

中国东北、韩国东南和日本西南部早白垩世非海相与海相地层对比, 非海相软体动物的生物年代学和古地理意义^①

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摘 要: 根据非海相与海相, 特别是共同的海相和非海相软体动物化石的对比, 并结合放射性同位素测年, 中国东北黑龙江东部和辽宁西部, 韩国东南部庆尚盆地, 日本西南部内带岐阜县北部牧户/庄川地区和外带四国德岛和物部地区早白垩世地层得到了对比, 产自这些地层的非海相软体动物的时代也因此受到了约束。著名的中国东北含煤地层龙爪沟和鸡西群, 盛产热河生物群/动物群的热河群的时代均为欧特里沃期/巴列姆期-阿普特期, 它们的上覆地层桦山群和孙家湾组为阿尔必期。韩国东南部新洞群和除金洞组以外的河阳群为阿普特期-阿尔必期, 不整合于新洞群之下的卵谷组主要为欧特里沃期。日本西南部内带的牧户/庄川地区的手取群和外带德岛和物部地区的物部川群均为欧特里沃期-阿尔必期。*Cuniopsis kihon gi*, *Nakamuraia leei*, *Koreanaia cheong i* 和 *Trigonioides (Wakinoa) tetoriensis* 的时代为欧特里沃期-早巴列姆期。*Viviparus onogoensis*, *Unio ogamigoensis*, *Myrene (Mesorcorbicula) tetoriensis* 及 *Tetoria (Tetoria) yokoyami* 为欧特里沃期-阿普特期。*Arguniella cf. quadrata*, *A. cf. ventricosa*, *Sphaerium (Sphaerium) anderssoni*, *Probaicalia vitimensis* 和 *Pr. gerassimovi* 为欧特里沃期/巴列姆期-阿普特期。*Nakamuraia chingshanensis*, *Plicatounio (Plicatounio) multiplicatus*, *Sphaerium (Sphaerium) coreanicum* 和 *Micromelania? katoensis* 为阿普特期-阿尔必期。*Nipponoia sinensis*, *Nip. tetoriensis*, *Nip. ryosekiana* 和 *Trigonioides (Wakinoa) wakinoensis* 是阿普特期的标志。*Trigonioides (Trigonioides) quadratus*, *T. (T.) heilongjiangensis*, *Plicatounio (Plicatounio) naktongensis*, *Unio longus* 与 *Sphaerium (Sphaerium) chintaoense* 为晚阿普特期-阿尔必期或阿尔必期的标志化石。我国东北、韩国东南和日本西南部非海相, 特别是淡水软体动物接近的相似性表明这三地区在早白垩世时相连, 并处于同一水系。但是, 在欧特里沃期-阿尔必期期间, 这一陆块的东部, 即濒临古太平洋的日本西南部的的外带因地势低而多被海水覆盖, 在牧户/庄川和黑龙江东部存有遭受海侵的浅而窄的海湾, 凡兰吟期, 特别是欧特里沃期/巴列姆期之前, 中国东北-韩国东南部-日本西南部陆块为受造山运动引起的隆起和沉降活动影响的高低不平的高原, 经受了广泛而长期的剥蚀。多数含有包括熔岩和凝灰岩在内的火山岩, 并与北东-北北东方向的断裂带近于平行分布的非海相白垩纪盆地直至欧特里沃期/早巴列期(有些地区可能稍早(凡兰吟期))(134~126 Ma), 即华北克拉通破坏的高峰期(130~120 Ma)才形成。这一现象表明, 这些盆地受断裂, 特别是伴随有强烈火山喷发和时而局部海侵的沿着古太平洋西北缘和郯-庐断裂带的构造运动的控制。

关 键 词: 非海相与海相, 生物地层对比, 非海相软体动物的生物年代学, 古地理意义, 早白垩世, 中国, 韩国, 日本

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NON-MARINE AND MARINE STRATIGRAPHIC CORRELATION OF EARLY CRETACEOUS DEPOSITS IN NE CHINA, SE KOREA AND SW JAPAN, NON-MARINE MOLLUSCAN BIOCHRONOLOGY, AND PALAEOGEOGRAPHIC IMPLICATIONS

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Abstract On the basis of non-marine and marine correlation, particularly between the common marine and non-marine molluscan fossils, together with radiometric dating, the Early Cretaceous strata of eastern Heilongjiang and western Liaoning in NE China, the Gyeongsang Basin of SE Korea and the Makito/Shokawa area of northern Gifu in the Inner Zone, and the Tokushima and Monobe areas of Shikoku in the Outer Zone of SW Japan are correlated, and, as a result, the ages of the non-marine molluscs yielded from these strata are constrained. The well-known coal-bearing Longzhaogou and Jixi groups and the Jehol Biota/Fauna-bearing Jehol Group of NE China are all Hauterivian/Barremian–Aptian in age, and the overlying Huashan Group and Sunjiawan Formation are Albian. The Sindong Group and the Hayang Group, with the exception of the Jindong Formation, in SE Korea is Aptian–Albian, and the Myogog Formation unconformably underlying the Sindong Group is mainly Hauterivian. The Tetori Group in the Makito/Shokawa area and the Monobegawa Group in the Tokushima and Monobe areas of SW Japan are both Hauterivian–Albian. *Cuniopsis kihongi*, *Nakamuraia leei*, *Koreanaia cheongi* and *Trigonioides (Wakinoa) tetoriensis* are Hauterivian–early Barremian in age. *Viviparus onogoensis*, *Unio ogamigoensis*, *Myrene (Mesocorbicula) tetoriensis* and *Tetoria (Tetoria) yokoyami* range from Hauterivian to Aptian. *Arguniella cf. quadrata*, *A. cf. ventricosa*, *Sphaerium (Sphaerium) anderssoni*, *Probaicalia vitiensis* and *Pr. gerassimovi* range from Hauterivian/Barremian to Aptian. *Nakamuraia chingshanensis*, *Plicatounio (Plicatounio) multiplicatus*, *Sphaerium (Sphaerium) coreanicum* and *Micromelania? katoensis* are Aptian–Albian. *Nippononaia sinensis*, *Nip. tetoriensis*, *Nip. ryosekiana* and *Trigonioides (Wakinoa) wakinoensis* are good indicators of the Aptian. *Trigonioides (Trigonioides) quadratus*, *T. (T.) heilongjiangensis*, *Plicatounio (Plicatounio) naktongensis*, *Unio longus* and *Sphaerium (Sphaerium) chintaoense* are good indicators of late Aptian–Albian or Albian. The close resemblances of Hauterivian–Albian non-marine, particularly freshwater, bivalves in NE China, SE Korea and SW Japan indicate that all three areas were connected and contained a single fluvial system during the Early Cretaceous. However, the eastern part of this landmass, the Outer Zone of SW Japan facing the Palaeo-Pacific, was low topographically and mainly occupied by the sea in Hauterivian–Albian time, and there were some shallow and narrow embayment(s) that were subjected to marine transgressions in the Makito/Shokawa area and eastern Heilongjiang. Before the Valanginian, and particularly before the Hauterivian/Barremian, the NE China–SE Korea–SW Japan landmass was a plateau that was affected by uplift and subsidence associated with orogeny, which led to widespread and long-lasting erosion. The non-marine Cretaceous basins, containing volcanic rocks including lavas and tuffs, oriented subparallel to NE- to NNE-trending fault zones, mostly did not develop until the Hauterivian/Barremian, although possibly a little earlier (Valanginian) in some areas (134–126 Ma), within the peak time (130–120 Ma) of destruction of the North China Craton, indicating that they were controlled by faults, associated with tectonic movements and violent volcanic eruptions and local transgressions along the northwestern margin of the Palaeo-Pacific and the Tan–Lu fault system.

