Chapter

Deciphering Magmatic Evolution through Zoned Magmatic Enclaves and Composite Dikes: An Example from the Late Cretaceous Taejongdae Granite in Busan, Korea

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Abstract

Late Cretaceous granitic intrusions are common in the southeastern Korean Peninsula. Most of these intrusions enclose abundant microgranular enclaves (MEs) and dikes of almost identical age to their plutons. The granitic intrusion in the Taejongdae area encloses a distinct type of enclave known as zoned MEs. The zoned MEs in this region are composed of multiple zones originated from different magmas that have the same origin and age. Several petrological, mineralogical, geochemical, SHRIMP U-Ph age dating, and Lu-Hf isotopic studies have been conducted for the Taejongdae granitoid to identify how different magmas have interacted and formed the zoned MEs. In this chapter, we reviewed previous studies and added some new data to give a comprehensive picture of the Taejongdae granite and emphasize the importance of zoned enclaves and composite dikes in determining the genesis and evolution of granitoids. We interpret that the MEs distributed in the southeastern part of the Korean Peninsula with the age of 75–70 Ma might be closely related to the breakdown of the subducted Izanagi oceanic slab under the Eurasian plate. This tectonic process enhanced the input of new primitive magma into granitic magma chambers and, therefore, restricted the mixing or mingling process, forming the zoned MEs.

Keywords: magmatic enclaves, composite dikes, Gyeongsang Basin, magmatic arc, Cretaceous granite, fractional crystallization

1. Introduction

The interaction of different magmas profoundly influences the genesis and evolution of various granitoids [1–3]. Magmatic enclaves (MEs) within granitic rocks are commonly regarded as a reliable evidence for magma interaction [4]. Consequently, understanding the controlling processes of the development of MEs can thus provide a vital insight into the characteristics of the parental magmas as well as the magmatic processes that drive the evolution of granitic plutons [5–7].

During the Mesozoic, the Korean Peninsula was subjected to three episodes of magmatism: Songnim (Triassic), Daebo (Jurassic), and Bulguksa (Late Cretaceous) [8, 9]. Due to the shallow subduction of the Izanagi plate beneath the northeast Asian continental margin, tectonic and magmatic activities in the Korean Peninsula exhibited a landward-younging trend and extended 1000 km into the continent from the ancient trench during the Early to Middle Jurassic; however, Cretaceous magmatism in the Korean Peninsula exhibited a trenchward-younging trend [10]. The major deformations generated by the subduction of the Izanagi plate are represented by the Tanu-Lu fault in China (to the west) and the Median Tectonic line in Japan (to the east) (**Figure 1a**) [12]. The Korean Peninsula, located between those two main deformation belts, was subjected to left-lateral strike-slip movement. As a result, the Gyeongsan Basin formed in the southeastern part of the Korean Peninsula, along with several minor basins in the southwest (**Figure 1b**). Almost two-thirds of the Cretaceous granitoids are concentrated around the Gyeongsang Basin [10]. Using zircon Hf isotopes [13], the Cretaceous plutonic rocks in the Korean Peninsula were described as Cretaceous–Paleogene granitoids in a magmatic arc (Gyeongsang Arc). They concluded that the Gyeongsang granitoids originated from crustal reworking.

The Late Cretaceous Bulguksa granitoids mainly intruded into the Gyeongsang Basin and recorded variable magmatic fractionation, mixing, and mingling processes. From the previous studies, based on the magmatic events, the Late Cretaceous intrusions in the Gyeongsang Basin could be divided into three main groups: Group 1 consists of granodiorite, enclave-rich porphyritic granite, enclave-poor porphyritic granite, and quartz-monzodiorite, which results from the mixing and mingling of two magmas of different physical properties. Group 2 includes equigranular granite, coarse-grained porphyritic granite, and fine-grained micrographic granite, which result from magma fractionation [14]. Group 3 contains adakite-like granitoids generated by amphibole-dominated fractional crystallization of Bulguksa Arc magma, which is reported in the Jindong area [15]. Most of the Late Cretaceous granitic intrusions in the Gyeongsang Basin enclose microgranular enclaves (MEs) that have almost the same ages as their host granitoids [14].

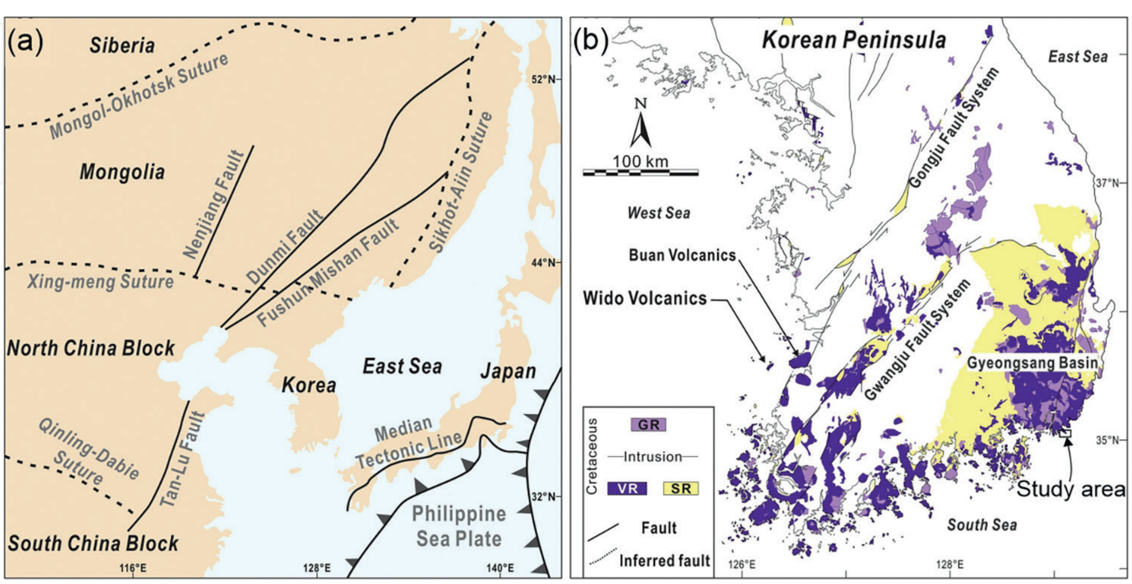

Figure 1.
Tectonic settings of (a) East Asia, and (b) the Korean Peninsula [11]. GR, Cretaceous granitic rocks; VR, Cretaceous volcanic rocks; SR, Cretaceous sedimentary rocks.

The Taejongdae granite, developed in the southeastern part of the Korean Peninsula, contains a distinctive pattern of magmatic enclaves (zoned MEs) made up of multiple different rock zones [16]. The zoned MEs in the Taejongdae granitoid may indicate the magmatic processes that occurred before the intrusion of the granitic pluton in the study area [17]. The first comprehensive petrographic and geochemical study for the Taejondae granitoid and its unique zoned MEs were conducted [16]. In addition, they examined amphibole chemistry within the zoned MEs and the host granite to understand the dynamic process and temperature change during the magmatic evolution. It was concluded that the zoned MEs in the Taejongdae region were formed by mingling and mixing of two magmas: a dioritic magma with a relatively deep crystallization level (7.1–7.7 km) represented by the dioritic zone in the zoned MEs and a shallow-level granitic magma (1.7–2.4 km) represented by the host granite.

