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East Asia-Wide Flat Slab Subduction and Jurassic Synorogenic Basin Evolution in West Korea

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1. Introduction

The interplay between oceanic plate subduction and the development of continental margins is of considerable geological interest, and of a particular interest for Asian structural geologists and petrologists is the subduction of the present and ancient Pacific plates, which triggered orogenic development and contributed to crustal evolution in the circum-Pacific regions through the Phanerozoic [1, 2]. Since the Triassic, the northwestern circum-Pacific region (also known as the East Asian continental margin) initiated the evolution of a continental arc stretching several thousand kilometers, which resulted in an East Asia-wide crustal shortening and thickening, orogenic basin formation, and landward magmatic progradation [2, 3, 4, 5, 6, 7, 8, 9]. It is noted that although the paleo-Pacific subduction along this region was also present in Paleozoic time, it did not exert a major tectonic impact on the Asian continents [10, 11, 12], and that this lack of impact was probably related to the fact that the Paleotethys Ocean lay between Laurasia and Gondwana until the Triassic period when the East Asian continental blocks had not been yet assembled [13, 14].

The Korean Peninsula, situated in the middle of the East Asian continental margin (Fig. 1), was plunged into a tectonically active phase in Mesozoic time, and three major orogenies are recorded; the Songnim, Daebo, and Bulguksa [4]. Among these, the Songnim orogeny (260–220 Ma) is represented by regional metamorphism in a close association with the final amalgamation of Chinese continental blocks in Permian–Triassic period [15, 16]. A drastic tectonic transition followed this orogeny, and the evolution of a continental-magmatic arc occurred during the Daebo (190–135 Ma) and Bulguksa (100–45 Ma) orogenies, which resulted from the flat slab subduction and subsequent slab rollback of the western paleo-Pacific plates, respectively [5, 8, 17, 18]. It is evident that the Songnim–Daebo tectonic transition led to a radical shift of the Korean sedimentary environments, from Paleozoic marine to Mesozoic

nonmarine domains [12, 19]. The evolution of the continental arc ultimately produced a derivation of Korean-derived detrital sediments in the Pacific-side regions, such as in the Inner Zone of Southwest Japan [20, 21, 22, 23, 24, 25].

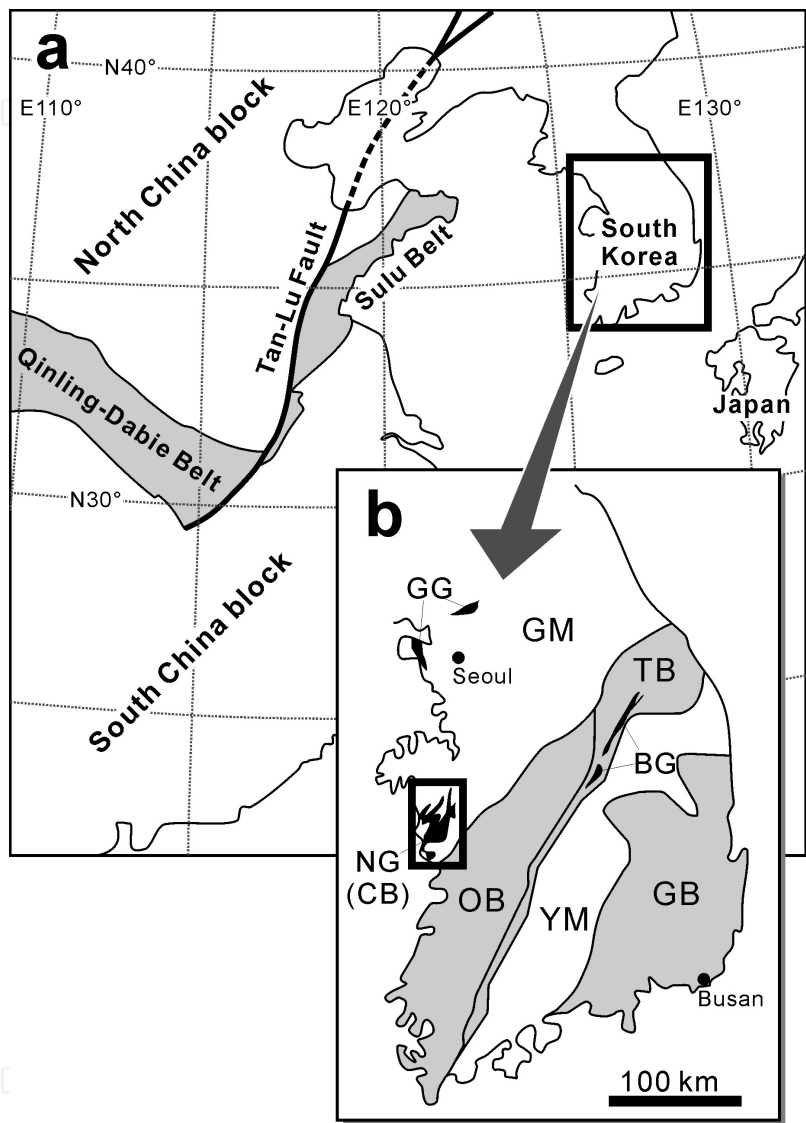


Figure 1. (a) Simplified tectonic map of East Asia, and (b) close-up of South Korea showing the major tectonic provinces with the study area (boxed) (modified after Egawa and Lee [7]). BG, Bansong Group; CB, Chungnam Basin; GB, Gyeongsang Basin; GG, Gimpo Group; GM, Gyeonggi Massif; NG, Nampo Group; OB, Okcheon Belt; TB, Taebaeksan Basin; YM, Yeongnam Massif.

The tectonism, magmatism, and sedimentation of South Korea have been systematically well reviewed and summarized by Korean geologists [4, 12, 19, 26, 27]. However, such work has included only limited description and minor discussion on Jurassic basinal evolution because of the very limited distribution and publication of research in comparison with studies related to other Phanerozoic basins (Fig. 1). In contrast, many of Jurassic structural and igneous events have been reported and detailed [4, 5, 18, 28, 29, 30, 31].

It has been conventionally interpreted that Jurassic non-marine basins are interorogenic basins, formed during the period between the Songnim and Daebo orogenies [4, 19, 32]. However, recent radiometric dating of detrital zircon [30, 33, 34] has provided an alternative view of this conventional interpretation and has shown that the depositional age of these Jurassic basins corresponds to the early phase of the Daebo orogeny; indicating a close association with the subduction-induced continental arc evolution.