Key words non-marine and marine, biostratigraphic correlation, non-marine molluscan biochronology, palaeogeographic implications, Early Cretaceous, China, Korea, Japan

1 Introduction

The international chronostratigraphic framework chart and time scale of the Cretaceous System, established by the International Commission on Stratigraphy (Gradstein et al., 2004a, 2004b; Ogg, 2004; Ogg et al., 2004, 2008; <http://www.stratigraphy.org>), are based on marine rocks/fossils and radiometric ages. However, abundant non-marine (fresh- and brackish-water) Cretaceous deposits exist globally, particularly in central, eastern and southeastern Asia, where most of the Cretaceous deposits are non-marine and usually associated with volcanic and/or volcanoclastic rocks. Geoscientists have long argued about the ages, subdivision and correlation of these strata, and particularly about the location of the Jurassic-Cretaceous boundary. Yin (1980) and Gu (1982a) proposed the approach of correlating non-marine with marine strata to resolve the problems.

How does such non-marine and marine correlation work? It is mainly achieved on the basis of the biostratigraphy of, and radiometric dating obtained from, the strata concerned. Through correct taxonomic identification of both marine and non-marine fossils in alternating marine and non-marine strata, and correlation of these strata with the international chronostratigraphic chart, the ages of the non-marine deposits can be determined or constrained (chronostratigraphy). The intervening tuffs, tuffaceous rocks and lavas can also be radiometrically dated (geochronology), hence providing a basis for accurate age determinations of the associated sedimentary rocks and the fossils they contain (Sha, 2005, 2007a).

In the Yunshan–Longzhaogou–Peide–Zhushan (YLPZ) areas (Fig. 1, A) and the Jixi–Boli–Muling (JBM) basins (Fig. 1, B) of eastern Heilongjiang, NE China, there are alternating non-marine and marine Early Cretaceous strata (including the coal-bearing Longzhaogou and Jixi groups and the overlying Huashan Group; Fig. 2, A, B) with marine index molluscs of Early Cretaceous age and non-marine molluscs including bivalve members of the Jehol Biota/Fauna and non-marine Cretaceous trigonoidid bivalves (Fig. 3, A, B) (Sha, 1990, 1991, 1992a, 1992b, 1992c, 1992d, 1999, 2002, 2007a; Sha & Fürsich, 1993a, 1993b, 1994; Kelly et al., 1994; Sha et al., 1994, 2002, 2003, 2007, 2008, 2009; Futakami et al., 1995; Gu, 1995; Gu et al.,

1997). In western Liaoning, NE China, particularly in the Beipiao–Fuxi (BF) basins (Fig. 1, C), the Early Cretaceous rocks (including the Tuchengzi Formation, Jehol Group and Sunjiawan Formation; Fig. 2, C) are non-marine with occasional brackish-water depositional intercalations in the upper Jehol Group. The Jehol Group yields the colourful Jehol Biota/Fauna consisting of various plant mega- and microfossils, vertebrates and invertebrates, including non-marine trigonoidid bivalves (Fig. 3, C) (Yu et al., 1987; Chen & Jin, 1999; Chang et al., 2001, 2003; Sun et al., 2001; Ji et al., 2004; Sha et al., 2007), which has a wide distribution in eastern and northern China and environs (Chang et al., 2001, 2003). In the Gyeongsang Basin of SE Korea (Fig. 1, D), the Lower Cretaceous (including the Myogog Formation, Sindong Group and lower Hayang Group; Fig. 2, D) is entirely non-marine and yields various freshwater molluscs (Fig. 3, D) (Chang in Lee, 1987; Yang in Lee, 1987; Yang, 2002; Kozai et al., 2005), particularly trigonoidid bivalves, which are widely distributed not only in Asia but also in southern England and Spain (Sha, 2007b, 2010). Some forms of these molluscs have been recorded in the Lower Cretaceous, including the Jehol and Huashan groups of NE China (Fig. 3, B, C). In the Makito (= Makido)/Shokawa area of the northern Gifu Prefecture, Inner Zone of SW Japan (Fig. 1, E), the Lower Cretaceous, i.e., the Tetori Group (Fig. 2, E), is dominated by non-marine deposits, but these are intercalated with marine and brackish-water beds, particularly in the lower part, and it contains both marine and non-marine molluscs (Fig. 3, E) (Hayami, 1959a, 1959b, 1960, 1975; Kimura et al., 1991; Matsukawa & Ido, 1993; Matsukawa & Nakada, 1999; Fujita, 2003; Kozai et al., 2005; Matsukawa et al., 2006). Among these, some marine bivalve species have also been recognized in the Early Cretaceous Longzhaogou Group of eastern Heilongjiang, NE China (Fig. 3, A) (Sha & Hiromich, 2012), and some non-marine molluscs (Fig. 3, E) have been reported from the Lower Cretaceous in NE China (Fig. 3, B) and SE Korea (Fig. 3, D). In the Monobe area of the Kochi Prefecture, central Shikoku and the Tokushima area of east Shikoku, SW Japan (Fig. 1, F), the Lower Cretaceous Monobegawa Group (Fig. 2, F) is dominated by ma-

rine strata with intercalations of brackish-water and occasional freshwater deposits, and its lower part contains a freshwater molluscan fauna, including unionids, trigonioiodids and viviparids (Fig 3, F) (Tashro & Okuhira, 1993; Kozai & Ishida, 2003; Kozai et al., 2005, 2012), which also occur in the Jehol and Jixi groups of NE China (Fig. 3, C), the Myogog Formation and Sindong Group in SE Korea (Fig. 3, D), and the Tetori Group of the Inner Zone in SW Japan (Fig. 3, E).

It is clear, therefore, that in the Lower Cretaceous, there are conspecific marine molluscs in the Longzhaogou Group of eastern Heilongjiang, NE China, and the Tetori Group of the Makito/Shokawa area of the Inner Zone of SW Japan, and non-marine molluscan species and genera common to NE China, SE Korea and SW Japan. Furthermore, all of these groups/formations and their overlying and underlying rocks are more or less intercalated with volcanic rocks, including lavas and tuffs, which provide possibilities for dating the sedimentary strata and fossils by measuring the radioisotopic ages of the volcanic rocks.

Consequently, through linking common non-marine and marine molluscan taxa and isotopic dating, not only could the non-marine Early Cretaceous stratigraphic correlation chart for NE China, SE Korea and SW Japan above be established under the frame work of international chronostratigraphy of the Cretaceous System, but also the ages of the non-marine fossils could be constrained or even precisely dated. Such biochrons could be very helpful for improving the accuracy of the Asian and even global non-marine Early Cretaceous stratigraphic correlation and dating, and for understanding Asian Early Cretaceous geohistory, particularly its tectonic and palaeogeographic evolution, which are the aims of this article.

2 Stratigraphic correlation

2.1 Lower Cretaceous of eastern Heilongjiang, NE China

The Lower Cretaceous of eastern Heilongjiang is composed of the coal-bearing Longzhaogou Group, the coeval Jixi Group, and the overlying Huashan Group (Fig. 2, A, B).