Additional data of whole-rock geochemistry, SHRIMP U-Pb zircon age, and Lu-Hf isotope data from zircon grains in the host granite and zoned MEs provide further information on the origin and geochemical characteristics of the dioritic and host granitic magmas and their mutual interaction to produce the zoned MEs [18]. In addition, they compared their geochemical and chronological results with those of other Mesozoic granitoids in the region and proposed some models for the evolution of the Taejongdae granitoids. Furthermore, an ideal composite dike, composed of a felsic granitic interior and mafic margins, which are located approximately 1.2 km from the Taejongdae granitoid to the southeast and hosted in volcano-sedimentary rocks, were reported [19]. The U-Ph zircon age of the felsic granitic interior of the composite dike is almost similar to the age of the Taejongdae granitoid.

In this chapter, we will review the previous studies in the study area to suggest a comprehensive magmatic evolution model and to emphasize the importance of zoned enclaves and composite dikes in determining the magmatic evolution and granitoids' genesis.

2. Petrography and field relationships

Apart from the Taejongdae granite and its associated enclaves in the study area, a variety of mafic dikes are also present, including an ideal composite dike. The enclaves in the study area are divided into two types: simple-type (composed of a single rock type) and composite-type (zoned MEs) (**Figure 2**) [16]. The host granite shows various micro-structural and compositional relationships with the MEs.

The host granite shows a porphyritic texture, miarolitic cavities, and schlieren in certain areas and is composed of albite, orthoclase, and minor amphibole phenocrysts in felsic groundmass minerals. The zoned MEs are characterized by crenulated edges, indicating a mingling relationship between host granite and MEs (**Figure 2a** and **3**) [16, 20]. The simple enclaves, on the other hand, exhibit sharp contact with the host granite, confirming their xenolith origin (**Figure 2b-d**).

The zoned MEs have circular to elliptical shapes and are bordered by three distinct rock zones arranged as follows, from center to rim (**Figure 2a** and **3**):

Zone a is made up of mafic rocks with a porphyritic texture and large amphibole crystals that have been altered into chlorite, as phenocrysts, groundmass minerals, and mesostasis. The groundmass involves plagioclase and anhedral quartz grains. *Zone b* is a mafic rock with fine-to-medium-grained textures with an almost identical mineral composition to zone a. However, the texture of the grains in zone b is slightly finer, and anhedral quartz crystals are more prevalent compared to zone a.

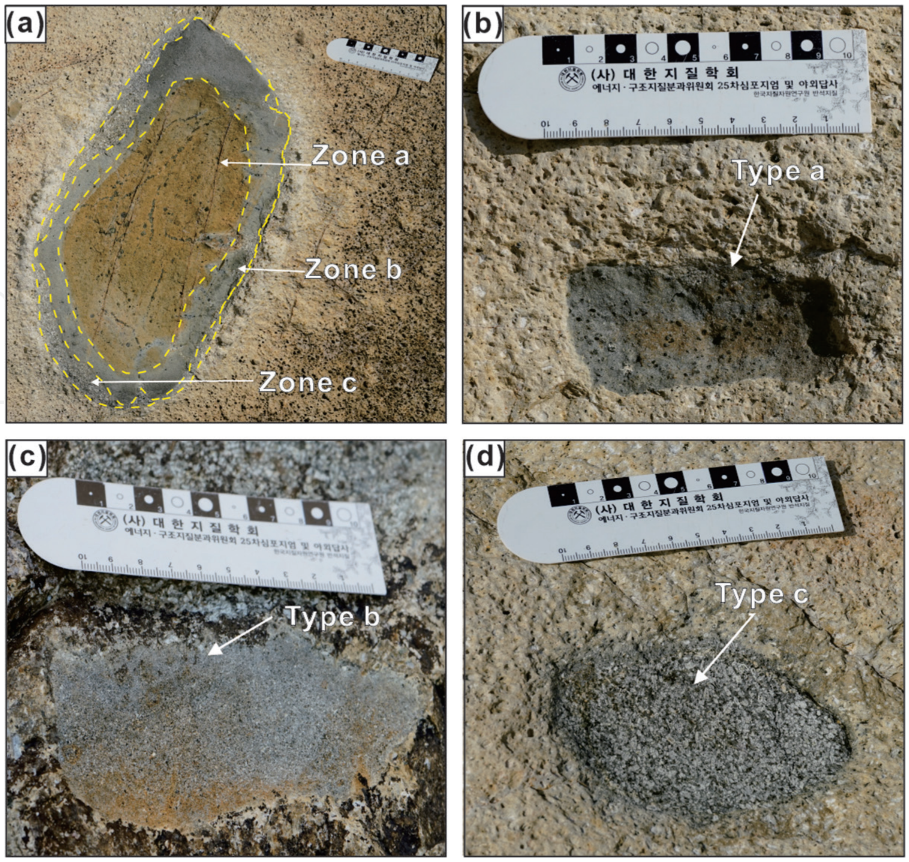

Figure 2.
Various types of MEs hosted in the Taejongdae granite. (a) Zoned ME. (b) Simple ME of type a. (c) Simple ME of type b. (d) Simple ME of type c [16].

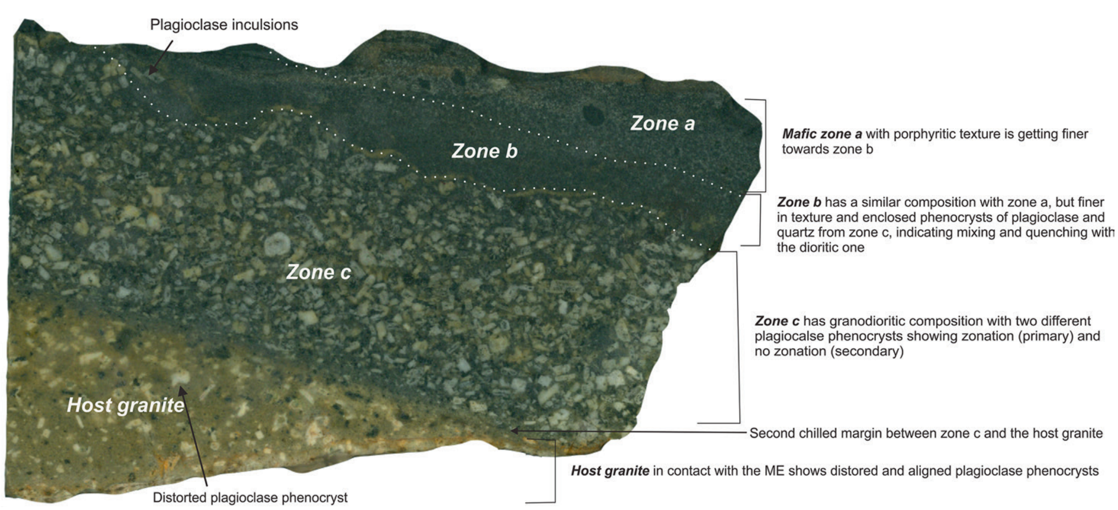

Figure 3.
Polished sample of zoned ME showing the relationship between the different zones and the host granite [16].

Zone c is a felsic rock with a coarse grained texture and made up of hornblende, albite, and orthoclase macrocrysts as well as quartz and feldspar microcrysts and opaque minerals. We can see from the polished sample of a zoned ME (**Figure 3**) [16] that the texture of *zone a* changes gradually from being porphyritic to fine in *zone b* and is surrounded by dioritic *zone c*. This gradual change in texture is caused mostly by the rapid cooling

Simple type MEs		
a	**b**	**c**
Hb + Pl + Q	Hb + Pl + Q	Hb + Pl + Q + Kf
Zoned type MEs		
Zone a	*Zone b*	*Zone c*
Hb + Pl + Q + Chl	Hb + Pl + Q	Hb + Pl + Q + Kf
Composite dike		
Mafic margin a	Felsic core	Mafic margin b
Pl + Bi + Q	Q + Pl ± Or	Pl + Bi + Q

Hb, hornblende; Kf, K-feldspar; Mgt, magnetite; Mus, muscovite; Pl, plagioclase; Q, quartz; Chl, chlorite; Bi, biotite.

