CHAPTER 7

Conclusion and Discussion

7.1 The Felsic to Mafic Volcanic/ Hypabyssal Rocks in the areas of Nakhon Sawan and Uthai Thani Provinces

Igneous rocks in the areas of Nakhon Sawan and Uthai Thani Provinces, upper Central Plain Thailand are classified as intrusives and extrusives, and occur as lava flows, stocks and dikes. They form north-south trending chains of small hills or mountains, and smaller intrusive masses in sedimentary rocks. They have been interpreted to be the southern extension of any volcanic belt in the north and have the most problems concerning field relationships, ages, occurrences, and tectonic settings of formation mainly because of Mae Ping fault zone. Evidences from field, petrographic and geochemical studies suggest that the intrusive rocks are plutonic (granite, granodiorite and diorite) and hypabyssal rocks that occur as variably sized stocks; some may intrude the Permian and Silurian-Devonian sedimentary rocks and genetically related to the capped volcanic rocks. The pyroclastic rocks include flow and fall deposits. These rocks range compositionally from basic to acid and are composed largely of pyroclastic rocks, with minor volcanic rocks (basalt, andesite, dacite and rhyolite) and hypabyssal rocks (microdiorite, microgabbro and diorite/gabbro). The volcanic breccias are made up largely of andesitic and rhyolitic blocks that sit in the finer-grained matrix. Of these pyroclastic rocks, volcanic breccias of primary and/or secondary origins are the most abundant rock types. The volcanic and volcaniclastic rocks range in composition from andesite to rhyodacite and form as lava flows and ejectas overlying the Permian and pre-Permian rocks. The rhyolitic pyroclastic rocks have been formed in the late stage of igneous activities. They are interbedded with sandstone, shale and carbonate rocks of the Middle Triassic. The volcanic rocks are andesite and rhyolite tuff. The andesite is locally overlain by rhyolitic tuff. The Triassic rocks overly unconformably on the Paleozoic rocks.

The felsic to mafic volcanic/hypabyssal rocks in the study area are separated into five groups, i.e. Group I, Group II, Group III, Group IV and Group V, based on geochemical signatures. They are distributed in the areas of Tha Tako, Krok Phra and Chum Ta Bong, covering an area of approximately 200 km^2. The Group I rocks are composed largely of rhyodacite/dacite, with minor andesite and basalt in the Tha Tako area, and one sample of micrograbbro/microdiorite in the Krok Phra area. The Group II rocks are diorite/gabbro in the Chum Ta Bong area. The Group III rocks and Group IV rocks are composed largely of microgabbro/microdiorite with minor andesite/basalt in Tha Tako and Krok Phra areas. The Group V rocks are composed of rhyodacite/dacite in the Tha Tako area.