From recent petrologic analyses and radiometric dating, the Chungnam region in western South Korea (known as the Hongseong Belt) has been interpreted as being an eastern extension of the Qinling–Dabie–Sulu Belt (the collisional belt between the North and South China blocks) (Fig. 1) [15, 35]. In the Chungnam region, it appears that Proterozoic to Paleozoic basement rocks were regionally metamorphosed with a high to ultra-high pressure facies during the Songnim orogeny [35, 36, 37, 38, 39]. The subsequent rapid uplift and denudation of these basement rocks then delivered their detritus into the Jurassic Chungnam Basin [34], which was followed by a structural disturbance during the late stage of the Daebo orogeny [31, 40].

The author of this paper has been studying the Chungnam Basin for several years [7, 40, 41, 42, 43, 44], and has demonstrated that the basin filling and thermal history are closely related to the Daebo continental-arc evolution. This paper presents an overview of the characteristics and mechanisms of Mesozoic flat slab subduction in East Asia, and then summarizes the sedimentary and structural evolution of the Chungnam Basin during the Daebo orogeny, with the intention of promoting a better understanding of the basin-filling processes in West Korea and also of the interplay between basinal and crustal evolution at the active continental margin of East Asia.

2. Flat slab subduction

2.1. Evidence of flat slab subduction in and around Korea

Recent igneous studies suggest that the Mesozoic continental arc evolution was triggered by the flat slab subduction of the western paleo-Pacific plates underneath the East Asian continent [6, 45, 46]. According to the observation of modern subduction zones in the Andes, there is a close relationship between flat slab subduction, crustal shortening and thickening, and inlandward-migrating magmatism [47, 48, 49, 50]. Subducted slab dip is fundamentally constrained by slab buoyancy. Therefore, a slab with oceanic plateaus or ridges is flatly subducted over a long distance, while steeper subduction occurs when such features are absent [49, 51].

Evidence for the subduction of such buoyant oceanic materials is found in the Mesozoic accretionary complexes along the eastern margin of Asia, stretching a distance of several thousand kilometers, and is seen particularly in Japan and Russian Far East [2, 52]. These complexes generally consist of oceanic plateau basalts and deep marine deposits, which were accreted and underplated underneath the Asian continental crusts during subduction [53, 54, 55]. Paleomagnetic analysis has revealed that the Japanese Islands were geologically connected

to the Asian continent before the opening of the Japan Sea in Miocene epoch [6, 56], and that the Jurassic accretionary complex in Southwest Japan was situated next to South Korea during its formation [25, 29], which was initiated in, at the latest, the early Late Triassic period [57] and continued through the Jurassic period [52]. Adakitic granites, which are indicators of slab melting, intruded widely into the Korean continental crusts with an inlandward younging trend during the Jurassic period [5, 8, 18, 58], supporting the interpretation of inlandward slab migration [47, 48, 59].

2.2. Orogenic gaps between Korea and South China

The geology of South China records two major Mesozoic orogenies: the Indosinian orogeny (250–205 Ma) indicated by inlandward-migrating magmatic front with crustal thickening and shortening, and the Yanshanian orogeny (180–66 Ma) characterized by an oceanward-retrograding magmatic front with crustal thinning and stretching [6, 60]. These two orogenic events resulted from a flat slab subduction with a length of 1400 kilometers, and a subsequent slab rollback [6, 45]. The Korean Peninsula is situated just 500 km northeast of South China,

