZ leading to a slow down in magma production.

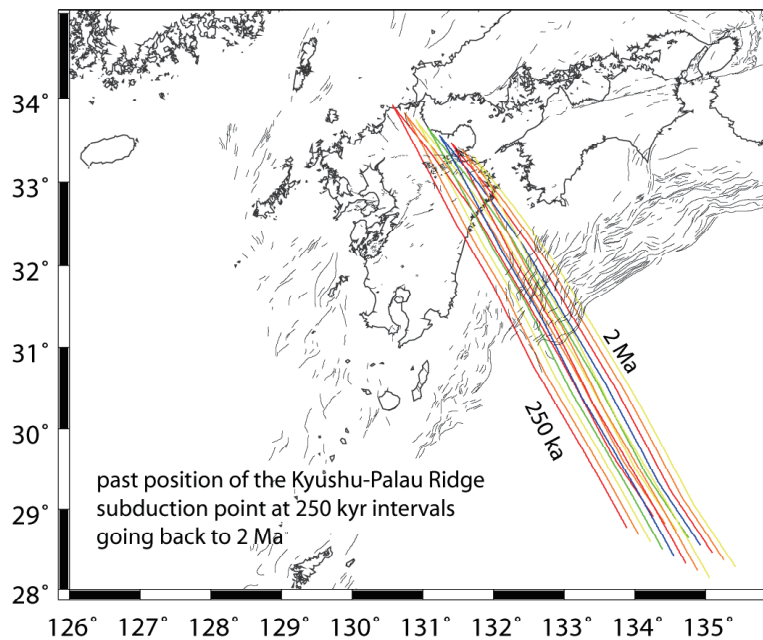


Figure 4.7: Reconstruction of the position of the Kyushu-Palau ridge from 250 ka to 2 Ma, shown at 250 ka intervals. Ridge position reconstructed based on present-day relative motion between the Philippine Sea Plate and the Amurian Plate. This shows that the ridge was subducting adjacent to the NE end of Kyushu at 2 Ma, and has since migrated southwest to its current position.

4.5 Present Day Tectonic Situation

Current tectonics in Kyushu is dominated by $\sim 72\text{--}79$ mm/a convergence of the PSP and the Amurian Plate at a slightly oblique (right-lateral sense) angle. Strike-slip and extensional faulting is ongoing in the BSG in central Kyushu (e.g., Kamata, 1992; Kamata and Kodama, 1999) (Fig. 4.8). Southwest, along-strike of the BSG, active back-arc rifting continues to occur in the Okinawa Trough (e.g., Lee et al., 1980; Sibuet, et al., 1987). Active extension also occurs in the Kagoshima graben in southern Kyushu (e.g., Aramaki, 1984; Kodama et al., 1995) at rates (from GPS) of $<7\text{--}8$ mm/a (Wallace et al., 2009) and there is some geological evidence for active normal faulting (e.g., Japan's Active Fault Research Centre's Active Faults Database: <http://www.aist.go.jp/RIODB/activefault/cgi-bin/index.cgi>). North-south extension in the Shimabara Graben, right lateral shear along the Oita-Kumamoto line, and strong left-lateral shear across southern Kyushu is evident from modern-day GPS velocities (see discussion in Section on Strain Rates from GPS). GPS velocities also suggest that anti-clockwise rotation of southern Kyushu may be ongoing today. Wallace et al. (2009) suggest that the left-lateral shear in southern Kyushu revealed by GPS measurements is a result of Kyushu-Palau Ridge collision (see Section on Strain Rates from GPS).