Table 1.
Summary of the minerals composition of different MEs in the study area (modified from 16).

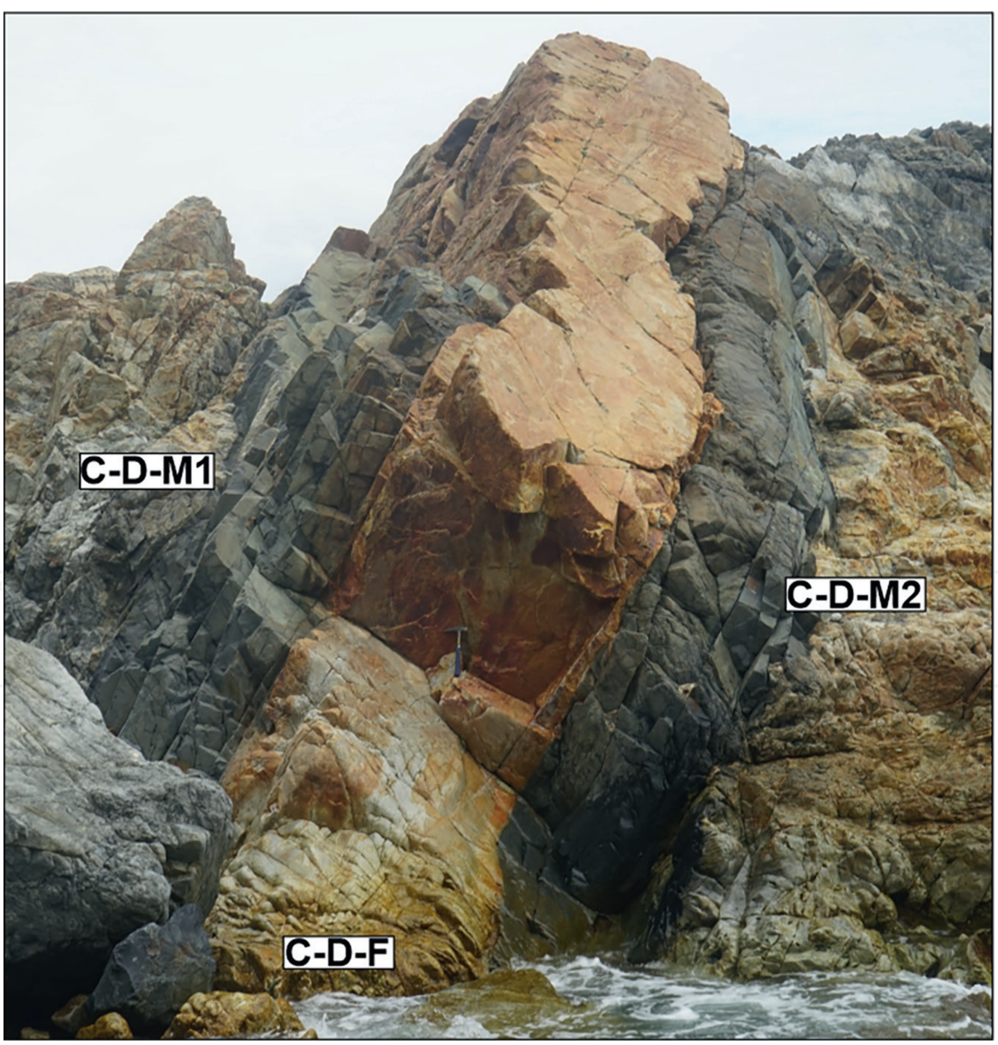

Figure 4.
Composite dike in the study area. C-D-M1 & C-D-M2 = mafic margins of the composite dike; C-D-F = felsic core of the composite dike [19].

(quenching) of a mafic magma by a felsic dioritic magma. Furthermore, *zone b* contains some feldspar megacrysts from the surrounding dioritic *zone c*, indicating felsic and mafic magma mixed/mingled during the development of the zoned MEs [21]. However, the sharp contact between *zone c* and the host granite indicates that there was no major mixing event between *zone c* and the host granite.

Simple MEs, on the other hand, have fairly angular forms and are relatively small in size compared to zoned MEs (**Figure 2b–d**). The simple enclaves are divided into three types [16] based on the mineral composition and texture (here, denoted by type a, b, and c). Most of the simple MEs (type a, b, and c in hand specimens and under the microscope) exhibit a high similarity with the *Zone a, b,* and *c* of the zonal MEs (**Table 1**). Therefore, it was concluded that most of the simple MEs have resulted from zoned MEs breaking mainly before their full solidification [16].

The composite dike in the study area is emplaced into volcanogenic sedimentary strata and characterized by a felsic interior and mafic margins (**Figure 4**). An abrupt change in chemical composition delineates the magmatic transition between the composite dike core and margins. The mafic margins show an andesitic composition of plagioclase phenocryst in a mafic groundmass, whereas the felsic core has a granitic composition of quartz phenocrysts in a felsic groundmass of plagioclase and quartz in addition to opaque minerals. Petrographically and, to some extent, chemically, the felsic core of the composite dike shows high similarity with the host granite of the study area [19].

3. Methodology

Comprehensive geological mapping was performed in the Taejondae area, including the Taejondae granite (Gamji beach) and the area of the nearby dikes. In addition, SHRIMP U-Pb zircon age, whole-rock geochemistry, and amphibole chemical composition studies were performed.

SHRIMP zircon U-Th-Pb dating was performed on three samples of the host granite, *Zone b* and *c* of the zoned MEs, and the felsic core of the composite dike. The calculated ages represent the zircon crystallization time of the host granitic magma, dioritic magma, mafic enclaves, and the emplacement of the felsic dike, respectively. To extract the zircon grains, samples were crushed for 10 seconds, then sieved, and pulverized for another 10 seconds [18]. They repeated this cycle until enough powder was obtained to collect zircon without breaking the zircon grains. Following that, we collected the zircon grains by applying density-based and magnetic procedures at Pukyong National University. Next, we scanned the zircon grains using cathodoluminescence (CL) to select suitable places for investigation while avoiding alteration and inclusion zones. The zircon grains were put on an epoxy mount, which was subsequently cleaned with petroleum ether and then gold-coated to improve surface conductivity. Following the analytical procedures [22], the SHRIMP method was used to analyze U-Th-Pb from the zircon at the Korean Basic Science Institute (KBSI).

For whole-rock major and trace elements analysis, 24 representative samples (12 for major elements and 12 major and trace elements) were collected from the zoned MEs and host granite (three samples from every zone and the other three from the host granite in different locations) [16, 18]. These samples were trimmed to eliminate weathered surfaces to avoid contamination. At Activation Laboratories Ltd. (ACT LABS) in Canada, the samples were ground to a size of 2 mm, splitted to make the samples representative, and crushed them to sizes >105 μm using a mild steel crusher. Between every two samples, cleaner sand was used. The samples were fused in an induction furnace after being combined with a flux of lithium metaborate and tetraborate. The fused samples were then diluted in a 5% nitric acid solution, thoroughly mixed, and analyzed in ACT LABS in Canada using a Perkin Elmer Sciex ELAN 6000, 6100, or 9000 Inductively Coupled Plasma Mass Spectrometry (ICP-MS). ICP-MS was used to analyze the major and trace elements, including transition metals (Ni, Co, and Cr) and rare earth elements (REEs).