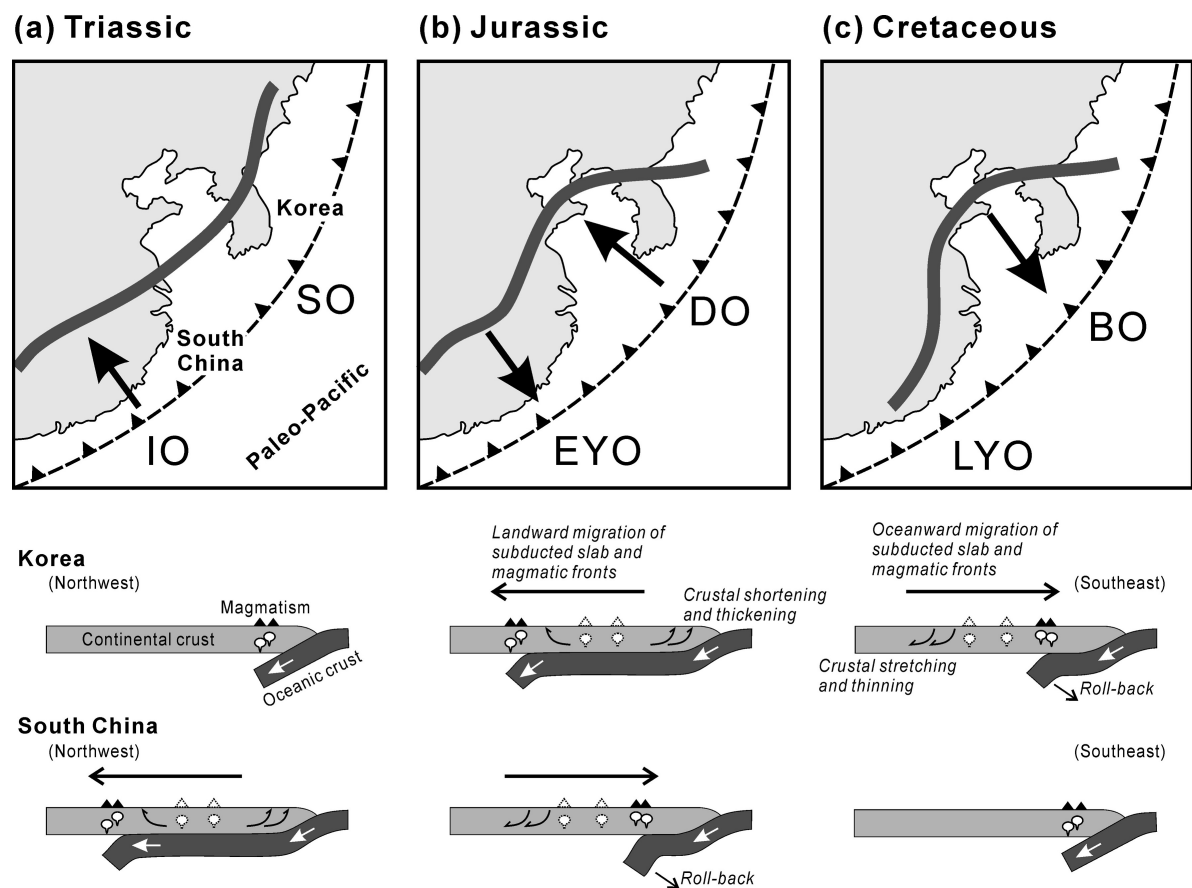


Figure 2. Landward and subsequent oceanward migration of subducted slab and magmatic fronts (direction indicated with a heavy line) in Korea and South China: (a) Triassic, (b) Jurassic, and (c) Cretaceous periods (modified after Li and Li [6], Choi et al. [8], Egawa [44], Kiminami et al. [46], and Zhou et al. [60]). Migration of magmatic front is linked to the morphology of the subducted slab of oceanic plate. BO, Bulguksa orogeny; DO, Daebo orogeny; EYO, Early Yanshanian orogeny; LYO, Late Yanshanian orogeny; IO, Indosinian orogeny; SO, Songnim orogeny.

and two peninsula-wide orogenies, the Songnim and Daebo orogenies, occurred almost contemporaneously with the Indosinian and Yanshanian orogenies, respectively. It has therefore been conventionally interpreted that these Chinese and Korean orogenies progressed under the same subduction processes [2, 4, 61].

It is necessary to reiterate here that the Songnim and Daebo orogenies are represented by a regional metamorphism related to the Chinese final assembly and by the evolution of the continental-magmatic arc associated with the paleo-Pacific subduction, respectively. Such facts therefore provide an alternative interpretation: there were distinct orogenic gaps between South China and Korea (Fig. 2) [8, 18]. This implies that when the Triassic flat slab subduction has already initiated the Indosinian orogeny in South China, the Songnim regional metamorphism in Korea was then caused by the ongoing final amalgamation of the Chinese continental blocks. The subsequent Daebo continental-magmatic arc evolution then occurred 60 m.y. later than the compressional Indosinian orogeny, and by this time South China was already in the phase of the extensional Yanshanian orogeny.

3. Synorogenic basin evolution in West Korea

The foregoing flat slab subduction then triggered and drove the Daebo orogeny in Korea, with a significant crustal shortening and thickening [4, 30]. This crustal deformation created an orogenic wedge in middle South Korea, which consists of the southeast- and northwest-vergent fold-and-thrust belts (Fig. 3) [62]. The former belt corresponds to a pro-wedge region, which includes the Okcheon Belt and the Taebaeksan Basin, and the latter-mentioned belt developed as a retro-wedge region, which includes the Chungnam region [4, 7, 30, 33]. Such wedge structures were probably formed under a NW–SE-directed compressional setting during the orogeny [63, 64].

The Chungnam Basin (consisting of several separated subbasins—the Ocheon, Oseosan, and Seongju subbasins, and other unnamed) was filled with a Jurassic nonmarine deposit, known as the Nampo Group (Fig. 4). This group unconformably covers the pre-Jurassic metamorphic basement rocks, and was structurally underlain by these rocks due to the postdepositional thrust faulting [40, 41]. The stratigraphy of the Nampo Group is subdivided into the Hajo, Amisan, Jogyeri, Baegunsa, and Seongjuri formations with decreasing age [65, 66]. Among them, the Hajo, Jogyeri, and Seongjuri formations are mainly composed of conglomerate and sandstone, whereas the Amisan and Baegunsa formations are dominated by an alternation of coal-bearing shale and sandstone. In this study, the stratigraphy of the Oseosan Subbasin (as defined by Egawa and Lee [7, 41]) is revised on the basis of the recognition of the Oseosan Thrust, which allows the structurally repetitive distribution of the Hajo and Amisan formations (Figs. 4, 5). The depositional age of the Nampo Group is inferred as being between Sinemurian and Aalenian, based on U–Pb zircon dating of regionally metamorphosed basement rocks (230–220 Ma) [35, 37, 38] and felsic lapilli tuff of the Baegunsa Formation (170 Ma) [30], which is synchronous with the magmatic event in the early stage of the Daebo orogeny (180–170 Ma; U–Pb sphene and Rb–Sr whole-rock ages) [5].

