3 The Geology and Tectonics of Kyushu. Part 1: Tectonic Setting and Evolution from 150 Ma to 15 Ma

Japan is part of the "Ring of Fire," the belt of earthquakes and volcanic activity that distinguishes the active margins of the Pacific ocean from the passive margins of the Atlantic ocean (Figure 3.1). In the 1920s, the great seismologist K. Wadati, discovered that earthquakes beneath northern Japan form an inclined zone extending from locations very near the Japan Trench to depths of about 500 km beneath the Japan Sea. This trench is a north-south trending bathymetric depression about 150 km east of the mainland that is as deep as 9000 m. The towering volcanoes of northern Japan are centred about 75 km from one another and form a curving line that is about 100 km above the inclined seismic zone. In the 1930s, Japanese seismologists discovered that many of the earthquakes near the Japan trench are the result of large thrust fault movements indicating the floor of the Pacific basin is moving beneath Honshu. A similar pattern of volcanism and earthquake activity is found along the Ryukyu trench that is as deep as 5200 m and extends 2200 km from Kyushu to Taiwan.

The cause of the active tectonic movements affecting the Earth was not well explained until the late 1960s when the realisation was made that the outer part of the Earth is divided into pieces, known as plates, about 100 km thick (Takeuchi et al., 1970). The plates consist of both the crust and cool uppermost mantle that has sufficient long-term strength that earthquake-generating ruptures can occur. Plate boundaries come in three forms that are recognised by the common type of fault movement: divergent with normal faulting, convergent with thrust faulting, and transform with strike-slip faulting. Plates separate from one another creating new ocean crust in the process of seafloor spreading at ocean ridges and come together consuming ocean crust in the process of subduction at locations demarked by ocean trenches, inclined seismic zones, and lines of explosive volcanoes. Plates slide past one another at transform boundaries.

Most of the geology of Japan is the result of subduction-related processes since the Mesozoic (Sugimura and Uyeda, 1973). The patterns of active faulting and seismicity along with direct GPS measurements delineate where tectonic motions are underway (Sagiya et al., 2000). To a first order, the current tectonics of the Japanese islands can be explained by the interaction of four plates: Pacific, Philippine Sea, Eurasian and North American (Figure 3.1). The eastern part of the Eurasian plate is broken with a large fragment, the Amur subplate moving at a slightly different speed and direction than the parent plate (Wei and Seno, 1998; Heki et al., 1999). With the development of GPS geodesy in the 1990s, small differential subplate movements can be directly measured. The North American plate continues across the Bering Sea into eastern Asia and down past the Kamchatka-Kurile trench segments to Japan. An elongate southern prong of the North American plate extends southwards to Japan. This prong has broken off and is moving as the Okhotsk subplate.

The active tectonics of Northeast Japan (northern Honshu and Hokkaido) are the manifestation of the interactions between the Amur and Okhotsk subplates with the Pacific plate. Subduction along the Japan Trench at a speed of about 9 cm/a (90 km/Ma) is concurrent with convergence near the eastern edge of the Sea of Japan at a speed of 1 to 1.5 cm/a (10 to 15 km/Ma) (Okamura et al., 1995). The active tectonics of Kyushu at the northern end of the Ryukyu arc-trench system are the focus of this Case Study. The active tectonics of Southwest Japan (Kyushu, Shikoku, and southwest Honshu) are the manifestation of the interactions of the Philippine Sea plate and Amur subplate (Seno, 1977; Taira, 2001). Plate convergence beneath Kyushu is at a speed of about 7 cm/a (70 km/Ma) (Seno et al., 1993; Zang et al., 2002). East-central Honshu, just south of Tokyo, near 34°N, is the convergent junction of three plates: a triple junction between the Philippine Sea, Pacific, and North American (Okhotsk) plates.

Prior to middle Cenozoic time, the entire length of the Japanese islands was underthrust by the Pacific plate (Taira, 2001). At about 45 Ma, tectonic movements changed in the western Pacific region and the Philippine Sea plate was created to the south. This plate is unique amongst the large plates in that it is nearly entirely surrounded by subduction zones. Because of the lack of a spreading ridge connection to a surrounding plate, the movement history of the Philippine Sea plate is not well determined (Hall et al., 1995; Lee and Lawver, 1995).