The Longzhaogou and Jixi groups are both characterized by alternating non-marine and marine deposits

and abundant high quality coals, although the former contains more and thicker marine beds than the latter, whereas the latter yields more and thicker coal beds than the former. The Longzhaogou Group is distributed in the coal-bearing areas of the YLPZ areas of the Wanda Hills (Fig. 1, A), the Jixi Group is located in the JBM basins, and in the Suibin, Jixian, Shuangyashan and Hegang coal basins, but only the JBM basins (Fig. 1, B) are involved in this paper. The Huashan Group occurs in the areas occupied by the Longzhaogou and Jixi groups (Fig. 1, A, B).

2.1.1 Longzhaogou Group The Longzhaogou Group consists of, in ascending order, the Peide, Qihulin, Yunshan and Zhushan formations (Fig. 2, A).

The Peide Formation consists of black, dark grey and yellowish-green volcanoclastic deposits, tuffs, fine-grained sandstones, siltstones, peats and coals, with a basal conglomerate. It unconformably overlies Permian strata or older granitic basement rocks. It yields only plant fossils, and is presumed to be of Hauterivian age, because of the absence of Jurassic fossils and by the fact that it disconformably underlies Barremian strata (Sha et al., 2000, 2002, 2003, 2007, 2008, 2009; Sha, 2002, 2007a).

The Qihulin Formation mainly comprises littoral or sublittoral black mudstones, and siltstones, with basal coarse-grained sandstones and coals. It disconformably overlies the Peide Formation and yields Barremian and younger ammonites (Sha, 1991, 1992a, 1999, 2007a; Kelly et al., 1994; Sha et al., 1994, 2002, 2003, 2007, 2008, 2009; Futakami et al., 1995), including *Phylloparhyoceras* sp. and *Pseudohaploceras* cf. *yatsushiroense* (Futakami et al., 1995), Barremian–Aptian bivalves, including Aptian *Thracia rotundata*, Barremian–Aptian *Filosina subovalis* (Fig. 3 A) (Gu et al., 1997; Sha, 1999, 2007a; Sha et al., 2000, 2002, 2003, 2007, 2008, 2009), and *Palaeonucula makitoensis* (= *Palaeonucula* cf. *makitoensis* of Gu et al., 1997, pp. 7–8, pl. 1, figs. 8–12), *Entolium inequivalve* (= *Entolium extensum* of Gu et al., 1997, pp.78–80, pl. 9, figs. 14–19, pl. 10, figs. 1–9), *Thracia shokawensis* (= *Thracia yunshanensis* and *T.* cf. *philipsi* of Gu et al., 1997, pp. 237–238, pl. 37, figs. 4–10; pp. 240–241, pl. 38, figs. 10–18) (Fig. 3, A) (Sha & Hirano, 2012), and a middle Barremian–Aptian

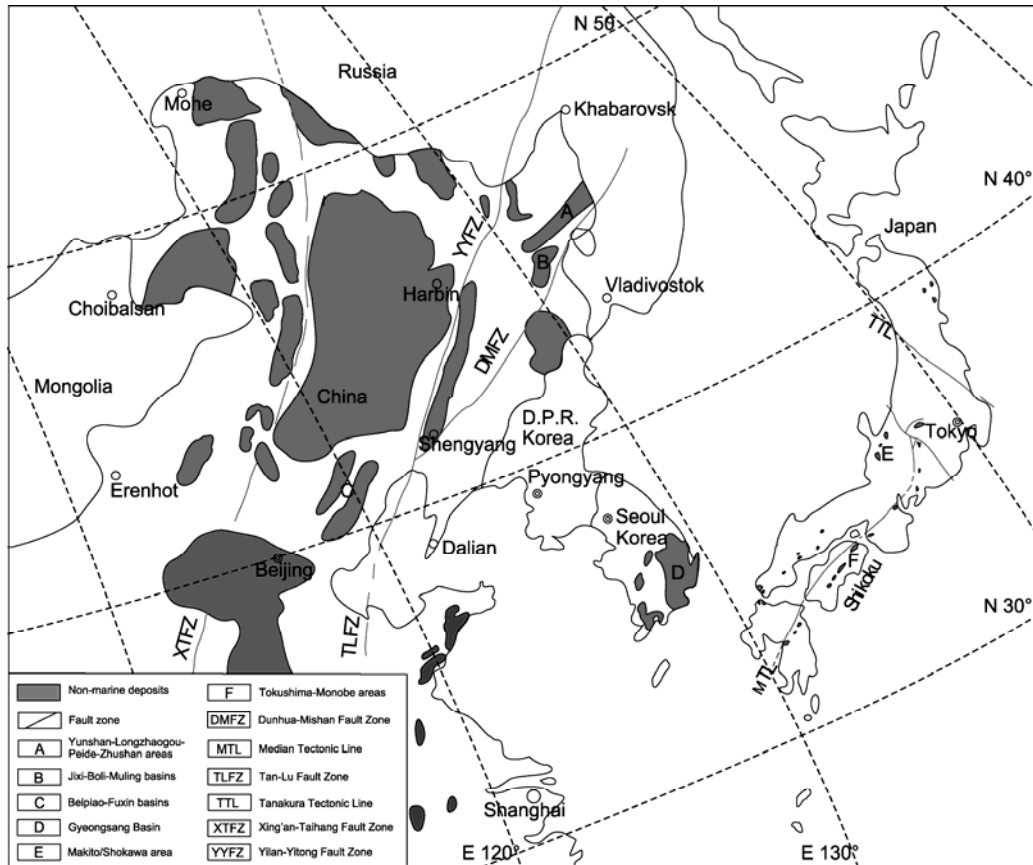


Fig. 1 Map showing the distribution of non-marine Cretaceous deposits and the locations of correlated areas (modified from Kozai & Ishida, 2003; Kozai et al., 2005, 2012; Matsukawa et al., 2006; Sha, 2007; Sha et al., 2007, 2008)

dinoflagellate cyst assemblage consisting of *Oligosphaeridium*, *Odontochitina operculata*, *Gardodinium trabeculosum* and *Palaeoperidinium cretaceum* (Sha et al., 2002, 2003, 2007, 2008, 2009; Sha, 2007a). This formation is suggested to be mainly Barremian based on the concurrent-range-zone of molluscs, which is consistent with the age-range indicated by the dinoflagellate cyst assemblages (Sha et al., 1994, 2000, 2002, 2003, 2007, 2008, 2009; Sha, 2002, 2007a).

The Yunshan Formation rests conformably on the Qihulin Formation. It consists of typical marine and non-marine alternations, and is composed of light to dark grey, greyish-yellow and yellowish-green andesites, lavas, tuffs and carbargillites, medium- to fine-grained sandstones, siltstones and mudstones, and coals. It yields plant mega- and microfossils, brachiopods, ostracods, gastropods and numerous bivalves, including bivalve assemblages of *Aucellina* (*Aucellina*) *caucasica*-*A. (A.) aptiensis*-*Filosina subovalis*-*Thracia rotundata* and *A. (A.) cf. caucasica*-*A. (A.) cf. aptiensis*, including *Sinopsammobia ovalis*, *Palaeonucula maktoensis*, *Entolium inaequalve*, *Thracia s hokawaensis*

and *Pleueromya hidensis* (Fig. 3, A) (Sha & Hirano, 2012), and a dinoflagellate cyst assemblage of *Odontochitina operculata*-*Vesperopsis di daoensis*. *A. (A.) caucasica* and *A. (A.) aptiensis* are latest middle Barremian/late Barremian–middle Albian indicators. *F. subovalis* and *T. rotundata* indicate Barremian–Aptian and Aptian ages, respectively (Sha, 1990, 1991, 1992a, 1992b, 1992c; 2012; Sha & Fürsich, 1993, 1994; Sha et al., 1994, 2002, 2003, 2007, 2008, 2009). Thus, the bivalves of the formation indicate an Aptian age.

