2 The Geology and Tectonics of the Tohoku Region

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. 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 trench are the result of large thrust fault movements indicating the floor of the Pacific basin is moving beneath northern Japan.

The cause of the active tectonic movements affecting the Earth was not well explained until the late 1960s, when the realization 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 recognized 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 in the process of seafloor spreading to form ocean ridges and come together in the process of subduction to form the ocean trenches, inclined seismic zones and curving lines of explosive volcanoes. They slide past one another at transform boundaries.

Most of the geology of Japan is a 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, Eurasian and North American (see Figure 2.1). The eastern part of the Eurasian plate is broken with a large fragment, the Amur subplate, currently moving as a distinct kinematic entity (Wei and Seno, 1998; Heki et al., 1999). 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 currently moving as a distinct kinematic entity, the Okhotsk subplate.

In detail, the current tectonics for southern Kyushu and the Ryukyu arc-trench system is a manifestation of the interaction of the Philippine and Eurasian plates. The current tectonics of Southwest Japan (Kyushu, Shikoku, and southwest Honshu) are a manifestation of the interactions of the Philippine plate and Amur subplate. The current tectonics of Northeast Japan (northern Honshu and Hokkaido) are a 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/year (90 km/Ma) is concurrent with convergence near the eastern edge of the Sea of Japan at a speed of about 1 to 1.5 cm/year (10 to 15 km/Ma) (Tamaki and Honza, 1985; Okamura et al.,1995).

Four arc segments merge to form the Japanese islands. The northern half of Honshu island is a subduction segment commonly referred to as northern or northeast Japan. Hokkaido is the southern end of the Kurlie trench and arc. East-central Honshu (Izu peninsula) is the northern end of the Izu-Bonin-Mariana trench and arc. These three arc-trench segments are all the product of the westward subduction of the Pacific plate. Kyushu island is the northern end of the Ryukyu trench and arc. The active tectonics of Kyushu and Shikoku islands are movements related to the northwestward subduction of the Philippine plate. East-central Honshu, just south of Tokyo, near 34°N is presently the convergent junction of three major plates.