7.1.1 The Group I Rocks

The Group I Rocks can be separated into three subgroups by rock types as rhyodacite/dacite, andesite/basalt and diorite/gabbro. The rhyodacite/dacite subgroup is generally fine-grained and dense, and has grayish red, brownish gray, and greenish gray colors. A representative of rhyodacite/dacite has a U-Pb zircon age of 345.5 $\pm$ 3.4 Ma. The rhyodacite/dacite are moderately to highly porphyric. The phenocrysts/microphenocrysts assemblages include (1) plagioclase + potassium feldspar + quartz, (2) plagioclase + potassium feldspar + opaque minerals, (3) plagioclase + opaque minerals + quartz, (4) plagioclase + potassium feldspar + biotite, (5) plagioclase + opaque minerals + amphibole, (6) plagioclase + potassium feldspar + amphibole + opaque minerals, and (7) plagioclase + opaque minerals + amphibole + potassium feldspar + quartz. The phenocrysts/microphenocrysts are mainly plagioclase, with subordinate potassium feldspar, amphibole and opaque minerals, and occasional quartz and biotite. These phenocrysts/microphenocysts commonly form as isolated crystals and plagioclase glomerocrysts, and uncommon as potassium feldspar and quartz glomerocrysts. Some samples contain plagioclase – amphibole, plagioclase – opaques, plagioclase – orthopyroxene and plagioclase – potassium feldspar cumulocrysts. The groundmass is glassy, and has partly undergone high-temperature devitrification and low-temperature recrystallization. It shows slightly to moderately trachytic and felty textures. In general, the groundmass constituents are largely plagioclase and quartz, with minor potassium feldspar, opaques, spherulite, amphibole, biotite, opaque and zircon. The andesite/basalt subgroup has greenish gray and dark greenish gray colors. They are moderately to highly porphyritic, except TK-12 that is seriate-textured. The phenocrysts/microphenocrysts assemblages include (1) plagioclase + clinopyroxene + opaque minerals and (2) plagioclase + clinopyroxene + amphibole + opaque minerals. The phenocrysts/microphenocrysts comprise mainly plagioclase, with subordinate clinopyroxene, opaque minerals and amphibole. These phenocrysts/microphenocysts occur as isolated crystals, plagioclase and clinopyroxene glomerocrysts, and as clinopyroxene - plagioclase, clinopyroxene - opaques, clinopyroxene - amphibole, amphibole - opaques, plagioclase - opaques, amphibole - plagioclase, amphibole - plagioclase - opaques and amphibole - plagioclase - clinopyroxene cumulocrysts. The groundmass is holocrystalline, and consists largely of plagioclase laths and clinopyroxene, with a small amount of opaque minerals. The diorite/gabbro subgroup has a greenish black color. It shows a seriate texture and is made up mainly of plagioclase, with subordinate unidentified mafic minerals and opaque minerals.

The Group I volcanic samples and hypabyssal rocks span the ranges in Zr/TiO_2 and Nb/Y from 0.01 to 0.08 and 0.09 to 0.33 respectively. Accordingly, they are classified as subalkalic rhyodacite/dacite and subalkalic andesite/basalt. The relationships between incompatible-element pairs for the Group I rock samples, such as Nb-Zr and Y-Zr, are linear, with ratios of Nb/Zr = 0.04 ± 0.007 and Y/Zr 0.20 ± 0.060. These signify that the Group I rocks might have been formed by different degrees of partial melting of a common source rock or by different degrees of crystal fractionation of the same parental magma. The Group I rock samples have typical REE patterns of calc-alkalic rocks, i.e. LREE enrichment and relatively flat HREE, with (La/Sm)cn and (Sm/Lu)cn ranging from 1.89 to

5.38 and 1.15 to 2.48, respectively. Their N-MORB normalized multi-element patterns are generally flat, with negative Nb and Ta anomalies. This indicates that the rhyodacite/dacite, andesite/basalt and diorite/gabbro have subduction-related signatures. The Group I rocks presented in this study are analogous to the basic rock (sample number S10) from Late Eocene Kuh-e Dom shoshonitic dikes, Urumieh-Dokhtar magmatic arc, Northeast Ardestan, Central Iran (Sarjoughian *et al.*, 2012) that have developed from remnant melt batches after cessation of active subduction, i.e. a post-collision setting.

7.1.2 The Group II Rocks

The Group II rocks are made up of diorite/gabbro that are hypabyssal in occurrence, and have light gray and medium dark gray colors. A representative sample of this group has a U-Pb zircon age of 225.4 ± 1.9 Ma. The Group II rocks are medium-grained, and show a seriate texture. The rock samples are made up mainly of plagioclase, with subordinate biotite, quartz, clinopyroxene and amphibole, and minor opaque minerals and zircon. The mineral assemblages include (1) plagioclase + potassium feldspar + clinopyroxene + quartz + amphibole + zircon, (2) plagioclase + potassium feldspar + clinopyroxene + quartz + opaque minerals + zircon, and (3) plagioclase + potassium feldspar + clinopyroxene + quartz + amphibole + opaque minerals + zircon.