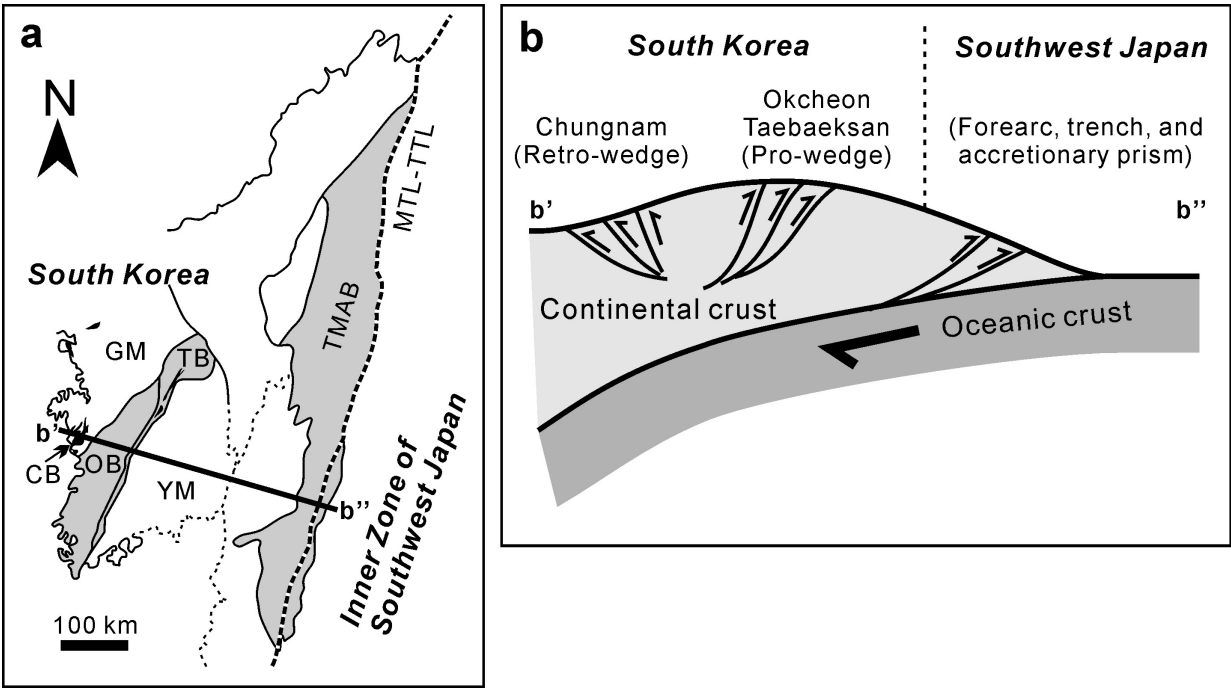


Figure 3. (a) The possible tectonic arrangement of South Korea and the Inner Zone of Southwest Japan during the Jurassic period (modified after Egawa and Lee [7]). CB, Chungnam Basin; GM, Gyeonggi Massif; MTL-TTL, Median Tectonic Line–Tanakura Tectonic Line; OB, Okcheon Belt; TB, Taebaeksan Basin; TMAB, Tanba–Mino–Ashio Belt (Jurassic accretionary complex); YM, Yeongnam Massif. (b) Schematic cross section along the b'–b'' section in (a) showing the possible evolution of a continental arc (not to scale).

3.1. Basin filling controlled by a tectonic cycle

Egawa and Lee [7] detailed and classified the nonmarine sedimentary characteristics of the Nampo Group into seven sedimentary facies associations: colluvial fan, alluvial fan, braidplain, delta plain, delta front, offshore lacustrine, and volcanoclastic plain (Fig. 5). A combination of these facies associations reveals a vertical cyclic pattern presented by the fining- to coarsening-upward lower and upper sequences of the alluvio-lacustrine system in the Ocheon, Oseosan, and Seongju subbasins. These depositional cycles are subdivided by the thick, progressive colluvial/alluvial fan deposits of the Jogyeri Formation, along with strong interformational unconformities occurring between the Amisan and Lower Jogyeri formations (U1 unconformity) and between the Lower and Upper Jogyeri formations (U2 unconformity).

Such stratigraphic features correspond to typical alluvial basin-filling patterns, and are attributable to tectonically-driven sediment flux or climate-driven diffusivity occurring over a relatively short time-scale [67, 68]). The lack of stratigraphic or temporal variations in the degree of chemical weathering [69], along with the presence of coal deposits [70, 71], indicates little or no climate fluctuation at the time of basin filling. This illustrates that a process of tectonically-driven sediment flux is most likely to have occurred. As variation of sediment flux is an index of tectonic activity, the remarkable gravel progradation of the Jogyeri Formation probably records a time of low sediment flux and quiescent tectonism (Fig. 6) [67, 72, 73]. Under this assumption, therefore, the fine-grained sediments in the