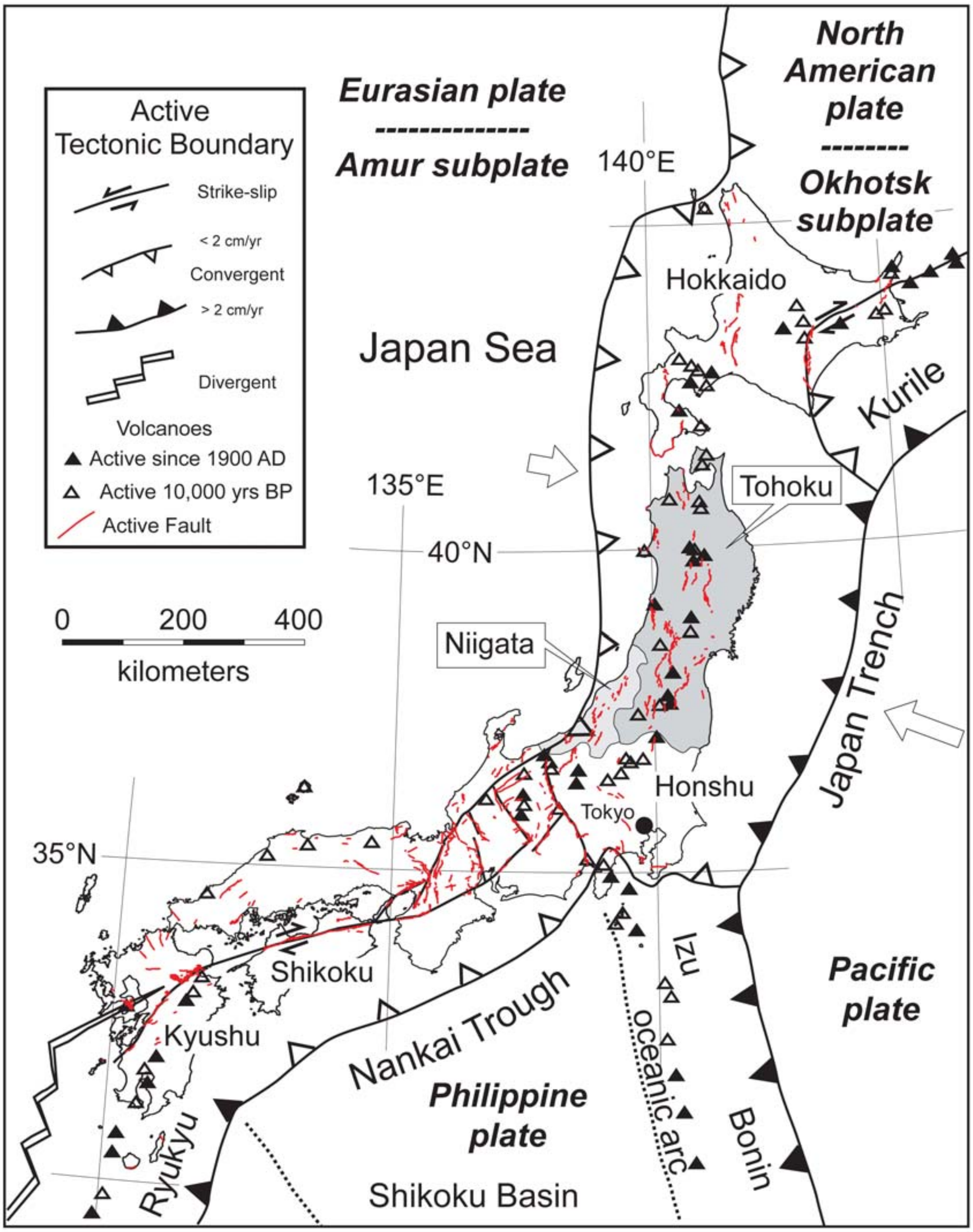

Figure 2.1: The principal plate tectonic features of Japan, showing the location of the Tohoku region of northern Honshu that forms the focus of this Case Study. The location of active faults and volcanoes that have been active in the last 10,000 years is also shown.

Prior to Eocene time, the entire length of present day Honshu was underthrust by the Pacific plate. At about 45 Ma, tectonic movements changed along the western margin of the Pacific Ocean. Whether the Philippine plate is a fragment broken off the edge of the Asian or the Pacific plates is debated. It is unique amongst the large plates in that it is nearly entirely surrounded by subduction zones. The eastern edge of the Philippine plate is underthrust by the Pacific plate forming the Izu-Bonin-Mariana arc and trench. The western edge of the Philippine plate subducts beneath Asia creating the Ryukyu arc and trench. The Izu arc and trench intersection with the Japan trench has progressively migrated along southwest Japan to its present position during the late Cenozoic. In so doing, subduction beneath Shikoku island and southwest Honshu at the Nankai Trough has changed from the underthrusting of the Pacific plate to the underthrusting of the Philippine plate.

2.1 Northern Honshu – Tohoku

Since the advent of plate tectonic theory, Northern Japan, from 35°N to 43°N, has been widely recognized as the type example of an active subduction zone. The northeast Japan subduction zone, like all others, can be subdivided into the trench axis, trench slope, forearc basin, volcanic arc, and backarc regions. The tectonic activity associated with subduction comes in the form of faulting, magmatic intrusions and extrusions and vertical movements that range from folding to tilting of fault blocks to regional warpings.

The earthquakes are the result of episodic (stick-slip) movements along faults. Arc volcanism is the result of water-fluxed melting deep in the mantle because subduction injects water. The melting generates hydrous basalts with elevated concentrations of most of the trace elements that are abundant in sediments. These magmas rise buoyantly towards the surfaces and centres of arc volcanism are located where the magmas work their way through the crust.

2.2 Basement of Tohoku

The basement of Japan is largely composed of Palaeozoic and Mesozoic subduction-related rock terranes created during westwards subduction along the eastern edge of Asia. The northernmost part of Honshu is underlain by the Oshima Belt, a Jurassic accretionary prism. Central Honshu is underlain by the Ashio Belt, largely composed of Triassic to Jurassic rocks that are variably deformed and little metamorphosed accretionary prism materials and the Abukuma Belt which is thoroughly metamorphosed under high-temperature / low-pressure conditions. Between these two Mesozoic terranes is the Kitakami Belt, a varied mixture of sedimentary, igneous and metamorphic rocks of Palaeozoic age. This juxtaposition makes it appear that the early Mesozoic history of subduction and accretionary prism growth was followed by an episode of transform faulting (Taira, 2001). Strike-slip faulting shuffled the accretionary prism - forearc basin terranes (Abukuma-Ashio and Oshima belts) with the arc-basement terrane (Kitakami Belt) that had formed along the edge of the Asian continent.