The Group II hypabyssal rocks span the ranges in Zr/TiO_2 and Nb/Y from 0.05 to 0.09 and 0.39 to 0.43, respectively; they have a subalkalic affinity. The relationships between incompatible-element pairs for the Group II rock samples, such as Nb-Zr and Y-Zr, are linear, with ratios of Nb/Zr = 0.04 ± 0.005 and Y/Zr 0.11 ± 0.010. These signify that all the rocks are essentially co-genetic. They might have been formed by different degrees of partial melting of a common source rock or by different degrees of crystal fractionation of the same parental magma.

The REE patterns of Group II rocks are typical of calc-alkalic rocks, i.e. LREE enrichment and relatively flat HREE, with (La/Sm)cn and (Sm/Lu)cn ranging from 3.24 to 4.79 and 2.29 to 2.54, respectively. Their N-MORB normalized multi-element patterns generally show negative Nb and Ta anomalies. This suggests that the Group II diorite/gabbro have a subduction-related signature. The studied Group II mafic hypabassal rocks may represent magma or cumulus crystals. They are chemically analogous to the dacite (sample number ER16) from the Quaternary Erciyes volcano, central Anatolia, Turkey (Notsu *et al.*, 1995) that have combined signatures of fractionation crystallization of basaltic magma and crustal assimilation under collision tectonic setting.

7.1.3 The Group III Rocks

The Group III rocks are composed of microdiorite/microgabbro/gabbro and andesite/basalt. The microdiorite/microgabbro/gabbro are fine- to medium-grained, and have dark greenish black and dark greenish gray colors. They show a seriate texture and consist mainly of plagioclase, with subordinate clinopyroxene, amphibole, orthopyroxene and opaque minerals. The mineral assemblages include (1) plagioclase + clinopyroxene + amphibole + orthopyroxene + opaque minerals and (2) plagioclase + clinopyroxene + opaque minerals. The andesite/basalt are fine-grained, and have a dark greenish gray color. They are almost totally porphyritic; only one sample is seriate - textured. The porphyritic rock sample has phenocrysts/microphenocrysts that are made up mainly of plagioclase, with subordinate unidentified mafic minerals and opaque minerals. The phenocrysts/microphenocysts form as isolated crystals and as plagioclase glomerocrysts. The groundmass is holocrystalline, and consists largely of plagioclase laths and unidentified mafic minerals, with a small amount of opaque minerals. The seriate-textured rock sample is composed largely of plagioclase, with subordinate clinopyroxene, orthopyroxene and opaque minerals.

The Group III volcanic and hypabyssal rocks span the ranges in Zr/TiO_2 and Nb/Y from 0.009-0.010 and 0.16 to 0.30 respectively. They are classified as subalkalic andesite/basalt on the Zr/TiO_2-Nb/Y diagram. The Group III volcanic and hypabyssal rock samples have similar chemical compositions suggesting either a common source rock or a common parental magma. The relationships between incompatible-element pairs for the Group III mafic volcanic/hypabassal rock samples, such as Nb-Zr and Y-Zr, are linear, with Nb/Zr = 0.048 ± 0.007 and Y/Zr = 0.206 ± 0.030. These signify that all the rocks are essentially co-genetic. The Group III rocks have typical REE patterns of tholeiitic rocks, i.e. slightly LREE enriched patterns, with (La/Sm)cn and (Sm/Lu)cn ranging from 1.18 to 1.53 and 1.38 to 1.85, respectively. Their N-MORB normalized multi-element patterns generally show relatively flat patterns with negative niobium anomalies. These indicate that the subalkalic andesite/basalt have been crystallized from MORB-like magma that contain a crustal signature. The Group III rocks are analogous to the basaltic andesite (sample number PA-92) from the Quaternary Maca volcano, Patagonian Andes (~45°S, Chile) (D'Orazio *et al.*, 2003) that was erupted in an active continental margin.