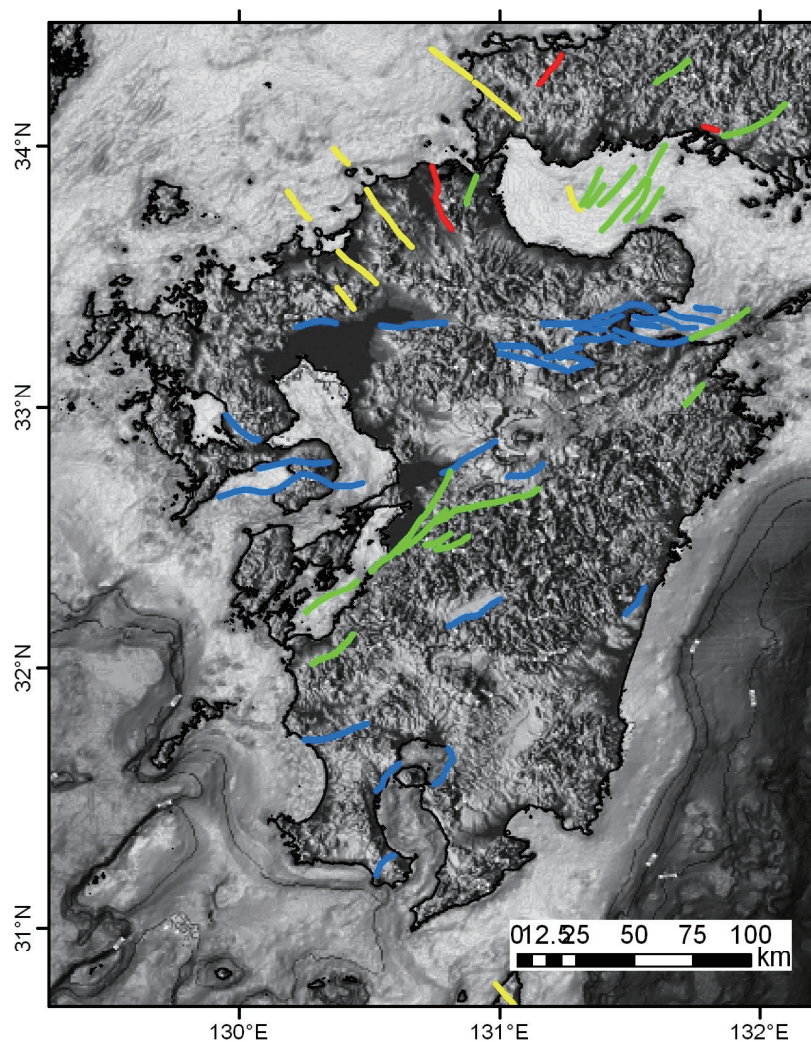


Figure 4.8: Active faults in southwest Japan from the Active Fault Research Centre's active fault database (<http://www.aist.go.jp/RIODB/activefault/cgi-bin/index.cgi>). The faults are color-coded by sense of movement (green = dextral; blue = normal, red = reverse, yellow = sinistral).

In general, historical seismicity in Kyushu consists of numerous offshore thrust earthquakes related to subduction at the Nankai/Ryukyu Troughs, and normal and strike-slip events within central Kyushu related to deformation in the BSG (Figure 4.9). Most normal faulting earthquakes in central Kyushu indicate approximately north-south directed extension,

consistent with geological studies. There is also a zone of east-west trending left-lateral strike-slip earthquakes northwest and northeast of the Kagoshima Graben, which corresponds with the zone of high left-lateral shear strain from GPS. Similarly, in northern Kyushu, there are several significant left-lateral strike-slip earthquakes with focal planes that strike transverse to the margin that correspond to some known, active left-lateral faults (Figure 4.9, and see Figure 4.8 for location of left-lateral faults near these earthquakes in northwest Kyushu). The March 2005 M_w 7.0 earthquake offshore Fukuoka City is related to this zone of faulting in northern Kyushu. Previous workers have suggested that these left-lateral events occur due to “bookshelf” style faulting within a region of overall right-lateral transpression (Kanaori and Kawakami, 1996). A large variety of earthquakes representing virtually every sense of faulting occur in Kyushu, reflecting the complex and dynamic active tectonic setting there.