The present phase of westward dipping subduction began at about 130 Ma (Engebretson et al., 1985). Cretaceous and Cenozoic intrusives and volcanics of the northern Honshu arc are emplaced into and on top of these basement terranes. Early Cretaceous plutonics are most abundant near the eastern coastline and occur offshore (Finn, 1994). Late Cretaceous arc magmatism appears to have been concentrated near the west coast of Honshu. These magmatic rocks were down-dropped during the rifting associated with the opening of the Sea of Japan and deeply buried by younger sediments (Finn et al., 1994). The volcanic arc appears to have established it present position since about 20 Ma. Crustal thickness beneath most of northeast Honshu is between 30 to 35 km.

Most of the plutonic rocks were emplaced at depths less than 10 km as the feeder roots of volcanoes very similar and perhaps identical to those dominating the landscape of today. Most ancient volcanoes were destroyed by erosion long ago, but relicts of various ages are found in many locations. In most of northern Japan, the plutonic rocks are emplaced into older plutons and volcanics or a basement of sedimentary rocks that was deformed and metamorphosed to varying degrees.

2.2.1 Forearc region

The forearc region is directly underlain by the subducting Pacific plate. The geology of the forearc region of northeast Japan records a long history of subsidence and volcanogenic sediment accumulation. Because the upwards flow of heat through the descending plate beneath the forearc block is slower than the speed of subduction, geothermal gradients are very low across the forearc region (Honda, 1985). High-pressure/low-temperature blueschist facies metamorphism is occurring at depth. The crystalline basement underlying the forearc region is cold and strong. Consequently the sediments in the overlying forearc basin are little deformed.

The forearc region of northeast Japan has a rather smooth slope down to the Japan Trench. The Cenozoic tectonic history of the forearc region has largely been one of non-accretion and slow subsidence resulting from subduction erosion of the base of the hanging wall block above the descending Pacific plate (von Huene and Lallemand, 1990; Heki, 2004).

2.2.2 Volcanic arc region

The area around active volcanic arcs is a region of high heat flow because heat is advected to shallow levels in magmas. Recent seismic tomography studies indicate most of the active volcanic centres in northeast Japan are centred above areas with slow seismic velocities in the upper mantle and crust (Tamaru et al., 2002). The current volcanic arc position was established at about 20 Ma (Kondo et al., 2004). Since the mid-Miocene, numerous magmatic centres have formed and decayed. The lifespan of typical large arc-type composite volcanoes appears to be about 1 to 2 million years (Davidson and De Silva, 2000). Volcanic arcs are noted for giant composite volcanoes. But clusters of satellite cones and flows are typical. Along the northeast Japan arc, ten volcanic clusters are about 50 km wide that are separated by gaps between 30 to 75 km wide (Tamura et al., 2002).

Many subduction zones, including northern Japan, have scattered occurrences of volcanism in the backarc. Whether these occurrences are a manifestation of limited magma generation in the underlying mantle or limited pathways for intrusion to the surface is a matter of debate. In some cases, as is currently occurring in the Okinawa Trough behind the Ryukyu Arc, the backarc is a region of extensive volcanism because of seafloor spreading. Where this occurs, the amount of volcanism in the backarc region will greatly exceed the activity along the arc.

2.2.3 Backarc region

The geology of the backarc and arc region of northeast Japan records a history of profound change. Until mid-Cenozoic time, the crust forming the bulk of the basement of Japan was the edge of Asia. The Japan Sea formed by continental rifting which evolved into seafloor spreading with ocean crust formation between 23 to 14 Ma (Jolivet et al., 1994). This rifting event was centred along the volcanic arc that had formed a line delineated by the western edge of Honshu.