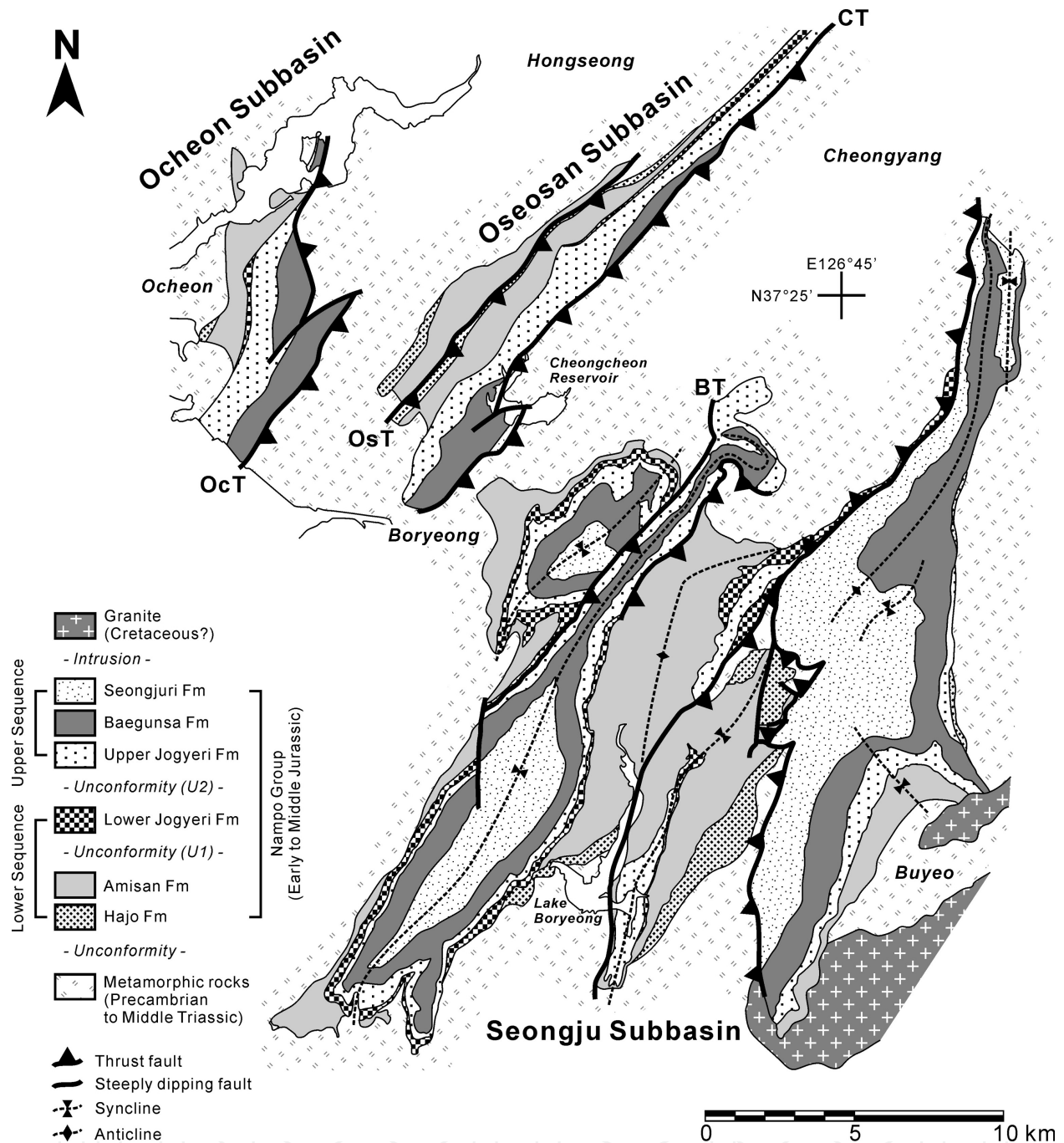


Figure 4. Geological map of the Chungnam Basin (which consists of the Ocheon, Oseosan, and Seongju subbasins) filled with the Jurassic Nampo Group (modified after Egawa and Lee [7]). BT, Baegunsa Thrust; CT, Cheongla Thrust; OcT, Ocheon Thrust; OsT, Oseosan Thrust.

other four formations are interpreted to have been deposited under active tectonism. It is assumed that the phase of Jogyeri gravel progradation reflected the progressive encroachment of deformation into the foreland [74, 75] due to the subduction-induced crustal shortening. These relationships permit a possible interpretation of the Chungnam Basin as being a piggyback or wedge-top basin [76, 77].

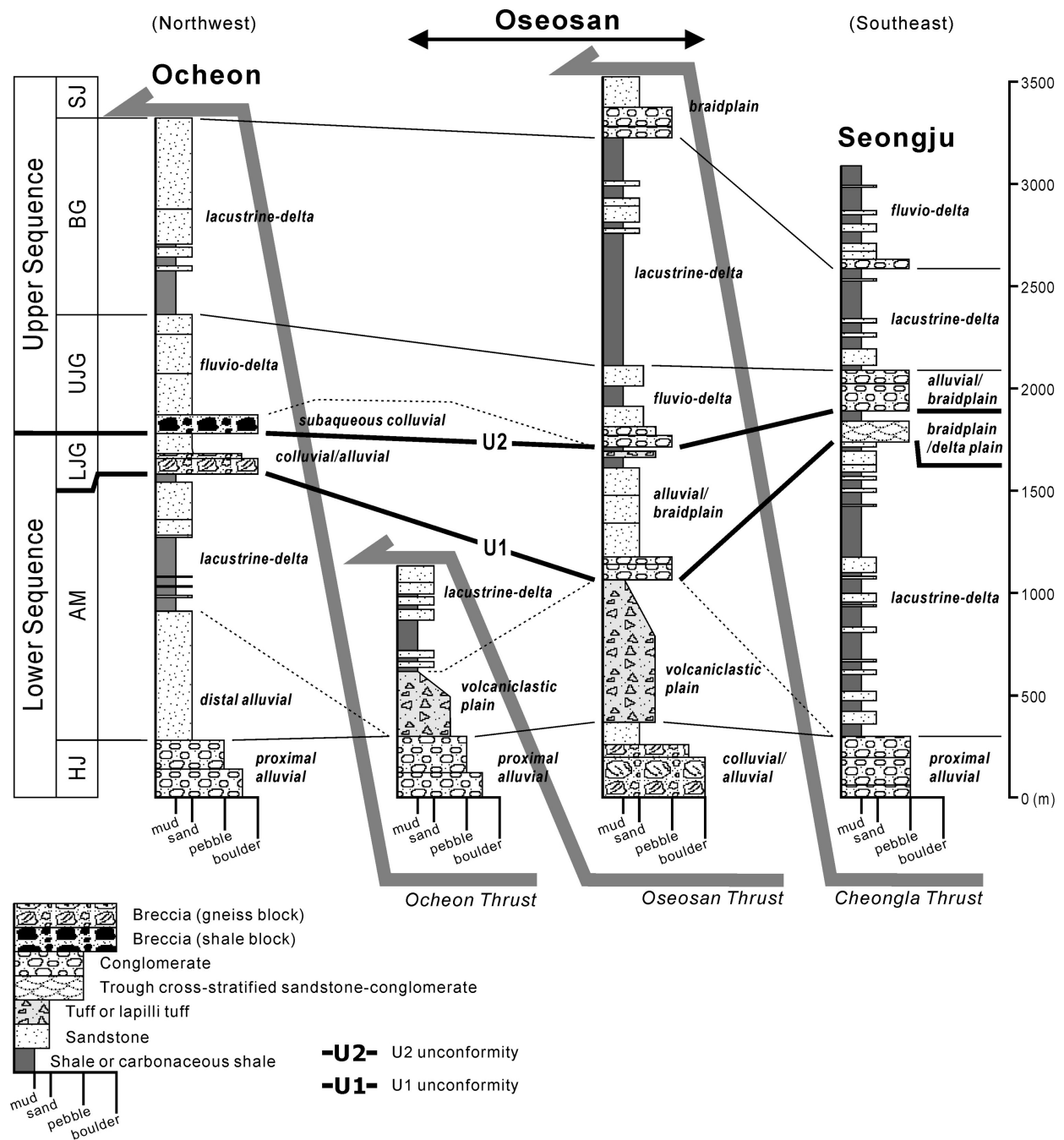


Figure 5. Strato-sedimentological interpretation of the Jurassic Nampo Group in the Ocheon, Oseosan and Seongju subbasins (modified after Egawa and Lee [7]). HJ, Hajo Formation; AM, Amisan Formation; BG, Baegunsa Formation; LJG, Lower Jogyeri Formation; SJ, Seongjuri Formation; UJG, Upper Jogyeri Formation.