The chemical compositions of amphiboles in a zoned ME and the host granite were investigated [16] at Pusan National University using electron microprobe analysis and CAMECA (France) SX100, 2003. The beam had a diameter of 5 μm, 15 keV accelerating voltage, and 20 nA beam current during analysis. Geothermobarometry of amphiboles is used to determine the P-T condition, H_2O melt, and fO_2 of amphiboles during the crystallization in the zoned MEs and the host granite.

4. Geochemical characteristics and age dating

4.1 Mineral chemistry

The chemical composition of amphibole is susceptible to pressure, temperature, oxygen, and water content variations. Such variations in these characteristics could provide useful information for the evolution of magmatic chamber [23]. One of the most widely used geobarometers is the aluminum content of amphibole. The amphiboles in the *zones a, b,* and *c* of a zoned MEs and the host granite were investigated for major elements using the EPMA technique to comprehend the dynamic operation and the change in temperature during the formation of the host granite in the Taejongdae region [16, 24]. The P–T conditions, H_2O melt, and fO_2 of the amphibole in zones (b) and (c), as well as the host granite, are calculated using the proposed formula [25]. The geobarometer calculations revealed that zone (b) amphibole crystallized at T = 798–827°C, P = 134–174 MPa, NNO = 0.9–0.5, fO_2 = 13.–12.8, H_2O melt = 6.1–6.9 wt%, which corresponds to the continental depth = 5.1–6.6 km, whereas zone (c) amphibole crystallized at T = 877–900°C, P = 187–205 MPa, ΔNNO: 0.4–0.7, fO_2: −11.6 – −11.2, H_2Omelt: 4.6–5.3 wt% and continental depth of 7.1–7.7 km. The host granite exhibits the following crystallization state; T = 727–775°C, P = 45–65 MPa, NNO = 1.9–2.2, fO_2 = 13.4–12.5, H_2O melt = 4.4–4.5 wt%, and the continental depth = 1.7–2.4 km. From these results, we concluded that the zoned MEs in the Taejongdae area were made by mixing and mingling of two different magmas [16]: the first is a dioritic magma with a relatively deep crystallization level (7.1–7.7 km), represented by the dioritic zone c in the zoned MEs, and the second is a shallow level granitic magma (1.7–2.4 km). We also reported the geochemical characteristics and origins of the two magmas (dioritic and host granite magmas) and how they interacted to produce the zoned MEs [18]. Furthermore, we compared their geochemical and temporal results with other Mesozoic granitoids in the research area and provided proper models to demonstrate the evolution mechanism of the Taejongdae granitoid.

4.2 Age dating and Lu-Hf isotope analysis

The host granite and zoned MEs were studied using SHRIMP U-Pb zircon age, and Lu-Hf isotope analysis [18]. In addition, SHRIMP U-Pb zircon age dating from the felsic core of the composite dike was conducted [19]. The age dating results indicate that all the rock samples from the host granite, zone b and c of the zoned MEs and the

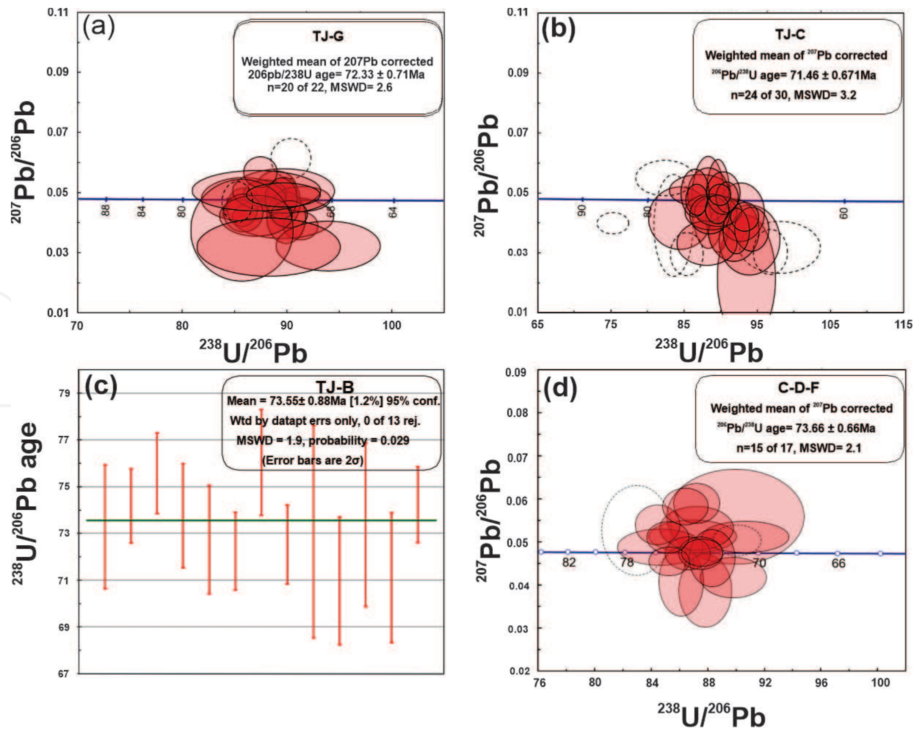

Figure 5.
Concordia diagrams of zircon U-Pb analytical results for samples from the host granite, zoned MEs [18] and core of composite dike [19]. (a) Host granite. (b) Zone c. (c) Recalculated concordia age of the zone b zircon. (d) Felsic core of the composite dike [19].

core of the composite dikes displayed $^{206}Pb/^{238}U$ age of 72.3 ± 0.7 Ma, 71.5 ± 0.7 Ma, 73.5 ± 0.9 Ma, and 73.66 ± 0.66 Ma, respectively (**Figure 5**). Whereas the Lu-Hf isotope data from the host granite and zoned MEs show nearly identical Hf(t) (Hf at the time zircon crystallized) values ranging from −2.0 to +17.4 but grouped around +5, while TDM (depleted mantle model ages) are clustered around 600 Ma.

4.3 Whole-rock geochemistry

The granitic magma of the host granite and the dioritic magma, as seen in zone c of the zoned MEs, were likely combined to form the zoned MEs in the Taejongdae area [16]. The chemical properties of representative samples from the host granite and zone c of the zoned MEs have been studied [18] to determine the characteristics of those two magmas.

From using TAS (SiO_2 vs. $Na_2O + K_2O$; [26]), AFM diagram [27], K_2O versus SiO2, and A/CN-A/NK plots, the host granite samples are identified as high-K calc-alkaline, peraluminous granites (**Figure 6**). Furthermore, the primitive mantle and chondrite normalized REE and trace elements of the host granite exhibit negative Eu anomalies and depleted Nb, P, and Ti patterns (**Figure 7**). Such geochemical characteristics of the granite in the Gyeongsang Basin are typical of the Bulguksa granite. Furthermore, in terms of chemical characteristics and crystallization ages, the Taejongdae host granite is similar to Group IV Cretaceous granitoids (according to the classification of [10]) (**Figure 7a** and **8k**).