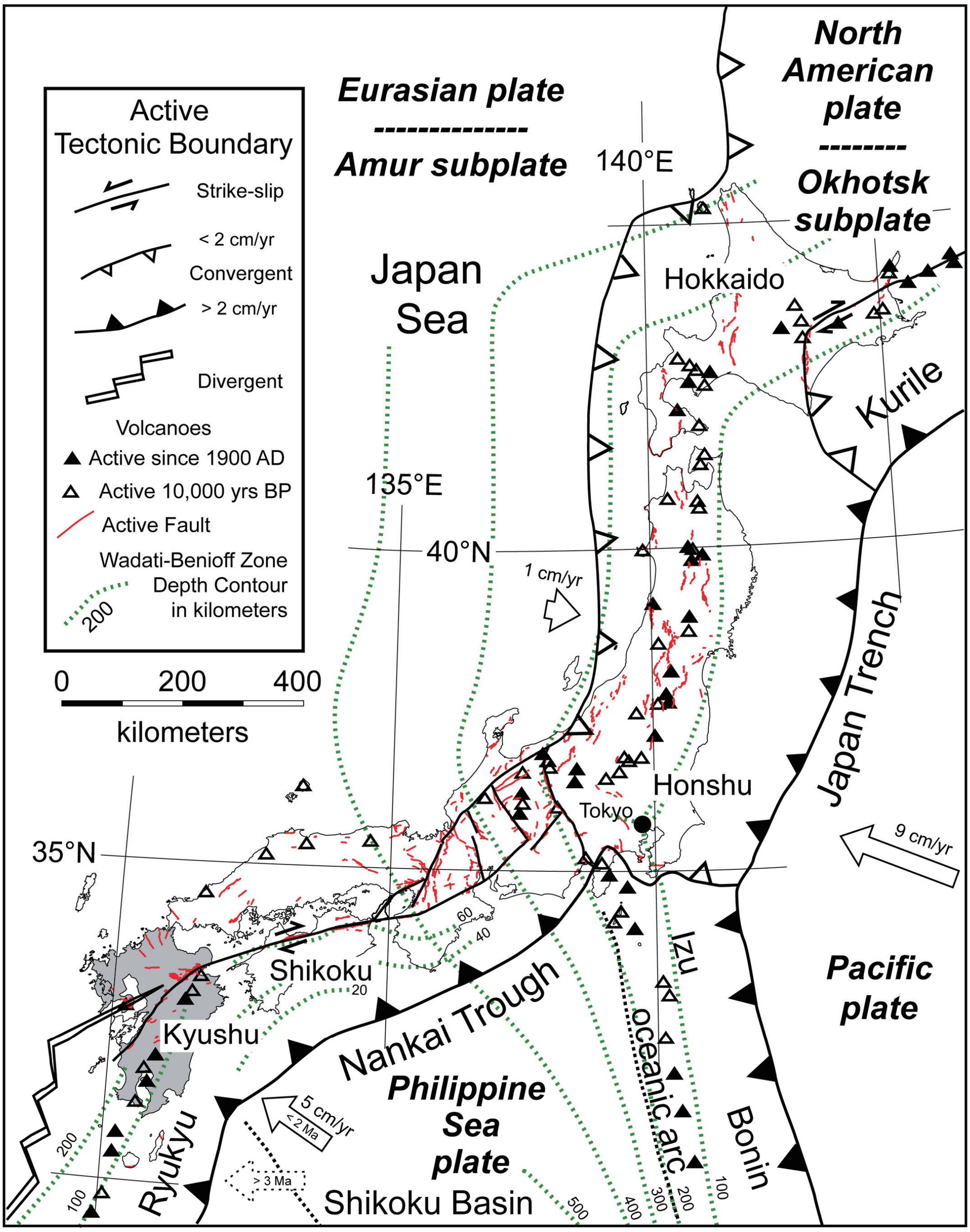

Figure 3.1: Tectonic setting of Kyushu within the Japanese island arc. The locations of active faults and volcanoes that have been active in the last 10,000 years are also shown.

The eastern edge of the Philippine Sea plate is underthrust by the Pacific plate forming the Izu-Bonin-Mariana arc-trench system. The western edge of the Philippine plate subducts beneath Asia creating the Ryukyu arc-trench system. The Izu arc and triple junction interSection has migrated northwards along the Ryukyu trench passing southern Japan to its present position. In so doing, subduction beneath Shikoku, and southwest Honshu changed from the underthrusting of the Pacific plate to the underthrusting of the Philippine plate along the Nankai Trough.