3.2. Postdepositional thermal events

In the late stage of the Daebŏ orogeny (late Jurassic to earliest Cretaceous time), the orogenic activity was further accelerated by the oblique subduction of the paleo-Pacific plates with strike-slip motion [29, 78, 79, 80], leading to significant crustal shortening and thickening represented by thrust-imbricate stacking [4, 30, 31]. Most of the Daebŏ granites were synde-

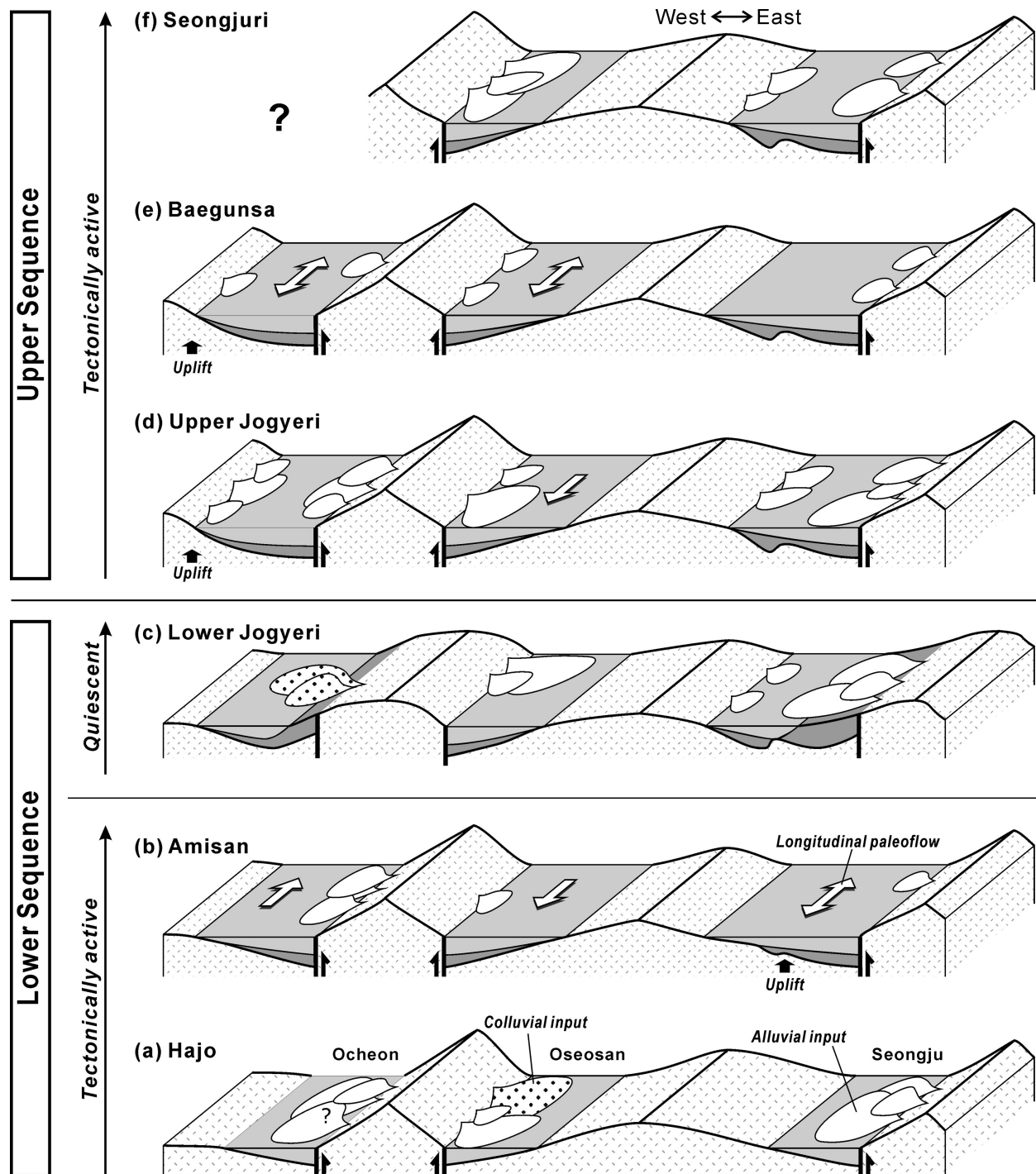


Figure 6. Schematic syntectonic evolution of the Chungnam Basin in the depositional stages of (a) the Hajo, (b) Amisan, (c) Lower Jogyeri, (d) Upper Jogyeri, (e) Baegunsa, and (f) Seongjuri formations (modified after Egawa and Lee [7]) (not to scale).

positionally intruded in the early stage of the orogeny, followed by a quiescent phase of magmatic activity of ca. 60 m.y. before the initiation of the Bulguksa orogeny (Fig. 7) [2, 5]. Such a magmatic hiatus is likely to have resulted from the existence of oceanic plateaus or ridges subducting underneath the East Asian continental crusts [81, 82]. South China, however,

shows no interval of quiescent magmatism between the Indosinian and Yanshanian orogenies, and this is probably related to the slab delamination and rollback that occurred immediately after the flat subduction [6, 45].

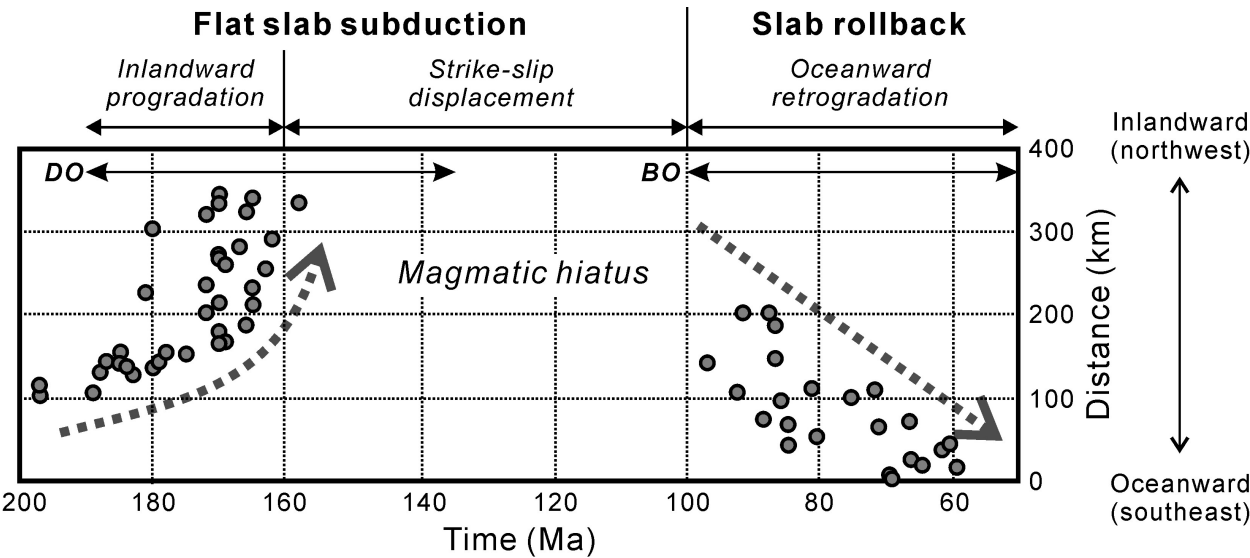


Figure 7. Inlandward and oceanward migration of the Daebo and Bulguksa granites in South Korea, respectively (modified after Kim [4], Sagong et al. [5], and Park [17]). BO, Bulguksa orogeny; DO, Daebo orogeny.