The Zhushan Formation consists of non-marine coal-bearing deposits intercalated with littoral beds that are mainly grey and greyish-green siltstones, mudstones, tuff breccias, tuffs, coal, and pebbly sandstones. It rests conformably on the Yunshan Formation and yields the bivalve *Sinopsammobia ovalis* (Fig. 3, A), which is very common in the *Aucellina (A.) caucasica*-*A. (A.) aptiensis*-*Filosina subovalis*-*Thracia rotundata* assemblage of the Yunshan Formation, suggesting that it is late Aptian or late Aptian–early Albian in age (Sha et al., 1994, 2000, 2002, 2003, 2007, 2008, 2009; Sha, 2002, 2007a).

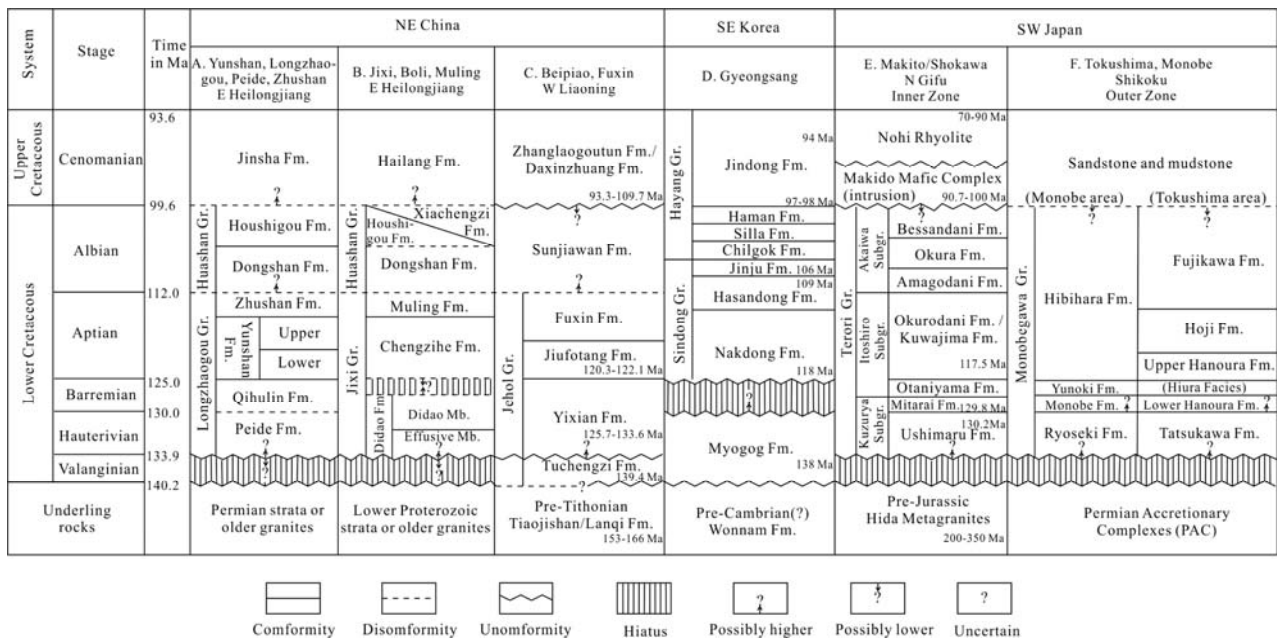


Fig. 2 Stratigraphic correlation framework chart for the Early Cretaceous rocks of NE China, SE Korea and SW Japan
(for sources of information, see text)

2.1.2 Jixi Group The Jixi Group in Jixi, Boli and Muling basins consists of, in ascending order, the Didao, Chengzihe and Muling (= Muleng) formations (Fig. 2, B).

In the JBM coal basins, the Didao Formation unconformably overlies the Lower Proterozoic Mashan Group or older granites and is divided into two members: the Effusive Member (lower) and the Didao Member (upper). It is mainly composed of a basal conglomerate, volcanoclastic sediments, tuffs, sandstones, siltstones, mudstones and coal, but the Effusive Member also contains andesite. The Didao Member yields plant mega- and microfossils, including the slightly brackish-water *Vesperopsis didaoensis*-*Lagenorhytis granorugosa* dinoflagellate cyst association. This formation has been assigned a Hauterivian–Barremian age, mainly because *Vesperopsis* mostly occurs in Barremian–Albian deposits, *Lagenorhytis* ranges from Berriasian to Hauterivian in successions outside China, and the formation is disconformably overlain by the Aptian Chengzihe Formation. The Didao Formation of the Jixi Group and the Peide Formation of the Longzhaogou Group are basically coeval units (Sha et al., 2000, 2002, 2003, 2007, 2008, 2009; Sha, 2002, 2007a).

The Chengzihe Formation is dominated by non-marine coal-bearing deposits with littoral depositional intercalations. It consists mainly of off-white or

yellow, fine- to medium-grained sandstones, siltstones, gravelly sandstones, and coal, and yields plant mega- and microfossils, including angiosperms, dinoflagellate cysts and chlorophyte algae, ostracods, fish, reptiles, abundant bivalves and acritarchs. The lower part of the formation yields an *A. (A.) caucasica-Filosina subovalis-Thracia rotundata* marine bivalve assemblage (Fig. 3, B), and dinoflagellate cyst assemblages of *Odontochitina operculata-Muderongia tetracantha* and *Vesperopsis didaoensis*. The middle and upper parts of the formation yield non-marine bivalve members of the Jehol Biota/Fauna, *Arguniella* cf. *quadrata-Unio* aff. *obrutschewi* (= *Unio* cf. *grabaui*), an assemblage including *A.* cf. *ventricosa* and *U.* cf. *ogamigoensis* (= *Unio* sp. nov. Gu et al., 1997, p. 153, pl. 21, fig. 10), and a *Sinopsamobia ovalis-Filosina subovalis* marine bivalve assemblage (Fig. 3, B), and the marine beds in the upper part of the formation yield a *Canningia reticulata* dinoflagellate cyst assemblage. The marine bivalves indicate an Aptian age, which is consistent with the dinoflagellate cyst taxa recorded. Clearly, this formation corresponds to the Yunshan Formation of the Longzhaogou Group because the marine bivalves *A. (A.) caucasica*, *Filosina subovalis* and *Thracia rotundata*, and the dinoflagellate cysts *Odontochitina operculata* and *Vesperopsis didaoensis* are common to both formations (Sha et al., 1994, 2000, 2002, 2003, 2007, 2008, 2009; Sha, 2002, 2007a).

rarely intercalated with marine and brackish-water sediments. In the JBM basins, this formation contains non-marine mollucan members of Jehol Biota/Fauna, including the *Sphaerium* (*Sphaerium*) *subplanum*–*S. (S.) selenginense* bivalve assemblage (Fig. 3, B), and the brackish-water Aptian–Albian dinoflagellate cyst *Cribroperidinium?* *parorthoceras* (Wan et al., 2000; Sha, 2002, 2007a; Sha et al., 2002, 2003, 2007, 2009), marine Hauterivian–Campanian dinoflagellate cysts (Yang et al., 2003), and a Barremian–Aptian miospore association (Yang et al., 2007).

The concurrent-range-zone of the bivalves, dinoflagellate cysts and miospores is Aptian in age, in common with the Zhushan Formation of the Longzhaogou Group (Fig. 2, A).