Samples from zone c of the zoned MEs (representative of the dioritic magma) exhibit similar characteristics to the Bulguksa granite of dioritic, calc-alkaline, peraluminous magma (**Figures 6** and **7a–c**). The major element chemistry of zone c exhibits some adakitic signatures with SiO2 > 56%, Na2O > 3.5%, Al2O3 > 15%, K2O/Na2O ratios ~0.4, and a positive-to-flat Eu anomaly [31]. Adakite and Archaean tonalite–trondhjemite–granodiorite (TTG) are generally known to originate from slab-melting

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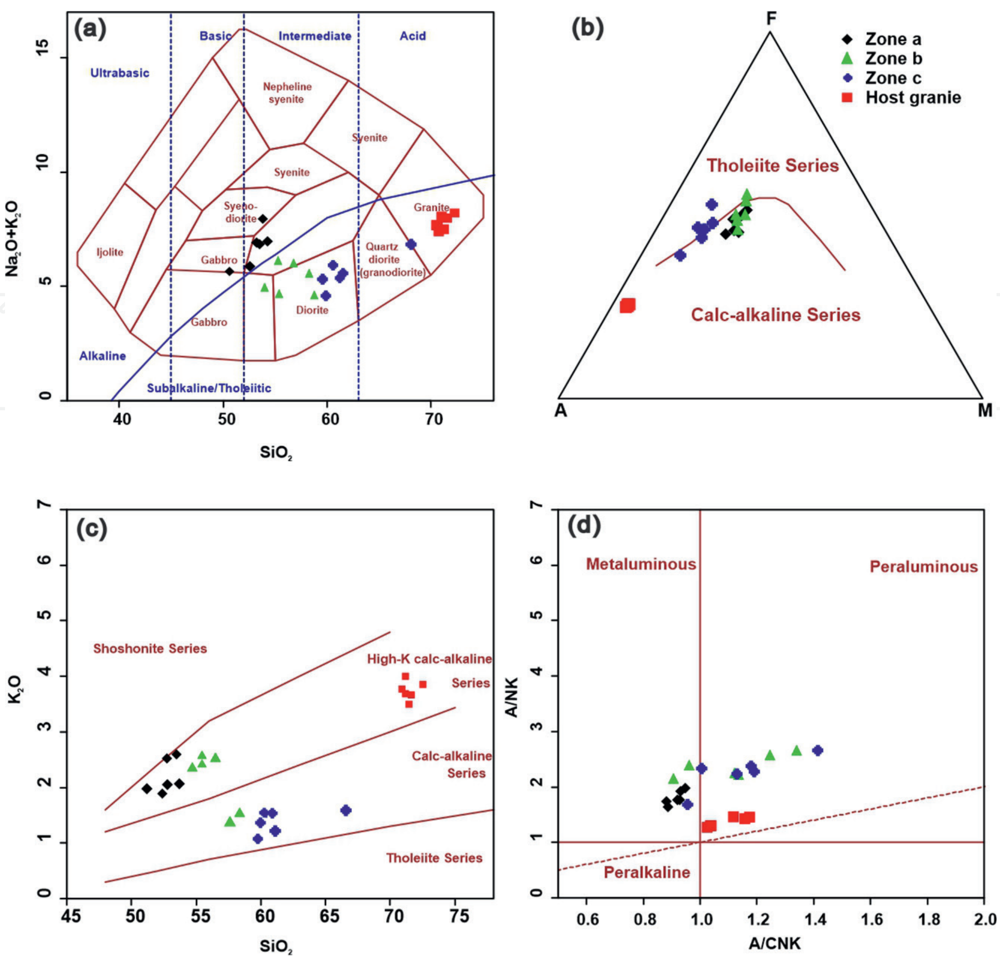

Figure 6.
Geochemical classification of zoned MEs and the host granite samples from the study area [16, 18]. (a) Classification of the zones of zoned MEs and the host granite rocks based on the total alkali versus silica of TAS diagram (SiO_2 versus Na_2O + K_2O; [25]. (b) AFM diagram showing the boundary between tholeiitic and calc-alkaline fields; the majority of the samples plotted in the calc-alcaline field [27]. (c) Classification of the samples using SiO_2 versus K_2O diagram, with fields defined by [28]. d) Plot of a/NK versus a/CNK for the samples. Zones b, c, and the host granite are weak peraluminous, whereas zone a is metaluminous. A/NK = molar ratio of Al_2O_3/(Na_2O + K_2O), a/CNK = molar ratio of Al_2O_3/(CaO + Na_2O + K_2O).

[32]. However, the trace element chemistry of zone c samples show low Sr./Y and La/Tb ratios, which is not consistent with the general feature of adakites and TTG. Thus, it is unlikely that rocks in zone c are adakites. Therefore, we classified zone c dioritic magma as originating from Bulguksa granitic magma [18]. However, to distinguish from the host granite magma, we described zone c dioritic magma as low-K magma.

5. Evolution of the Taejongdae granite

5.1 Origin of the Taejongdae granite

The Bulguksa granitoids in the Gyeongsang Basin (Eonyang area) are classified into several groups and described as porphyritic granitic plutons, or "enclave-rich porphyritic granite (ERPG)" [14]. It is believed that the ERPG was formed by the mixing and mingling of magmas generated from melting of the base of the continental crust (igneous origin) by basaltic magma, which in turn was produced from the upwelling of the asthenosphere beneath the eastern part of the Eurasian continent.