3.1 Kyushu Basement Terranes

Kyushu is the third largest Japanese island with an area of nearly 36,000 square kilometers. Most of the basement of Kyushu is composed of four geologic terranes, from north to south: Sangun, Ryoke, Chichibu, and Shimanto belts. The brief descriptions of these terranes that follows are mostly summaries from Kimura et al. (1991) and Taira (2001).

The basement of the northern part of the island is primarily composed of the Sangun Metamorphic Belt, a terrane largely composed of Permian to Triassic sedimentary rocks that were variably metamorphosed under high-pressure/low-temperature conditions (Nishimura, 1998). This terrane was intruded and widely metamorphosed by voluminous Jurassic to Cretaceous arc plutons. The southern boundary of the Sangun belt is the Oita-Kumamoto Tectonic Line.

The Ryoke Belt includes sedimentary rocks of late Paleozoic to Middle Mesozoic that was metamorphosed by voluminous Cretaceous (~100 to 80 Ma) arc plutons. The Higo subterrane, located only in west-central Kyushu, consists of greenschist to granulite facies rocks that were metamorphosed in the Triassic (Hamamoto et al., 1999). The extent of high temperature/low-pressure metamorphism varies greatly in intensity depending upon proximity to the Cretaceous plutons. The Ryoke belt is separated from the southern basement terranes by the Usuki-Yatsushiro Tectonic Line, an extension of the Median Tectonic Line that continues as a well-defined right-lateral strike-slip fault zone into Shikoku and the Kii peninsula. No Mesozoic magmatic rocks occur south of the Usuki-Yatsushiro/Median Tectonic Line.

In east-central Kyushu and south of the Usuki-Yatsushiro/Median Tectonic Line is a 10 km wide peninsula underlain by a wedge-shaped exposure of the Sanbagawa Belt. This outcrop area is the southwestern limit of the 700 km long belt that is well exposed in northern Shikoku and central Kii (Banno and Nakajima, 1992). The Sanbagawa Belt is composed of high-pressure/low-temperature blueschist facies metabasalts with lesser sediments recrystallised in the middle Cretaceous, between 90 to 70 Ma (Wallis, 1998). The Ryoke and Sanbagawa belts were recognised as the classic example of paired metamorphic belts (Miyashiro, 1961) that were later juxtaposed along a major strike-slip fault zone.

The Sanbagawa Belt is in fault contact with the Chichibu Belt, a 10 to 20 km wide terrane that trends northeast across the middle of Kyushu. This terrane is composed of weakly metamorphosed Carboniferous to Jurassic strata with local chaotic melange zones containing blocks of greenstone, chert, and limestones. The southern boundary of the Chichibu Belt is the Butsuzo Tectonic Line.

The southern third of the island is composed of the Shimanto Belt, the late Cretaceous to Paleogene accretionary prism that is the western end of the 1800 km long terrane that forms the southern half of Shikoku and the Kii peninsula of Honshu (Taira et al., 1982; Mackenzie et al., 1987). The Shimanto Belt is composed of two main units: relatively coherent sequences of interbedded sandstone and shale and chaotically mixed units of shale-matrix melange containing slabs and blocks of basaltic lavas that are commonly pillowed, limestones and radiolarian cherts.

3.2 Tectonic History of Kyushu Region

Most of the bedrock of the Japanese islands was assembled as a result of westward subduction along the eastern margin of Asia. Large accretionary prisms were constructed in the late Paleozoic to early Jurassic that are mostly composed of deep ocean sediments (shales, cherts, and pelagic limestones) and trench deposits (sand-rich) that were deformed by folding, faulting, and flowage during offscraping and underplating and then locally blanketed by slope deposits. In the Mid-Jurassic, between about 175 to 135 Ma, a major period of strike-slip faulting occurred along the margin of Asia that created the Oita-Kumamoto Tectonic Line and other high-angle fault contacts between displaced pieces of the late Paleozoic to early Jurassic accretionary prism.

In the very latest Jurassic or earliest Cretaceous, a major phase of fast subduction began that continues to this day off northeast Japan. This generated the enormous volume of arc magmas that invaded the Ryoke and Higo terranes and caused widespread high-temperature/low-pressure metamorphism. At the same time, the Sanbagawa and Chichubu terranes were accreted. The Sanbagawa terrane is largely composed of ocean crust and overlying sediments that was imbricated and underplated beneath the leading edge of the new subduction zone and thoroughly metamorphosed and intensely deformed under high-pressure/low-temperature conditions. The Chichubu Belt and the older part of the Shimanto Belt are mostly trench sediments that were offscraped or slope deposits that accumulated at the same time. All of this accretion and metamorphism was caused by the subduction of the Pacific plate beneath the eastern edge of Asia.