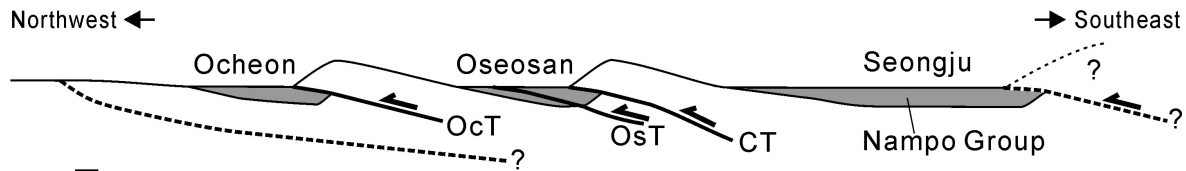
The Nampo Group has experienced high-grade diagenesis or low-grade metamorphism. This is evidenced by the presence of very high-rank coals (anthracite to meta-anthracite) and by the very high vitrinite reflectance values (5 to 6%) which occur entirely in the Seongju Subbasin [70, 71], as well as the high illitization occurring within the three subbasins which ranges in the thermal grade of anchizone to epizone [40]. Both coal and illite in sediments are commonly used as an indicator of paleotemperature, and Egawa and Lee [40] classified this postdepositional thermal event into early and late histories: tectonic burial metamorphism and hydrothermal alteration, respectively.

3.2.1. Tectonic burial metamorphism

The early tectonic burial resulted from crustal loading induced by the postdepositional basement overthrusting on the Nampo Group (Fig. 8). The grade of mechanical compaction textures in sandstones tends to increase down the sequence (Fig. 9), and the lowermost strata (Hajo Formation) appear to have been deformed in a ductile manner [40, 41, 83]. Similarly, the illite in sandstones shows a down sequence increase in its crystallinity, from anchizone to epizone (Fig. 9). Based on the equations proposed by Underwood et al. [84] and Kosakowski et al. [85], the measured illite crystallinity approximates the possible maximum paleotemperature and total burial depth of the Nampo Group in the Ocheon Subbasin as being 340 °C and 9700 m, respectively, although the total depositional thickness is 3300 m. This estimation is in good agreement with the observations of ductile deformation, epizonal metamorphism, and basement overthrusting.

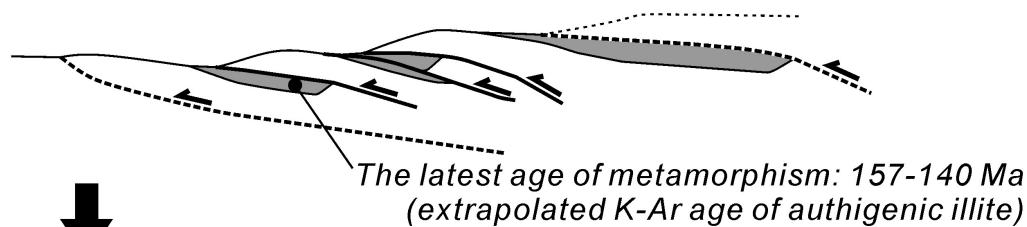
(a) Middle Jurassic

Initiation of the basement overthrusting



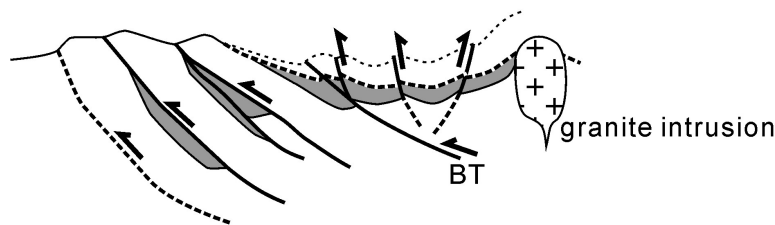
(b) Late Jurassic to earliest Cretaceous

Tectonic burial and crustal loading



(c) Cretaceous

Vertical rotation and hydrothermal alteration



(d) Present

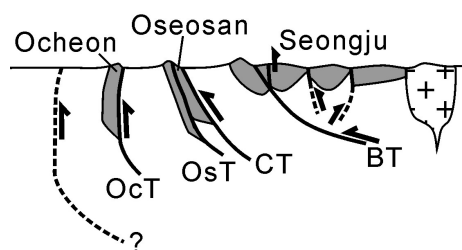


Figure 8. Conceptual structural models showing the postdepositional crustal shortening and thickening in the Chungnam region (modified after Egawa and Lee [40, 42]) (not to scale). BT, Baegunsa Thrust; CT, Cheongla Thrust; OcT, Ocheon Thrust; OsT, Oseosan Thrust.

Radiometric dating of illite in sediments is helpful in constraining the latest diagenetic and low-grade metamorphic ages [86, 87], and is used to interpret the timing of regional over-