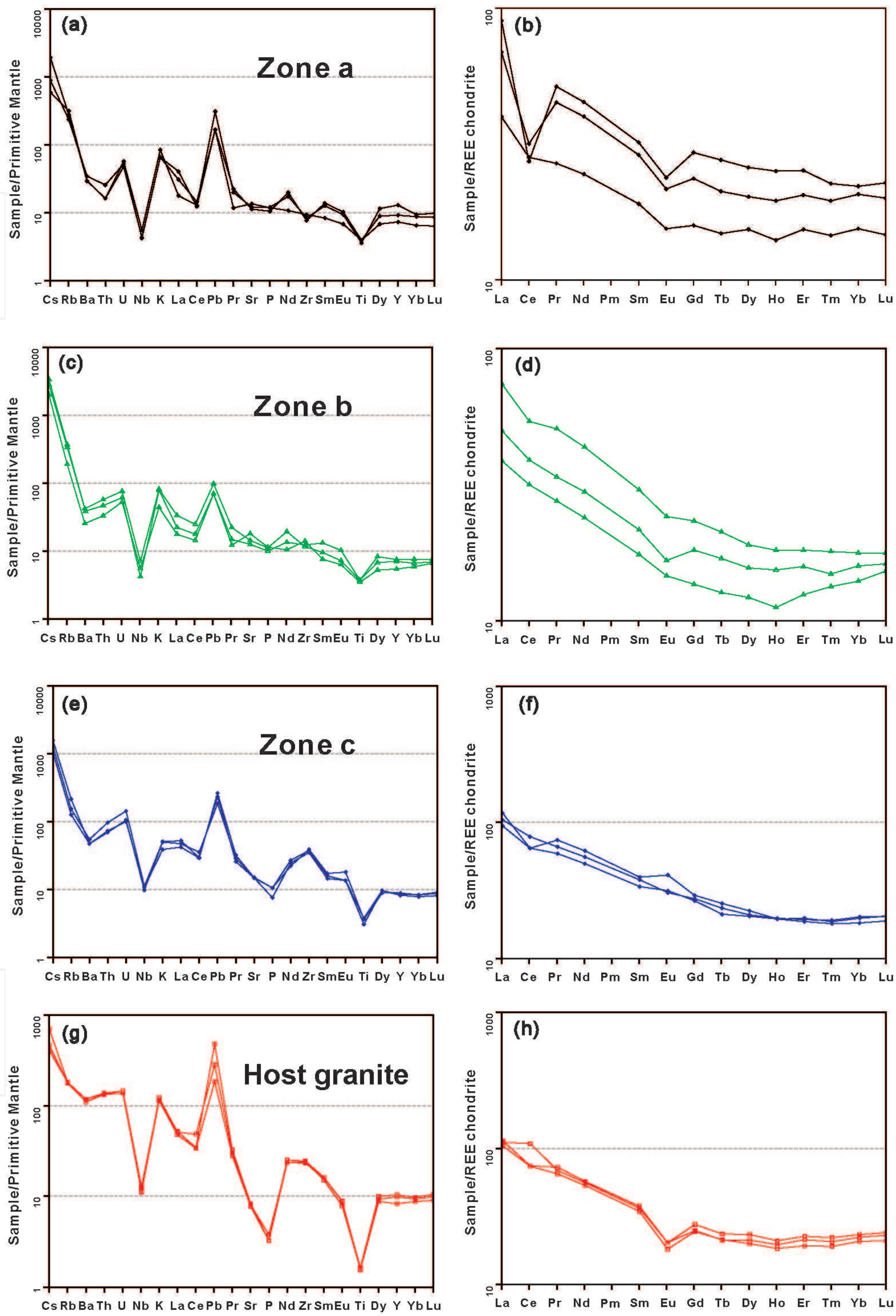

Figure 7.
Whole-rock REE and trace-elements concentrations of the zones a, b, and c and the host granite, normalized to the primitive mantle [29] and chondrite normalized values [30]. (a–b) Zone a samples. (c–d) Zone b samples. (e–f) Zone c samples show positive-to-no anomaly. (g–h) Host granite samples. Data from [18].

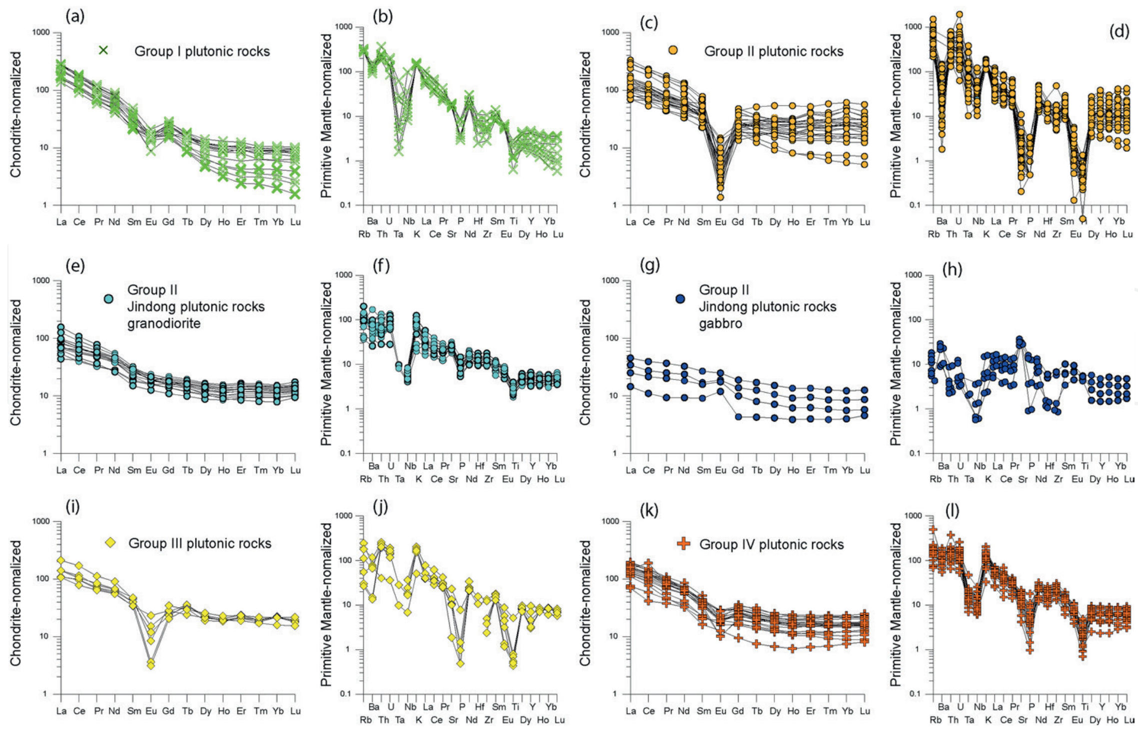

Figure 8.
Chondrite-normalized rare earth elements and primitive mantle-normalized trace elements of the cretaceous plutons in the Korean Peninsula [10].

The upwelling of the asthenosphere was triggered by the formation of a slab window in the subducted Izanagi–Pacific plate beneath the eastern part of the Asian continent [14, 33]. The results of age dating and Lu-Hf isotopes for the Taejongdae granitoid also indicate Late Cretaceous age and the same mixed origin with $^{176}Hf/^{177}Hf$ ratios of 0.282670–0.282978 and $_{\varepsilon}$Hf (t) values ranging from −2 to 8.8 [18]. These data implied that the host granite was formed from a combination of primitive basaltic melts and preexisting crustal rocks of the Paleozoic to Neoproterozoic age [18]. Therefore, the host granite in the Taejongdae area could be classified as Bulguksa granitoid and further classified as the ERPG.

Among the four classified groups of Cretaceous granitoids [10], the dioritic magma of zone c (low-K magma) has similar chemical characteristics to group II granitoids and gabbro (Jindong plutonic rocks), despite their age difference. Both Taejongdae and Jindong granitoids are calc-alkaline and are slightly enriched in LREEs; they also exhibit flat-to-positive Eu anomalies and depleted patterns in P, Nb, and Ti. Such calc-alkaline-like magma with adakitic signatures has also been reported in two granitic intrusions in the southern part of the Korean Peninsula: (i) the Cretaceous Jindong granite in the Gyeongsang Basin and (ii) the Bongnae granitic intrusion in the southeastern part of the Korean Peninsula. From a detailed study of the Jindong and Bongnae granitoids [15], it is concluded that the Cretaceous Jindong pluton was formed neither from adakitic nor TTG magma but from amphibole-dominated fractional crystallization of hydrous Bulguksa-like arc magma. In contrast, the Triassic Bongnae plutons formed from a K-rich C-type adakite-like magma.

The $^{176}Hf/^{177}Hf$ ratios of 0.282801–0.282977 and $_{\varepsilon}$Hf (t) values of 2.6–8.8 of the low-K magma [18] confirm that they have the same source as the host granite. However, different fractional crystallization processes of the same magma could generate different products. Therefore, it was suggested that the low-K magma represents arc magma generated in the Late Cretaceous as the host granite magma (calc-alkaline hydrous Bulguksa-like arc magma) [18]; however, it was crystallized by amphibole-dominated fractional crystallization as Jindong granitoid.

5.2 Evolution of the Taejongdae granite and formation of the zoned MEs

We suggested a model of two stages for the evolution of the Taejongdae granite and the formation of the zoned MEs, by an interaction between the two magmas (the host granite and low-K magma) [16]. In addition, $^{206}Pb/^{238}U$ age, whole-rock geochemical data, and the Lu-Hf isotope analysis from zircon support the two-stage model and a new possibility that the host granite magma may have formed due to rhyolitic melt segregation from the low-K magma [18]. However, rhyolitic melt segregation requires regional compaction [34]. Furthermore, from the study of the composite dike [19], the felsic core of the composite dike has the same emplacement age as the host granite, and the felsic core of the composite dike formation requires an extensional setting. Therefore, the rhyolitic melt segregation model has no enough solid evidences be considered as the formation mechanism for the Taejongdae granite.