7.1.4 The Group IV Rocks

The Group IV rocks consist mainly of microdiorite/microgabbro and andesite/basalt. The microdiorite/microgabbro are fine- to medium-grained, and generally show dark greenish gray and greenish black colors. They show a seriate texture, and are made up mainly of plagioclase, with subordinate unidentified mafic minerals, clinopyroxene, amphibole and opaque minerals. Mineral assemblages are (1) plagioclase + unidentified mafic minerals + opaque minerals, (2) plagioclase + clinopyroxene + opaque minerals and (3) plagioclase + amphibole + opaque minerals. The andesite/basalt are fine-grained and dense. Two samples display a porphyritic texture and have a grayish black color. Five samples show a seriate texture and have a dark greenish gray color. The phenocrysts/microphenocrysts of slightly porphyritic- textured rock samples are made up mainly of plagioclase, with subordinate clinopyroxene, orthopyroxene and opaque minerals. The mineral assemblages include (1) plagioclase + clinopyroxene + orthopyroxene + opaque minerals and (2) plagioclase + clinopyroxene. These phenocrysts/microphenocysts form as isolated crystals, plagioclase glomerocrysts and plagioclase - clinopyroxene cumulocrysts. The groundmass is holocrystalline, and consists largely of plagioclase laths and clinopyroxene, with a small amount of opaque minerals. The seriate-textured samples are made up mainly of plagioclase, with subordinate unidentified mafic minerals and opaque minerals. The mineral assemblages include plagioclase + unidentified mafic minerals + opaque minerals.

The Group IV rocks span the ranges in Zr/TiO_2 and Nb/Y from 0.004 to 0.009 and 0.05 to 0.12, respectively. Both of the volcanic and hypabyssal rock samples have similar chemical compositions suggesting either a common source rock or a common parental magma. They are classified as subalkalic andesite/basalt, using the Zr/TiO_2-Nb/Y diagram. The relationships between incompatible-element pairs for the studied mafic volcanic/hypabassal rock samples, such as Nb-Zr and Y-Zr, are linear, with $Nb/Zr = 0.022 \pm 0.005$ and $Y/Zr = 0.309 \pm 0.058$. These signify that all the rocks are essentially co-magmatic. They might have been formed by different degrees of crystal fractionation of the same parental magma. The studied subalkalic andesite/basalt suite have typical REE patterns of tholeiitic rocks, i.e. LREE and HREE relatively flat, with $(La/Sm)_{cn}$ and $(Sm/Lu)_{cn}$ ranging from 0.87 to 1.49 and 1.25 to 1.84, respectively. In terms of N-MORB normalized multi-element patterns, the rocks generally show flat patterns, with negative niobium anomalies. These indicate that the subalkalic Group IV rocks have been crystallized from MORB-like magma that contains a crustal signature. The Group IV rocks are analogous to the basalt (sample number As-5) from the Pliocene Asahiura basalt, Eastern zone, Southwest Hokkaido, northern NE Japan arc (Takanashi *et al.*, 2011) that was erupted in an active continental margin.

7.1.5 The Group V Rocks

The Group V rocks are composed of rhyodacite/dacite and are generally fine-grained and dense. They have dark greenish gray and pale blue green colors, and are highly porphyritic. Their phenocrysts/microphenocrysts are made up mainly of plagioclase, with subordinate potassium feldspar, quartz, amphibole and opaque minerals. The phenocrysts/microphenocysts form as isolated crystals, plagioclase glomerocrysts and as plagioclase – amphibole cumulocrysts. The groundmass is glassy, but KK-20 has undergone high-temperature divitrification, and low-temperature recrystallization, giving rise to common plagioclase, potassium feldspar, quartz and spherulite, and a small amount of amphibole.

The Group V rocks range in Zr/TiO_2 and Nb/Y from 0.038 to 0.039 and 0.20 to 0.21 respectively. They are classified as subalkalic rhyodacite/dacite. The Group V rocks have typical REE patterns of shoshonitic rocks, i.e. La-Dy enrichment and relatively flat Dy-Lu, with (La/Dy)cn and (Dy/Lu)cn ranging from 5.00 to 6.72 and 1.72 to 2.22, respectively. In terms of N-MORB normalized multi-element patterns, the rocks generally show flat patterns with negative Nb and Ta anomalies. This suggests that the subalkalic rhyodacite/dacite have characteristics of subduction-related magma. The Group V rocks are analogous to the intermediate rock (sample number S15) from Late Eocene Kuh-e Dom shoshonitic dikes, the Urumieh-Dokhtar magmatic arc, Northeast Ardestan, Central Iran (Sarjoughian *et al.*, 2012) that have developed from remnant melt batches after cessation of active subduction, i.e. in a post-collision setting.