2.1.3 Huashan Group Both the Longzhaogou and Jixi groups are disconformably overlain by the Huashan Group, which disconformably underlies the non-marine deposits of the Hailang or Jinsha Formation (Fig. 2, A, B). It is composed of the Dongshan and Houshigou/Xichengzi formations.

The Dongshan Formation is mainly composed of dark grey to black tuffs, tuff breccias, basalt, tholeiite and mudstones with yellowish-green trachyandesite, and tuffaceous mudstones, siltstones and siltstones. The mudstones yield plant fossils and fish.

The Houshigou Formation is composed of greyish-yellow sandstones intercalated with tuffs and siltstones, and yellowish-grey mudstones. It yields plant fossils and a non-marine bivalve assemblage comprising *Trigonioides* (*T.*) *heilongjiangensis* (Fig. 3, B), *Plicatounio?* sp., and probably *Corbicula* (Sha et al., 2003, 2009; Sha, 2007a).

The Xichengzi Formation, which corresponds to the Houshigou Formation, crops out in the Xichengzi–Yilin region on the southwest margin of the JBM basins (Fig. 1, B). It is composed of black, grey and greenish-grey fine-grained sandstones, siltstones, silty illitic claystones with feldspar debris and muddy siltstones, occasionally interbedded with beds containing marine bivalves. It yields non-marine fossils, including plant mega- and microfossils, charophyte algae, insects, ostracods, gastropods, bivalves, reptile debris, and fish scales. The non-marine bivalves comprise the *Trigonioides* (*T.*) *heilongjiangensis*–*Sphaeri-*

um (*S.*) *chientaoense* (= *S. (S.) yanbianense*) assemblage, including *Unio longus* (= *Unio heilongjiangensis*), *Plicatounio* (*P.*) cf. *naktongensis*, *Pisidium* (*Pis.*) cf. *fujianese*, *S. (S.) chientaoense* (= *S. (S.) yanbianense*), *S. (S.) coreanicum*, *S. (S.) selenginense*, and *S. (S.) fujianense* (Fig. 3, B). The marine bivalves comprise the *Solemya*–*Inoceramaya?* assemblage (Sha, 2002; Sha et al., 2003, 2007, 2008, 2009), and gastropods include *Gyraulus* sp. (Yu & Zhu, 1983). *T. (T.) heilongjiangensis* is mainly Albian and *P. (P.) naktongensis* is Aptian–Albian in age (Sha, 2007b). *Unio longus*, *S. (S.) chientaoense* and *S. (S.) coreanicum* also occur in the Khuren Formation of the northern Choyr Basin, southeast Mongolia, and have been confirmed as Albian by Sha et al. (2006). The Houshigou/Xichengzi Formation or the Huashan Group is, therefore, Albian in age (Sha et al., 2000, 2002, 2003, 2007, 2008, 2009; Sha, 2002, 2007a).

2.2 Lower Cretaceous in the Beipiao and Fuxin basins of western Liaoning, NE China

The Lower Cretaceous rocks in the BF basins of western Liaoning (Fig. 1, C) consist of, in ascending order, the Tuchengzi Formation, Jehol Group and Sunjiawan Formation (Fig. 2, C).

2.2.1 Tuchengzi Formation The Tuchengzi Formation rests disconformably and probably locally unconformably on the pre-Tithonian Lanqi (Tioajishan) Formation in which the radioisotopic age of the basalt, basaltic andesite, andesite and rhyolite is 153~166 Ma (Yang & Li, 2008). It is dominated by reddish-variegated thin- to medium-bedded (locally thick-bedded) tuffs, tuffaceous shales and sandstones, siltstones, silty mudstones, muddy siltstones and shales, and conglomerates. It yields plant mega- and microfossils, conchostracans, ostracods and vertebrate (dinosaur, Sauropoda) remains. Wang et al. (2004) dated the formation as late Middle–early Late Jurassic based on various fossils. However, all of the bivalves, insects and many vertebrates, conchostracans, ostracods and even spores and pollen grains listed in their monograph are recorded from the so-called Tuchengzi Formation outside western Liaoning. The radioisotopic age of tuff in the Tuchengzi Formation is 139.4 ± 0.19 (1SD) ± 0.05 (SE) Ma (Fig. 2, C) (Swisher et al., 2002), indicating a Valanginian age.

2.2.2 Jehol Group In ascending order, the Jehol Group consists of the Yixian Formation (= Jingangshan, Tuhulu, Jianchang, Lower Volcanic, Volcanic Rocks and Dalinghou formations), Jiufotang Formation (= Shahai Formation) and Fuxin Formation (= Binggou, Haizhou, lower Banlashan and Upper Volcanic formations) (Fig. 2, C).

The Yixian Formation unconformably overlies the Tuchengzi Formation. It is composed of grey to black and purplish-red andesites; basalts; greyish-green, greyish-yellow, off-white, and dark grey to black tuffs; tuffaceous sandstones, grits and sandy shales; silty mudstones, shaly tuffaceous silty mudstones and siltstones; sandy limestones, sandstones, and a basal tuffaceous conglomerate. It yields the typical Jehol EEL (*Eosestheria-Ephemeropsis-Lycoptera*) Fauna. Besides this index fauna, the conchostracan *Eosestheria* spp., the insect *Ephemeropsis trisetalis* and the fish *Lycoptera muroii*, this formation yields various plant mega- and microfossils, including angiosperms and charophytes, gastropods, bivalves, ostracods, shrimps, other insects and fish, amphibians, and reptiles, including feathered dinosaurs, birds and mammals. Gastropods include *Probaicalia gerassimovi* and *P. vitimensis*, and bivalves include *Arguniella* cf. *quadrata*, *A.* cf. *ventricosa* and *Sphaerium* (*S.*) *anderssoni* (= *S. jeholense*) (Yu in Yu et al., 1987; Chen & Jin, 1999; Chang et al., 2001, 2003; Sun et al., 2001; Ji et al., 2004; Sha et al., 2007; Pan, 2012, this issue), and *Pisidium* (*Pisidium*) *liaoningense* (Yu, Q.S. et al. in Yu et al., 1987) (Fig. 3, C).

The radiometric and palaeomagnetic dating of volcanic material from the Yixian Formation has provided an age of around the Hauterivian/Barremian–Aptian transition, such as 124.2~133.6 Ma (corresponding to the early Hauterivian–earliest Aptian) (Zhu et al., 2003), 133 Ma (early Hauterivian) (Yang & Li, 2008), 129.7 Ma (earliest Barremian) (Chang et al., 2009), 125.7 Ma (late Barremian) (Zhu et al., 2007), and 124.7 Ma (earliest Aptian) (Yang et al., 2007) (Fig. 2, C). However, the radioisotopic ages of 120.3 ± 0.7 Ma (He et al., 2004) and 122.1 ± 0.3 Ma (Chang et al., 2009) (both corresponding to the early Aptian) of zircon from tuffs in the overlying Jiufotang Formation (Fig. 2, C) have constrained the age of the Yixian

Formation to mainly Barremian, though possibly extending into both the Hauterivian and the Aptian; it is, therefore, dated as Hauterivian/Barremian (Fig. 2, C). This determination is consistent with the biostratigraphic data (Sha, 2007a; Sha et al., 2007). Although the bivalves *Arguniella* cf. *quadrata* and *A.* cf. *ventricosa* have also been recorded from the Chengzihe Formation of the Jixi Group in eastern Heilongjiang (Fig. 3, B) as mentioned above, the Chengzihe Formation, which overlies the Hauterivian–Barremian Didao Formation, has been confirmed as mainly Aptian on the basis of the marine molluscs it contains. The Yixian Formation is consequently correlated with the Didao Formation of the Jixi Group and Qihulin and Peide formations of Longzhaogou Group of eastern Heilongjiang, and not with the Chengzihe Formation (Fig. 2, A, B, C) (Sha, 2007a; Sha et al., 2007).