5.2.1 Two-stage model

In the first stage, amphibole-dominated fractional crystallization of calc-alkaline arc magma generated a low-K magma at 7.1–7.7 km depth [16]. At 73.55 ± 088 Ma, a trachy-andesitic magma was injected into the low-K granodioritic magma and formed magmatic enclaves. Due to the temperature difference between the trachy-andesitic and the low-K magma, zone b cooled rapidly while zone a cooled gradually. The tecture and

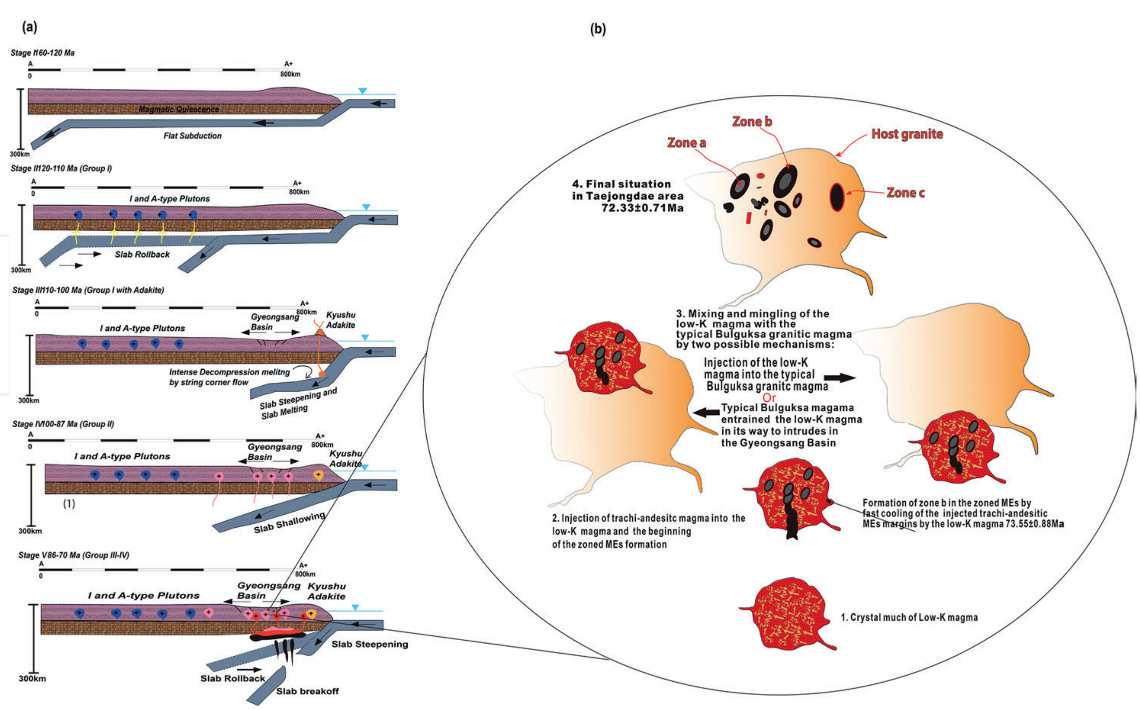

Figure 9.
Evolution of the Cretaceous granitoids in the Korean Peninsula [10]. a) Tectonic model of the Korean Peninsula during the late Jurassic to the Cretaceous illustrating the movement of the subducting oceanic plate and its control on the evolution of the Cretaceous granitoids (the cross section location A-A⁺ is marked in the appendix a). b) Simplified model for the mingling of low-K magma, the late Cretaceous Bulguksa granite, and the formation of zoned MEs in Taejongdae (modified from [16]), the figure is not to scale.

zircon age of zone b reflect the trachy-andesitic magma injection sequence. At the same time or slightly later, another Bulguksa calk-alkaline arc magma developed through fractional crystallization and reached the surface (which represents the host granite).

In the second stage, the two magmas could be combined through two possible manners. The first possibility is that the typical Bulguksa magma of the host granite intruded the basin and entrained the low-K magma and its magmatic enclaves as enclaves (second round of enclaves formation) without mixing (due to the physical properties differences) and solidified at a shallow level in the Gyeongsang Basin as the Taejeongdae granite. The second possibility is that the low-K magma with its trachy-andesitic enclaves were ascended and injected into the host granite magma, and consolidated at a shallow level in the Gyeongsang Basin (72.33 ± 0.71 Ma) (**Figure 9c**).

6. Tectonomagmatic setting

The diorite-granodiorite-granite plutons of the southeastern (or southern) part of the Korean Peninsula, including the Taejongdae region, are calc-alkalic granitoids with or without MEs. By mixing/mingling magmas, more mafic types (Group I of [14]) were generated. In contrast, granodiorite-granite plutons (Group II of [14]) were formed by the fractional crystallization of a parent magma. According to their geochemical characteristics, the 75–70 Ma diorite-granite plutons are high-K and calc-alkaline rocks related to subduction [10, 12].

The tectonic and magmatic activities, in the Korean Peninsula, during the Cretaceous (120–70 Ma) show an oceanward-younging trend and spread out approximately ~800 km into the continent from the subduction zone (the ancient trench) (**Figure 9a**). The magma from the old trench may indicate shallow subduction of the Izanagi plate [10, 35]. In the southeastern part of the Korean Peninsula, the tectonic and magmatic activities during 75–70 Ma might be closely related to slab steeping due to slab rollback of the Izanagi plate, leading to lithospheric and/or crustal thinning and oceanward arc migration [10]. The subduction slab rollback represents one of the main factors controlling the stress state transition from compression to extension [36]. During the same duration, the breakdown of the subducted oceanic slab created a slab window, having a narrow gap and permitting the asthenospheric upwelling (**Figure 9a**) [14, 37].

Therefore, based on our U-Pb zircon age and Lu-Hf isotope data, we suggest that these tectonomagmatic processes resulted in the emplacement of the Late Cretaceous (75–70 Ma) mafic and MEs-bearing granitoid plutons, having crustal isotopic signatures. The abundant MEs and dikes distribution in the southeastern part of the Korean Peninsula, during 75–70 Ma (appendix A), might be closely related to the breakdown of the subducted Izanagi oceanic slab under the Eurasian plate.

7. Conclusions

Taejongdae area, located in the southeastern part of the Korean Peninsula, was selected in this chapter as a case study for deciphering the magmatic evolution through the analysis of zoned magmatic enclaves and composite dikes.

The Taejongdae granite is believed to have originated from the mixing and mingling of magmas generated from the melting of the base of the continental crust by basaltic magma, which was produced from the upwelling of the asthenosphere beneath the eastern part of the Eurasian continent. The host granite was formed from a combination of primitive basaltic melts and preexisting crustal rocks of Paleozoic to Neoproterozoic age. The Taejongdae granite is classified as Bulguksa granitoid and further classified as enclave-rich porphyritic granite (ERPG).

The zoned MEs were formed in two stages due to the interaction of two magmas, the host granite and low-K magma. The low-K magma represents arc magma generated in the Late Cretaceous (similar to the host granite magma); however, it was crystallized by amphibole-dominated fractional crystallization.

The intense concentration of the Cretaceous MEs and mafic dikes in the southernmost part of the Korean Peninsula was primarily controlled by magma mixing induced by asthenospheric upwelling during the subduction of the Izanagi oceanic plate under the eastern margin of the Eurasian plate. The zoned MEs and composite dikes in the Taejongdae area indicates the characteristic magmatic process that took place in subduction zone setting. This study indicates that detailed analyses of enclaves and dikes could give very useful information on the understanding of the tectonic evolution as well as the magmatic interaction of the region.