Volcanic arcs can become centres of divergence that evolve into sea floor spreading centres. This has occurred at several sites along the western margin of the Pacific basin. Major episodes of backarc spreading occurred along Izu-Bonin-Mariana and Tonga-Kermadec subduction zones. In the backarc regions of these oceanic subduction zones, lines of extinct volcanoes parallel the current volcanic arc with a region of new ocean crust in between.

It is evident that rifting is localized to the part of the lithosphere that was sufficiently weakened by the ascent of magmas, so that a change in the force balance near the subduction zone led to lithospheric divergence that is centred on the arc. Backarc spreading is a subordinate process to subduction. During the time seafloor spreading created a 200 km width of new ocean crust beneath the Japan Sea, on the order of 2000 km width of Pacific plate was consumed by subduction at the Japan Trench.

2.3 Active Deformation: Earthquakes and Faulting

Since 1900, nineteen earthquakes of M 7 to M 8.2 have occurred directly beneath the coast to about 50 km offshore northeast Japan between depths of about 15 to 60 km (Kawakatsu and Seno, 1983). These events occur along the plate interface as a direct manifestation of the underthrusting of the Pacific plate. The updip cut-off is known as the seismic front with little seismicity occurring seaward in the hanging wall block. The origin of the abrupt seismic front along Northeast Japan and elsewhere is debated. The cessation of downdip seismicity is generally considered a manifestation of where the material along the plate interface is sufficiently heated so that it flows rather than fractures.

Less frequently, earthquakes occur beneath the land. Most occur at depths less than 15 km (Zhao et al., 2000). Seismicity is sparse and shallow in areas of high heat flow and nearly absent beneath centres of active volcanism.

A distinct belt of seismicity and surface faulting extends along the western coast of northeast Japan north and south of Niigata. Scattered reverse-slip earthquakes as large as M7.8 nucleate at depths of 10 to 20 km (Okubo and Matsunaga, 1994). Faulting and folding in the belt is a result of slow convergence between Amur and Okhotsk subplates. Most of this convergence is localized along the western edge of northern Honshu. This area of active folding, reverse faulting, uplift and erosion was an area of subsidence during the Miocene phase of rifting.

Normal faults created during rifting to form the Japan Sea were buried by highly volcanogenic sediment shed westward into the widening depression. The convergent deformation in the Niigata region began in the Pliocene, at about 3 Ma (Okamura et al., 1995). The crystalline basement in this region primarily deforms by reversing the movement on normal faults created during the rifting phase – 'inversion tectonics'. The overlying sediments respond to the deformation primarily by drape folding over the rising fault blocks. Geometrical complexities and new breakouts occur in many areas because the old fault system does not everywhere have optimal orientations for the imposed movements.

Some convergence is occurring within the region of the volcanic arc. These movements have created the Backbone Range, a topographic divide that has profoundly affected regional drainage and sedimentation patterns (Sato, 1994). Between volcanic centres, some of the shortening occurs by episodic earthquake-generating stick-slip along reverse faults (Zhao et al., 2000). Directly beneath most volcanic centres, the temperatures are so high that the crust is ductile and there is little seismicity. The uplift of the Backbone Range began since about 2 Ma (Sato and Amano, 1991).

In short, the tectonic environment of northern Japan is dominated by subduction at the Japan Trench causing arc magmatism with second-order convergent motions that are concentrated in the backarc (Niigata) region. The current mode of tectonism in northern Honshu began at about 4 Ma and has been well established since 2 Ma (Taira, 2001). The initiation of this tectonic regime is probably a manifestation of the creation and movement of the Amur and Okhotsk subplates. Why these convergent movements began, which are secondary compared to fast, long-term subduction at the Japan Trench, is not known but they are part of a modest change of plate motions around the Pacific basin that occurred between 5 to 3 Ma (Cox and Engebretson, 1986; Pollitz, 1986).

2.4 Example Locations

For the purposes of the present study, a group of fourteen locations ('example locations') was selected across the Tohoku region so that the results of the probabilistic rock deformation and volcanic evaluations could be discussed in terms of different tectonic settings within the region. Within the ITM methodology, the two evaluations produce quantitative estimates of future upper crustal strain and the likelihood of new magmatic intrusion, discretised into 5 x 5 km blocks across the whole region. Identifying example locations allows these quantitative estimates to be presented and discussed for varying tectonic regimes in the Tohoku region.