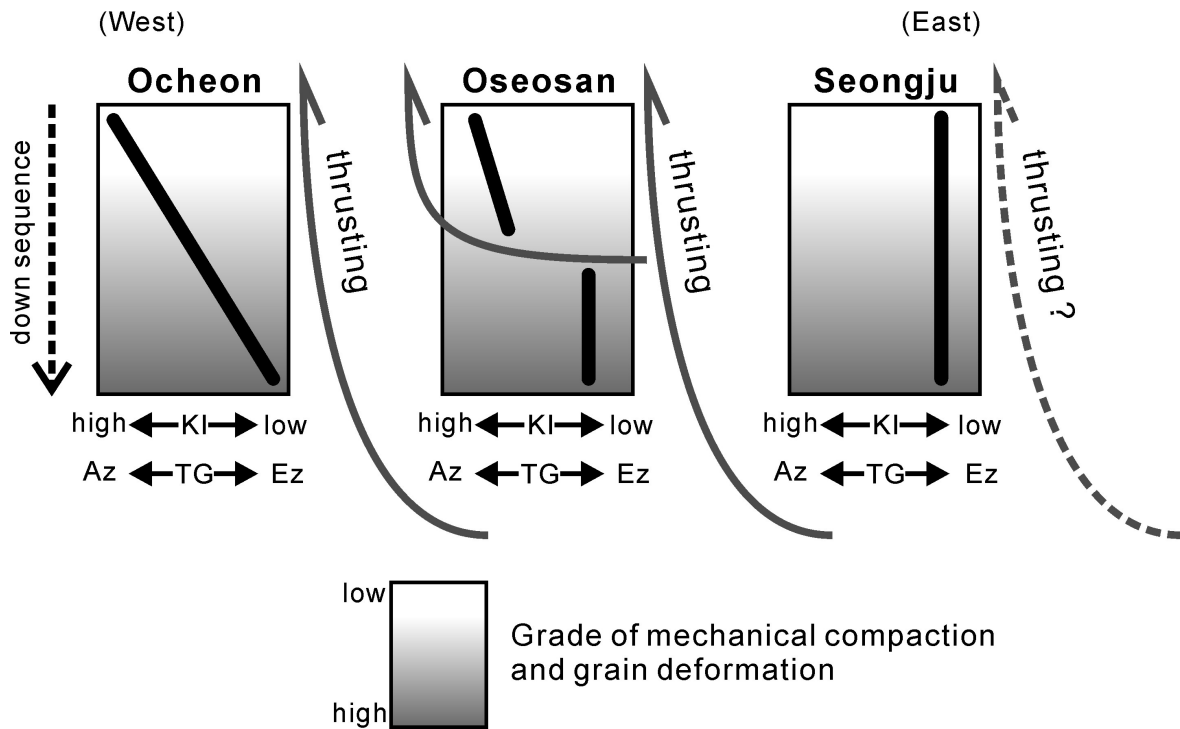


Figure 9. Simplified diagram showing the structural and diagenetic characteristics in the Ocheon, Oseosan and Seongju subbasins (modified after Egawa [43]). Az, anchizone; Ez, epizone; KI, Kübler Index; TG, thermal grade.

thrusting [88]. A mixture of authigenic ($1M_d$) and detrital ($2M_1$) components of illite is common in argillaceous sediments. Based on this knowledge, Egawa and Lee [42] measured the K–Ar ages of different-size clay fractions from the Amisan shale in the Ocheon Subbasin, and estimated the latest age of authigenic illite to be 157–140 Ma (Fig. 8), by using a linear regression model defined by the detrital amount and the K–Ar age of different size fractions [89, 90, 91]. The estimated age, therefore, is younger than the depositional age of the Nampo Group (~170 Ma) [30] and ranges within the duration of the Daebou orogeny (190–135 Ma) [4], which suggests that the tectonic burial metamorphism of the Nampo Group occurred in the late stage of the Daebou orogeny.

3.2.2. Hydrothermal alternation

The subsequent hydrothermal alternation was much affected by a magmatic intrusion and hot-fluid migration, probably during the Bulguksa orogeny [40]. The coal rank and illite crystallinity of the Seongju sediments plot into a very high thermal grade, with little stratigraphic variation (Fig. 9) [40, 70, 71]. When fluids warmed by pluton migrate along faults and fractures in the basin, they can transfer heat to the basin fills and lead to thermal alteration even at a relatively shallow depth of burial [85, 92, 93]. The Nampo Group in the Seongju Subbasin is highly faulted and folded in places, and there are granite intrusions into the southeastern subbasin (Fig. 4). These structures and intrusions probably enhanced the illitization and anthracitization after tectonic burial.

4. Conclusions

Mesozoic tectonism, magmatism, and sedimentation in East Asia were fundamentally controlled by a series of flat slab subduction and subsequent slab rollback of the northwestern paleo-Pacific plates, which allowed the evolution of an Andean-type continental arc several thousand kilometers-long. Paleo-Pacific oceanic crusts with buoyant materials (such as oceanic plateaus and ridges) had subducted and migrated inlandward underneath the Asian continent, leading to a significant magmatic progradation and crustal shortening and thickening. The subsequent delamination and rollback of the inland subducted slab resulted in the retrogradation of the magmatic front, together with crustal stretching and thinning. These dynamic events are closely associated with the evolution of major orogenies in Korea and South China: the flat slab subduction caused the Daebo and Indosinian orogenies, and the slab rollback produced the Bulguksa and Yanshanian orogenies. There is a clear time lag between the flat subduction- and rollback-induced orogenies in Korea and those in South China, which were initiated 60 m.y. and 80 m.y. later in Korea, respectively, probably due to the effect of the Chinese final amalgamation.

The Chungnam Basin in central western Korea was filled with a Lower to Middle Jurassic nonmarine succession, known as the Nampo Group, the deposition and structural development of which occurred simultaneously with the evolution of the flat subduction-induced continental-magmatic arc during the Daebo orogeny. An integrated stratigraphic, sedimentologic, diagenetic, and geochronologic analysis has demonstrated that the basin-filling processes and subsequent structural and thermal evolution of the Nampo Group were fundamentally controlled by subduction tectonics. The Nampo Group is composed of the two repeated, fining- to coarsening-upward alluvio-lacustrine sequences, separated by an interval of thick breccia-gravel progradation deposits and relative strong proximal unconformities. The observed relationships of the succession provide a record of sedimentation that was most likely controlled by the temporal variations of tectonism during the early stage of the Daebo orogeny. The postdepositional basement thrusting over the Nampo Group then led to a tectonic burial, resulting in low-grade metamorphism. Burial heating is strongly suggested by the down-sequence increase in illitization from anchizone to epizone, and in the degrees of mechanical grain compaction and ductile deformation. The maximum paleotemperature and burial depth of the Nampo Group are estimated to be 340°C and 10 km, respectively, and the extrapolated K–Ar illite dating of 157–140 Ma indicates that the tectonic burial metamorphism was completed at the end of the Daebo orogeny. A subsequent granite intrusion and hydrothermal alteration, probably occurring during the Bulguksa orogeny, have enhanced the illitization and anthracitization, regardless of the stratigraphy.

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