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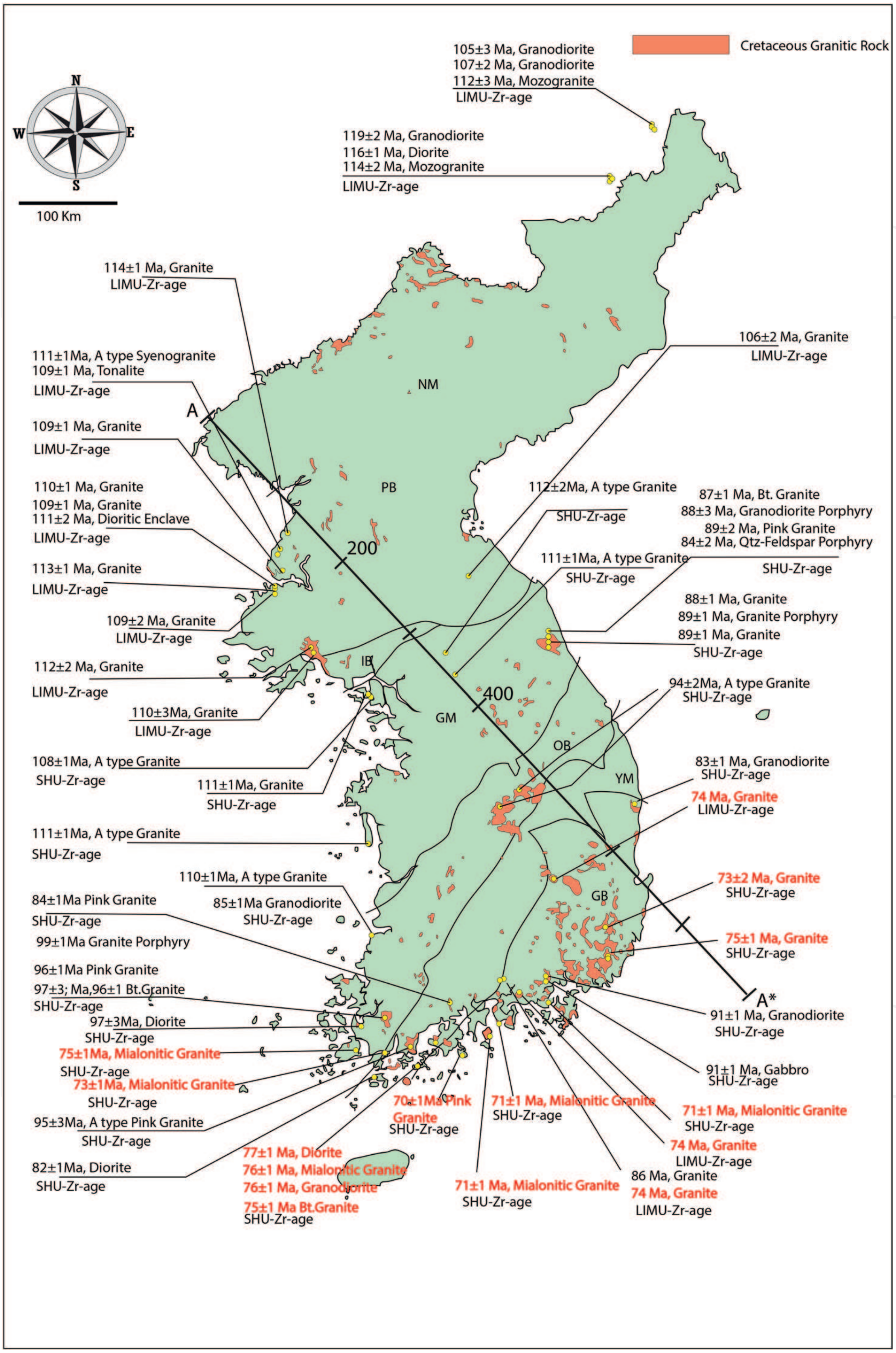
Conflict of interest

The authors declare no conflict of interest.

A. Appendix

Ages of the plutons from the previous studies. The Late Cretaceous granitoids (with red colors) are concentrated in the southern part of the Korean Peninsula (Modified from [10]).


Cretaceous Granitic Rock
N
W
E
S
100 Km
105±3 Ma, Granodiorite
107±2 Ma, Granodiorite
112±3 Ma, Mozogranite
LIMU-Zr-age
119±2 Ma, Granodiorite
116±1 Ma, Diorite
114±2 Ma, Mozogranite
LIMU-Zr-age
114±1 Ma, Granite
LIMU-Zr-age
106±2 Ma, Granite
LIMU-Zr-age
111±1Ma, A type Syenogranite
109±1 Ma, Tonalite
LIMU-Zr-age
NM
A
109±1 Ma, Granite
LIMU-Zr-age
110±1 Ma, Granite
109±1 Ma, Granite
111±2 Ma, Dioritic Enclave
LIMU-Zr-age
PB
112±2Ma, A type Granite
SHU-Zr-age
87±1 Ma, Bt. Granite
88±3 Ma, Granodiorite Porphyry
89±2 Ma, Pink Granite
84±2 Ma, Qtz-Feldspar Porphyry
SHU-Zr-age
200
113±1 Ma, Granite
LIMU-Zr-age
111±1Ma, A type Granite
SHU-Zr-age
88±1 Ma, Granite
89±1 Ma, Granite Porphyry
89±1 Ma, Granite
SHU-Zr-age
109±2 Ma, Granite
LIMU-Zr-age
IB
112±2 Ma, Granite
LIMU-Zr-age
400
94±2Ma, A type Granite
SHU-Zr-age
110±3Ma, Granite
LIMU-Zr-age
GM
OB
108±1Ma, A type Granite
SHU-Zr-age
111±1Ma, Granite
SHU-Zr-age
83±1 Ma, Granodiorite
SHU-Zr-age
YM
74 Ma, Granite
LIMU-Zr-age
111±1Ma, A type Granite
SHU-Zr-age
110±1Ma, A type Granite
73±2 Ma, Granite
SHU-Zr-age
84±1Ma Pink Granite
SHU-Zr-age
85±1Ma Granodiorite
SHU-Zr-age
GB
99±1Ma Granite Porphyry
75±1 Ma, Granite
SHU-Zr-age
96±1Ma Pink Granite
97±3; Ma,96±1 Bt.Granite
SHU-Zr-age
A*
91±1 Ma, Granodiorite
SHU-Zr-age
97±3Ma, Diorite
SHU-Zr-age
75±1Ma, Mialonitic Granite
SHU-Zr-age
91±1 Ma, Gabbro
SHU-Zr-age
73±1Ma, Mialonitic Granite
SHU-Zr-age
70±1Ma Pink Granite
SHU-Zr-age
71±1 Ma, Mialonitic Granite
SHU-Zr-age
71±1 Ma, Mialonitic Granite
SHU-Zr-age
95±3Ma, A type Pink Granite
SHU-Zr-age
74 Ma, Granite
LIMU-Zr-age
77±1 Ma, Diorite
76±1 Ma, Mialonitic Granite
76±1 Ma, Granodiorite
75±1 Ma Bt.Granite
SHU-Zr-age
82±1Ma, Diorite
SHU-Zr-age
71±1 Ma, Mialonitic Granite
SHU-Zr-age
86 Ma, Granite
74 Ma, Granite
LIMU-Zr-age

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