The example locations selected are shown in Figure 2.2. The Appendix to this report provides a brief description to each location, as well as showing the location-specific quantitative results of the deformation and volcanism evaluations. The evaluations themselves are discussed in detail in the following Sections (Sections 3 and 4).

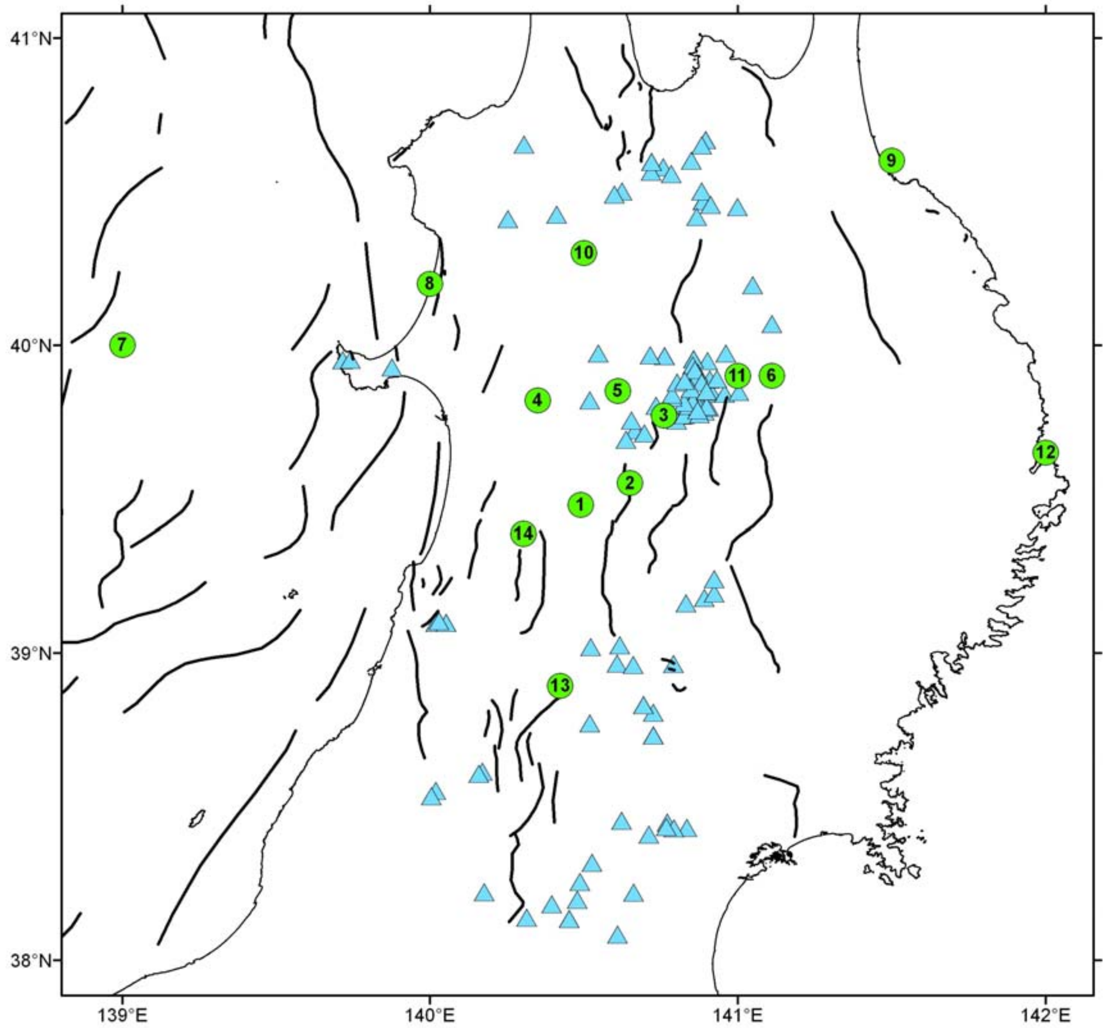

Figure 2.2: The fourteen example locations used in the Tohoku Case Study (green dots). Also shown are volcanic edifices (blue triangles) and active faults (bold, black lines). See Appendix for details.