The Jiufotang Formation rests conformably on the Yixian Formation. It consists mainly of grey to black, greyish-green, off-white, or yellowish-grey, thin-bedded tuffs, tuffaceous shaly siltstones and shales, siltstones, sandstones and grits, silty limestones, sandstones and gravelly sandstones, and coal beds and oil shales in the upper part of the formation. The EEL Fauna is also recorded from this formation. Besides this index fauna, it contains numerous plant mega- and microfossils, including rare charophytes, gastropods, bivalves, ostracods, some other insects and fish, amphibians, reptiles and birds. Gastropods include *Viviparus* cf. *onogoensis*, *Bellamyia* cf. *avilithiformis*, *Probaicalia vitimensis* and *P. gerassimovi*, and bivalves include *Arguniella* cf. *quadrata*, *A.* cf. *ventricosa*, *Margaritifera isfarensis*, *M. tugriensis*, *Nakamuraia chingshanensis* (= *Nagdongia soni*), *Nippononaia sinensis*, *Nip. yanjiensis*, *Sphaerium* (*S.*) *anderssoni* (= *S. jeholense*), *Pisidium* (*Pis.*) *liaoningense*, and *Sphaerioides yixianensis* (Fig. 3, C) (Gu et al., 1976; Gu, 1982b; Yu, Q.S. et al. in Yu et al., 1987; Chen & Jin, 1999; Chang et al., 2001, 2003; Sha et al., 2007). Although both the Jiufotang and Yixian formations yield the EEL Fauna, the trigonioidid bivalve *Nippononaia* first occurs in the upper Jiufotang Formation, and *Nippononaia yanjiensis* is mainly Aptian in age (Sha, 2007b). The radiometric ages of zircon from the tuffs of the formation are 120.3 ± 0.7 Ma (He

et al., 2004) and 122.1 ± 0.3 Ma (Chang et al., 2009) (Fig. 2, C), also indicating an Aptian age. It is correlated with the Chengzihe Formation of the Jixi Group in eastern Heilongjiang (Fig. 2, B) because the two formations are both of Aptian age and yield the non-marine bivalves *Arguniella cf. quadrata* and *A. cf. ventricosa* (Sha, 2007a; Sha et al., 2007).

The Fuxin Formation rests conformably on the Jiufotang Formation. It is characterized by coal-bearing siliciclastic rocks consisting of off-white, greenish-grey, greyish-green, yellowish-grey or grey sandy conglomerates, sandstones, siltstones, mudstones, carbonaceous argillites and coal beds. The formation yields plant mega- and microfossils, including rare charophytes and abundant brackish-water dinoflagellate cysts such as *Vesperopsis*, *Nyktericysta* and *Pseudoceratium*, gastropods including *Viviparus cf. onogoensis*, *Bellamyia clavilithiformis*, *Probaicalia vitiensis* and *P. gerassimovi*, bivalves including *Arguniella* spp., *Margaritifera tungriensis*, *Nippononaia sinensis*, *Nip. yanjiensis* and *Sphaerium (S.) anderssoni* (Fig. 3, C), some conchostracans and ostracods, rare reptiles and mammals (Gu et al., 1976; Yu et al. in Yu et al., 1987; Mao & Yu, 1990; Sha, 2007a). The composition of the bivalve association is similar to that of the Jiufotang Formation. In particular, both formations contain *Viviparus cf. onogoensis*, *Nippononaia sinensis*, *Nip. yanjiensis*, and *Sphaerium (S.) anderssoni* (= *S. jeholense*), which suggests that the Fuxin Formation should be regarded as Aptian, nearly corresponding to the Muling Formation and the upper part of the Chengzihe Formation of the Jixi Group in eastern Heilongjiang (Fig. 2, B, C) (Sha, 2007a; Sha et al., 2007). This conclusion is coincident with the Barremian–Albian age of the dinoflagellate cysts *Vesperopsis* and *Nyktericysta* recovered from the Fuxin Formation.

The Sunjiawan Formation rests disconformably on the Fuxin Formation and unconformably underlies the Zhanglaogongtun/Daxingzhuang Formation, which consists of volcanic rocks. It consists of alternating, purplish sandstones and conglomerate; there are no coal beds. The gastropods and bivalves, including *Nippononaia yanjiensis*, that have been recorded have come from the traditional lower part of the formation or the

Balashan Formation (Gu, 1982b), which should be merged with the Fuxin Formation. The K/Ar ages of overlying lavas at Jianguo are 93.32 ± 1.96 to 109.7 ± 1.0 Ma (Fig. 2, C) (Zhu et al., 2002), which correspond to the late Albian–early Turonian. The Sunjiawan Formation is presumably not younger than Albian and is coeval with the Huashan Group of eastern Heilongjiang (Fig. 2, A, B) (Sha, 2007a; Sha et al., 2007).

2.3 Lower Cretaceous of Gyeongsang Basin, SE Korea

In the Gyeongsang (= Kyongsang) Basin of SE Korea (Fig. 1, D), the Lower Cretaceous comprises the Myogog Formation, the Singdong Group and the lower part of the Hayang Group (Fig. 2, D).

2.3.1 Myogog Formation The Myogog Formation is in fault contact with the pre-Cambrian Wonnam Group and, hence, presumably unconformably overlies this group of mainly quartz feldspar gneiss with subordinate schist and crystalline limestone. It consists largely of dark grey to black shale and mudstone and subordinate light to dark grey siltstone and sandstone, but with intercalations of two or three coal beds in the lower part of the succession. This formation contains plants and molluscs, including the gastropod *Viviparus* (?) sp. cf. *V. onogoensis* and the bivalves *Nakamuraia* (= *Nagdongia*) *leei*, *Koreanaia cheongi*, and *Cuniopsis kihongi* (Fig. 3, D) (Yang, 1976, 1984; Yang in Lee, 1987; Choi in Geological Society of Korea, 1999; Park et al. 2003; Kozai et al., 2005).

This formation, including the molluscs above, has been assigned to the Late Jurassic (Yang, 1984, 1987, 2002; Chang in Lee, 1987; Yang in Lee, 1987; Choi in Geological Society of Korea, 1999), Early Cretaceous Valanginian–Hauterivian (e.g., Chang, 2002), ? Valanginian and Hauterivian–Barremian (Sha, 2007b), or Hauterivian (Chang & Park, 2003, 2008; Park et al., 2003), the last of these being confirmed by Kozai et al. in 2005 because *Viviparus onogoensis* also occurs in the Hauterivian–early Barremian Tatsukawa Formation, which is overlain by strata containing Barremian molluscs and radiolarians of the Monobegawa Group (Fig. 2, F) in the Tokushima–Monobe areas of Shikoku, Outer Zone, SW Japan.

The latest radioisotopic dating shows that the youngest SHRIMP U-Pb age of detrital zircons from

the Myogok Formation is 138 ± 2.1 Ma ($n = 7$) (Fig. 2, D) (Lee et al., 2011), which is similar to the K/Ar age (139.4 ± 0.19 Ma) of the lavas of the Tuchengzi Formation (Fig. 2, C) (Swisher et al., 2002) and corresponds to the middle Valanginian. This SHRIMP U-Pb age implies that the age of the Myogok Formation could range down from Hauterivian into Valanginian, roughly corresponding to the Yixian and Tuchengzi formations (Fig. 2, C) of western Liaoning.