Between 50 to 40 Ma, a profound tectonic event occurred. The Pacific plate changed direction from northwest to a more westerly trend. This change is recorded as the major kink (dated at 43 Ma) in the Hawaii-Emperor seamount chain as well as several other seamount chains in the Pacific plate farther to the south. The change in plate motion was coeval with the initiation of subduction along a major northwest-trending transform zone extending from New Zealand to a location north of the Equator. This formed the Izu-Bonin-Mariana and Tonga-Kermadec arc-trench systems (Hall et al., 1995; Lee and Lawver, 1995). Whether the initiation of subduction caused the change in Pacific plate motion or the change in Pacific plate motion caused the initiation of subduction is debated. Either way, the northern part of the Philippine Sea plate was bounded by a pair of westward-dipping subduction zones. The Eastern boundary of the Philippine plate north is the Izu-Bonin-Mariana arc-trench system. The western boundary north of Taiwan is a west-dipping subduction zone that generated the Ryukyu arc-trench system. South of Taiwan, the western boundary is east-dipping subduction zone that generated the Manila trench and Luzon arc as the edge of Eurasia descends beneath the Philippine plate. The trench-trench-trench (TTT) triple junction now located off the Izu peninsula that was established somewhere between Taiwan and Kyushu has migrated northwards ever since (Figure 1).

The TTT triple junction appears to have reached the southern tip of Kyushu at about 25 Ma (Kimura et al., 2005). From about 32 to 23 Ma, Japan began to rift from Asia (Jolivet et al., 1994). Seafloor spreading in the Sea of Japan created new ocean crust in the backarc region between 23 to 12 Ma as Southwest Japan (southern Honshu and Shikoku) rotated clockwise about 45 degrees and Northeast Japan shifted eastward with a small counterclockwise rotation (Ishikawa, 1997). As this occurred, the TTT triple junction migrated more eastward than northward resulting in highly oblique and very slow convergence beneath southwest Japan. This movement caused significant left-lateral strike-slip offset along the Median Tectonic Line. As the TTT triple junction migrated northwards, the plate interactions along southern Japan abruptly switched from the subduction of the Pacific plate to the Philippine Sea plate.

The tectonic changes along southern Japan were concurrent with a major event in the eastern edge of the Philippine Sea plate that may somehow be related. The Izu-Bonin-Mariana arc split with backarc spreading creating the Shikoku Basin between 25 to 15 Ma (Karig, 1974; Sdrolias et al., 2004). The Kyushu-Palau Ridge is the remnant arc, nearly 400 km behind the Izu-Bonin-Mariana arc. The opening of the Shikoku Basin created new ocean crust that was still hot as it was underthrust beneath Kyushu and Shikoku islands and the Kii peninsula. The combination of spreading and underthrusting accounts for the minor but very anomalous forearc magmatism from 17 to 12 Ma (Hibbard and Karig, 1990; Kimura et al., 2005) and the widespread, low-temperature metamorphism of the Shimanto Belt on Kyushu and Shikoku. The remnant of the split arc is the Kyushu-Palau submarine ridge, a segment of ocean crust greatly thickened by subduction-generated magmatism.

3.3 Summary

The overall geologic history that created the basement terranes of Kyushu is well understood as a result of the long-term westward subduction of the Pacific ocean seafloor. Subduction in the late Paleozoic to mid-Mesozoic created the Sangun accretionary prism, which makes up the northern part of the island. This accretionary event was followed by a period of major strike-slip transform faulting between about 175 to 135 Ma that shuffled the accretionary prism and made some of the high angle fault zones that are mapped as tectonic lines. The reinitiation of westward subduction in the very latest Jurassic or earliest Cretaceous generated voluminous magmatism that invaded the northern half of the island and the large accretionary prism that makes up most of the southern half of Kyushu. The major plate motion change at about 43 Ma that isolated the Philippine Sea plate led to the northwards migration of the trench-trench-trench triple junction that is now located at the Isu peninsula. As the triple junction passed south Japan, backarc spreading occurred to form the Sea of Japan. Slow convergence with left-lateral strike-slip movement along the Median Tectonic line caused the Ryoke belt with abundant Mesozoic plutons to become juxtaposed directly against the Sanbagawa-Chichibu-Shimanto accretionary terranes. Westward subduction of the Philippine plate generated the Ryukyu trench and arc.

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