In summary, the studied volcanic and hypabyssal rocks might have been formed in an active continental margin (Groups II, III and IV rocks) and a post-orogenic setting (Groups I and V rocks) on the basis of their modern analogs. The ages for these rocks were inferred to be in a period of post-Permian - pre-Jurassic (Department of Mineral Resources, 2007). The timing of igneous activities is well supported by the works of Boonsue (1986) and Intasopa (1993), and partly in agreement with the U-Pb zircon ages (345.5 ± 3.4 Ma for Group I rocks and 225.4 ± 1.9 Ma for Group II rocks) performed in this study.

7.2 Tectonic Evolution of Thailand

The tectonic evolution of Thailand may be depicted from the informative data either from this study or from previous studies as shown in Figure 7.1 In the Silurian, the Shan-Thai and Indochina terranes were separated by a major ocean basin, represented by the mid-ocean ridge basalt of the Central Loei volcanic sub-belt (Intasopa and Dunn, 1994; Panjasawatwong *et al.*, 2006). A west-dipping subduction zone formed at the leading edge of the Shan-Thai terrane, leading to a volcanic arc. This arc may have been rifted, forming an immature back-arc basin (Figure 7a), represented by the immature back-arc basin basalt and andesite in the Chiang Rai – Chiang Mai volcanic belt (Phajuy 2008). In the Devonian, a mature back-arc basin, represented by the Devonian radiolarian chert (Wonganan and Caridroit, 2005), have been developed (Figure 7b). In the Early Carboniferous to Middle Permian (Figure 7c), the mature back-arc basin might have been continued spreading, leading to a major ocean basin and the occurrences of ocean-island basalt and mid-ocean ridge andesite-basalt in the Chiang Rai – Chiang Mai volcanic belt (Phajuy, 2008). While the back-arc basin became wider to be a new ocean basin, the older ocean basin became narrower and then closed in Early Carboniferous. The amalgamation of arc and Indochina terrane might have been followed by post orogenic magmatism, represented by the studied Groups I and V rocks, in the Early Carboniferous. The closer of the older major ocean basin resulted in changing the spreading center of the new major ocean basin to a new subduction with reverse polarity to the extinct older one in the Late Permian (Figure 7d). The new ocean basin then became narrow and a new arc formed above the subduction zone in the Late Permian – Late Triassic (Figure 7e), as represented by volcanic arc rocks in the Loei – Phetchabun – Nakhon Nayok volcanic belt (Kamvong *et al.*, 2006; Marhotorn *et al.*, 2008; Tangwattananukul *et al.*, 2008; Nakchiya *et al.*, 2008; Boonsoong *et al.*, 2011, Kromkhun *et al.*, 2013), the Chiang Khong – Tak volcanic belt (Barr *et al.*, 2000; Phajuy 2001; Panjasawatwong *et al.*, 2003; Barr *et al.*, 2006; Qian *et al.*, 2013), and the studied Groups II, III and IV rocks. Finally, the Shan Thai and Indochina terranes might have been completely collided in the Late Triassic, giving rise to the Nan – Uttaradit suture, and then immediately followed by post-orogenic eruption (Wipakul, 2012) that superimposed on the Chiang Khong – Tak volcanic belt (Figure 7f).