2.3.2 Singdong Group The Singdong Group in the Gyeongsang Basin of SE Korea (Fig. 1, D) comprises, in ascending order, the Nakdong (= Naktong) Formation (= Yeonhwadong Formation), the Hasandong Formation and the Jinju (= Chinju) Formation (= Dongmyeong Formation) (Fig. 2, D).

The Nakdong Formation overlies unconformably the Myogok Formation and consists of conglomerate (pebble and cobble), sandstone, siltstone, shale and coaly shale (Chang in Lee, 1987). It contains freshwater molluscs including the bivalves *Nakamuraia chingshanensis* (= *Nagdongia soni*), *Koreanaia bongkyuni*, *Nippononaia ryosekiana*, *Pseudohyria (Matsumotoina) matsumotoi*, *Trigonioides (Wakinoa) wakinoensis*, *Plicatounio (P.) multiplicatus* (= *P. (P.) yooni*), *Schistodesmus antiquus*, *Viviparus keishoensis*, *V. spp.*, and *Micromelania? katoensis* (Fig. 3, D) (Yang, 1975, 1978a, 1979a–b, 2002; Chang in Lee, 1987); Yun & Yang, 2001a, b; Park et al., 2003; Kozai et al., 2005; Sha, 2007b), dinosaur bones and eggs and charophytes (*Clypeator ji uquanensis*) (Chang in Lee, 1987); Chang & Park, 2003). Furthermore, according to Yang (2002), the upper part of the formation also yields *Trigonioides (T.) kodairai* and *Plicatounio (P.) naktongensis*. Park et al. (2003) indicated that *Sphaerium (S.) coreanicum* also appears in the Nakdong Formation (Fig. 3, D). The Nakdong Formation or the non-marine molluscan fauna noted above have been regarded as Valanginian–Barremian (Chang in Lee, 1987), Barremian or late Barremian (Kozai et al., 2005; Chang, 2002; Chang & Park, 2003), Barremian–Aptian (Park et al., 2003), Aptian–Albian (Yang, 1978a, 2002), Aptian (Chang & Park, 2008), and Aptian but probably extending into the Barremian and the Albian (Sha, 2007b). The youngest SHRIMP U-Pb age of detrital zircons from the formation is 118 Ma (Fig. 2, D) (Lee et al., 2010; Hong & Lee, 2012), correspond-

ing to the early Aptian. It is closest to those of the Jiufotang Formation ($120.3 \pm 0.7 \sim 122.1 \pm 0.3$ Ma (Fig. 2, C) (He et al., 2004; Chang et al., 2009). As a result, the Nakdong Formation can be correlated to the Jiufotang Formation and probably the lower Fuxin Formation of the Jehol Group (Fig. 2, C) in the BF basins of western Liaoning on the basis of the appearance of *Nakamuraia chi ngshanensis* (= *Nagdongia soni*) and *Nippononaia* in, and the similar radioisotopic ages for these formations.

The Hasandong Formation rests conformably on the Nakdong Formation. It is composed of sandstone, conglomerate with reddish and grey silty/sandy shales and grey mudstone, black shale, and intercalations of calcareous nodules (Chang in Lee, 1987; Park et al., 2000). It yields freshwater molluscs including *Nakamuraia chingshanensis* (= *Nagdongia soni*), *Trigonioides (T.) kodairai*, *Trigonioides (Wakinoa) tamurai*, *T. (T.) quadratus* (= *T. (T.) jaehoi*), *Plicatounio (P.) naktongensis*, *P. (P.) multiplicatus* (= *P. (P.) yooni*), *P. (P.) okjuni*, *Brotiopsis wakinoensis* (= *B. ryohoriensis*), *B. kobayashii*, *Viviparus spp.*, and *Micromelania? katoensis* (Fig. 3, D), ostracods, vertebrate remains including dinosaur bones, teeth, egg shells and tracks, reptile jaws and claws, turtle carapaces and skeletons, fish, coprolites and plant remains (Yang, 1974, 1975, 1979b, 1983, 1989, 2002; Chang in Lee, 1987; Lee et al., 1990, 1997; Yun & Yang, 1997; Park et al., 2000, 2003; Yun & Yang, 2001a, 2001b, 2001c; Kozai et al., 2005; Sha, 2007b), and charophytes and palynomorphs (Park et al., 2000; Chang & Park, 2003). Yang (2002) indicated that *Nippononaia ryosekiana* also occurs in this formation (Fig. 3, D). The Hasandong Formation or the molluscan fauna noted above have been regarded as Hauterivian–Barremian (Chang in Lee, 1987), late Barremian (Kozai et al., 2005), Aptian–Albian (Park et al., 2000; Yang, 2002), Aptian (Chang, 2008), and Aptian but probably ranging down into the Barremian and up into the Albian (Sha, 2007b). The youngest SHRIMP U-Pb age of detrital zircons from the formation is 109 Ma (Fig. 2, D) (Lee et al., 2010; Hong & Lee, 2012), corresponding to the early Albian. However, considering that *Nakamuraia chi ngshanensis* (= *Nagdongia soni*) and *Nippononaia (N.) ryosekiana* extend upwards from the underlying Aptian Nakdong Formation, and *Trigonioides (T.) kodairai* and *Plica-*

tounio (*P.*) *naktongensis* were also recorded from the upper part of the Nakdong Formation (Fig. 3, D), the Hasandong Formation is conservatively dated as late Aptian–early Albian.

The Jinju Formation conformably overlies the Hasandong Formation and underlies the Hayang Group. It comprises grey sandstone, dark grey shale, and conglomerate (Chang in Lee, 1987), and contains freshwater molluscs including the bivalves *Nakamuraia chingshanensis* (= *Nagdongia soni*), *Trigonioides* (*T.*) *kodairai*, *T.* (*T.*) *quadratus* (= *T.* (*T.*) *jaehoi*), *Plicatounio* (*P.*) *naktongensis* and *Sphaerium* (*S.*) *coreanicum* and the gastropods *Viviparus* spp. (Fig. 3, D), and conchostracans, insects, fish, pterosaur teeth, stromatolites and plants (Yang, 1979b, 2002; Chang in Lee, 1987; Lee & Yang, 1990; Lee et al., 1990; Park & Chang, 1998; Yun & Yang 2001b; Park et al., 2003; Kozai et al., 2005). This formation has been assigned to the Barremian–early Albian (Park & Chang, 1998), Barremian (Chang in Lee, 1987), Barremian–Aptian (Park et al., 2003), Aptian (Chang & Park, 2008), and Aptian–Albian (Yang, 2002). The youngest SHRIMP U–Pb age of detrital zircons from the formation is 106 Ma (Fig. 2, D) (Lee et al., 2010; Hong & Lee, 2012), which indicates an early Albian age. It can be roughly correlated with the Huashan Group (Fig. 2, C) of eastern Heilongjiang, because *S. coreanicum* and cf. *P.* (*P.*) *naktongensis* have been reported from the Xiachengzi/Houshigou Formation (Fig. 3, B) (Sha, 1992d, 1995, 2007a, 2007b; Sha & Fürsich, 1993; Gu et al., 1997; Sha et al., 2003, 2009). Furthermore, the Singdong Group also yields the freshwater fish *Wakinoichthys aokii* (e.g., Yabumoto & Yang, 2000).