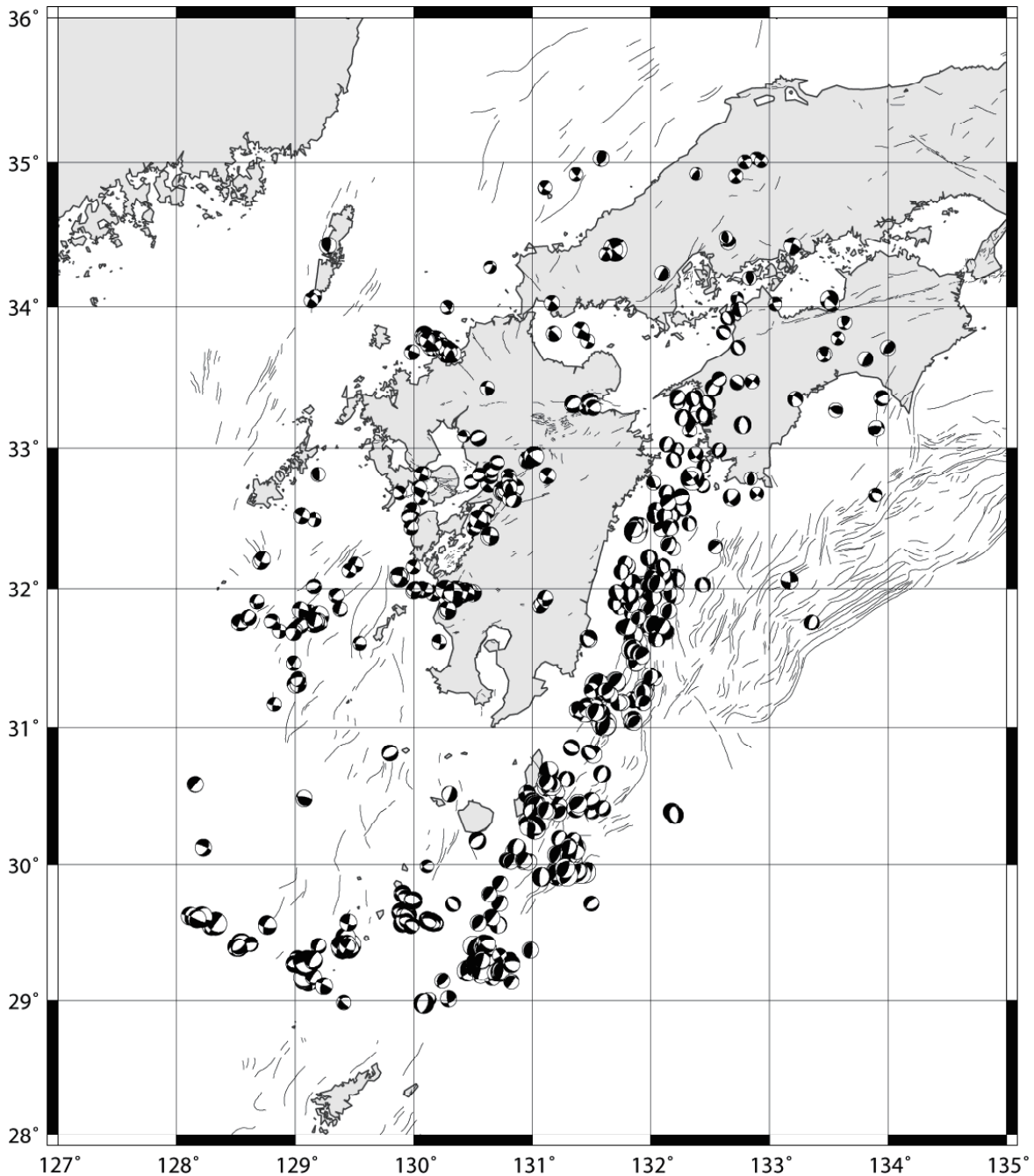


Figure 4.9: Focal mechanism plots for earthquakes in southwest Japan from 1997-2006. Based on CMT solutions from the JMA catalogue (data from <http://www.fnet.bosai.go.jp>).

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