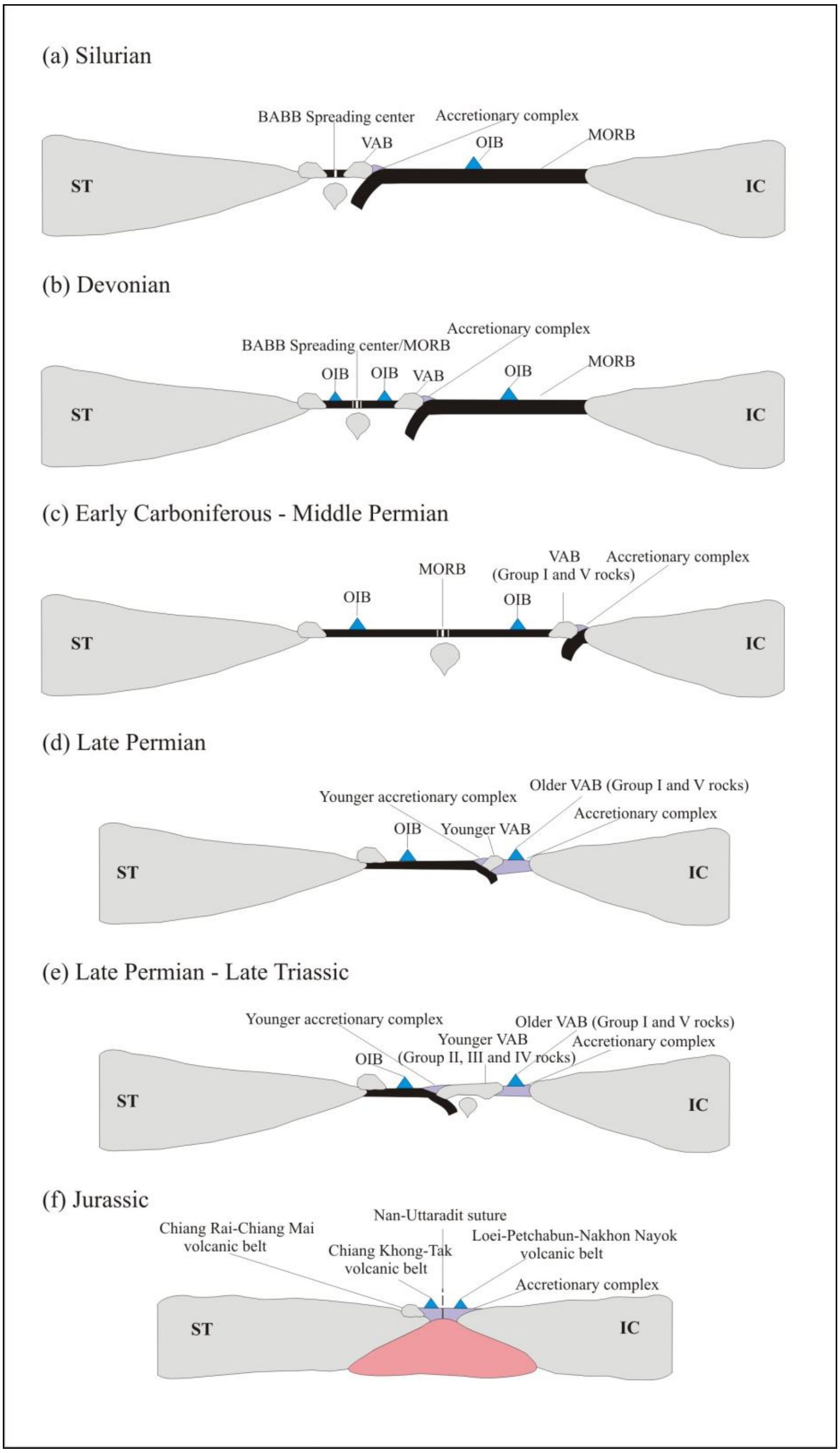

Figure 7 Schematic diagrams showing tectonic evolution of Shan-Thai and Indochina terranes. The abbreviations used are ST, Shan-Thai terrane; IC, Indochina terrane; MORB, mid-ocean ridge basalt (Paleotethys); VAB, volcanic-arc basalt; OIB, ocean-island basalt; and BABB, back-arc basin basalt.