The overlying Hayang Group (= Silla Subgroup) is composed of dark grey, grey, light grey, red, and reddish conglomerate, sandstone, siltstone, mudstone, shale (the dominant lithology), and volcanic rocks including lavas and tuffs (Yang, 1976, 1978b; Chang in Lee, 1987; Hong & Lee, 2012). In ascending order, it consists of the Chilgok (= Ch'ilgok), Silla and Haman formations, and Jindong (= Chindong, Jingong) Formation (= Jain Formation).

Dinosaur bones have been recorded from the Chilgok Formation (Chang in Lee, 1987; Lim et al., 1995), dinosaur bones and tracks including bird tracks (Chang in Lee, 1987; Lim et al., 1995) and con-

chostracans (Park & Chang, 1998) from the Haman Formation, and conchostracans (Park & Chang, 1998), dinosaur bones and tracks and bird footprints from the Jindong Formation (Chang in Lee, 1987; Lim et al., 1989; Lockley et al., 1994). So far, non-marine molluscs, including the bivalves *Trigonioides* (*T.*) *paucisulcatus* and gastropods *Thiara* (*Siragimelania*) *tateiwai* and *T.* (*S.*) *acuticostata*, have been only recorded from the Jindong Formation (Yang, 1978b, 1979b; Chang in Lee, 1987).

The Hayang Group has been assigned to various ages, such as Barremian–early Albian (Park & Chang, 1998), late Barremian–Albian (Chang in Lee, 1987); Aptian–Albian (Park et al., 2003), Aptian–early Albian (Chang, 2002), late Aptian–early Albian (Chang & Park, 2003), and Albian (Chang & Park, 2008).

However, *Thiara* (*Siragimelania*) *tateiwai* and *T.* (*T.*) *paucisulcatus* have also been recorded from the Mifune and upper Goshonoura groups, respectively (Yang, 1978b). The Mifune Group is Cenomanian–Turonian in age, and the Goshonoura Group is late Albian–Turonian based on marine fossils, including ammonites (e.g., Kimmura et al., 1991). Therefore, the Hayang Group can be roughly correlated with the Cenomanian–Turonian (Yang, 1978b), *Trigonioides* (*T.*) *paucisulcatus*-bearing strata. The Jindong Formation is Cenomanian, but its age may range up into Turonian (Sha, 2007b). Lee et al. (2010) considered the Hayang Group to have been deposited during the Cenomanian–early Campanian. The U–Pb zircon age from the tuff bed at the boundary between the Haman and Jindong formations is 97–98 Ma, and the K–Ar whole-rock age of the Chaeyaksan Andesite in the upper Jindong Formation is 94 Ma (Fig. 2, D) (Hong & Lee, 2012), both indicating that the Jindong Formation is approximately Cenomanian–Santonian in age (Hong & Lee, 2012), which is consistent with the correlation of Yang (1978b) and Sha (2007b). This result implies that all of the formations below the Jindong Formation should be Albian in age (Fig. 2, D).

2.4 Tetori Group of the Makito/Shokawa area of northern Gifu, Inner Zone of SW Japan

In the Makito/Sakawa area of the northern Gifu Prefecture, located in the eastern part of the Hakushan Region of the Inner Zone of SW Japan (Fig. 1, E),

the Tetori Group is composed of, in ascending order, the Kuzuryu Subgroup, including the Ushimaru Formation (including the Akahok Formation) and the Mitarai Formation, the Itoshiro Subgroup consisting of the Otaniyama Formation/Gomishima Conglomerate Member and the Okurodani/Kuwajima Formation, and the Akaiwa Subgroup composed of the Amagodani, Okura and Bessandani formations (Fig. 2, E) (Matsukawa & Ito, 1993; Matsukawa & Nakada, 1999; Kusuhashi et al., 2002, 2006; Matsukawa et al., 2003, 2006; Fujita, 2003; Sano et al., 2008; Matsukawa & Fukui, 2009; Lockley et al. 2012, this issue).

The Ushimaru Formation unconformably overlies basement rocks consisting of Hida Metagranites, which are older than 200 Ma (Kusuhashi et al., 2006). It is composed of black mudstone in the lower part, and fine- to medium-grained sandstone in the upper part (Matsukawa & Nakada, 1999; Matsukawa et al., 2006), locally intercalated with coal beds (5~10 cm thick) and greenish to yellow-brown tuffs in the upper part of the formation (=Akahoke Formation) (Kusuhashi et al., 2002). It contains brackish-water molluscs, including gastropods, the bivalves *Myrene* (*Mesocorbicula*) *tetoriensis*, and *Tetoria* (*Tetoria*) *yokoyami*, ostreids, and the marine ammonite *Lilloetia*? sp. (Fig. 3, E) (Matsukawa & Nakada, 1999) and plants (Kusuhashi et al., 2002).

This formation has commonly been dated as Jurassic, Bajocian–Tithonian (Matsukawa & Ido, 1993; Matsukawa & Nakada, 1999; Fujita, 2003; Matsukawa et al., 2006; Sano et al., 2008; Matsukawa & Fukui, 2009; Lockley et al., 2012, this issue), probably mainly because the overlying Mitarai Formation yields Callovian (Sato & Kanie, 1963), latest Jurassic–earliest Cretaceous (Sato et al., 2003) and Berriasian (Sato et al., 2008) ammonites. However, Sha & Hirano (2012) revised this to Hauterivian on the basis of a comparison of the bivalve faunas of the Mitarai Formation and Longzhaogou Group with a 130.2 ± 1.7 Ma zircon U-Pb age measured by Kusuhashi et al. (2006) from the tuff beds in the Ushimaru Formation. This radiometric dating indicates a Hauterivian/Barremian age, in common with that of the Yixian Formation of the Jehol Group (Fig. 2, C).

The Mitarai Formation rests conformably on the

Ushimaru Formation and is composed of monotonous black mudstone with a thin tuff layer (Matsukawa & Nakada, 1999; Matsukawa et al., 2006). It yields ammonites such as *Lilloetia* sp. (Sato & Kanie, 1963), *Partschiceras* cf. *otekense*, *Lytoceras* sp., *Delphinella* cf. *obtusenodosa* and *Berriasella* sp. (Sato et al., 2003), and *Neocosmoceras* sp. (cf. *N. hunevciense*) (Sato et al., 2008), and marine bivalves, including *Palaeonucula makitoensis*, *Modiolus maedae*, *Pinna* sp., *Inoceramus maedae*, *Entolium in equivalve*, *Tetorimyia carinata*, *Thracia shokawaensis*, and *Pleuromyia hidensis* (Fig. 3, E) (Hayami, 1959a, 1959b, 1960, 1975; Matsukawa & Nakada, 1999). The Mitarai Formation is, therefore, critical for determining the age of the Tetori Group because of the marine molluscs it contains. It has been dated as Callovian (Sato & Kanie, 1963; Hayami, 1975; Matsukawa & Nakada, 1999; Fujita, 2003), Callovian–Oxfordian (Matsukawa & Ito, 1993), Late Jurassic (Hayami, 1959a, 1959b), latest Jurassic/Tithonian–earliest Cretaceous/Berriasian, spanning the Jurassic/Cretaceous boundary (Sato et al., 2003; Matsukawa et al., 2006), and Berriasian (Matsukawa & Fukui, 2009; Lockley et al., 2012, this issue) based on the ammonites and bivalves. However, among the 11 bivalve species recorded from the Mitarai Formation, four (*Palaeonucula makitoensis*, *Entolium in equivalve*, *Thracia shokawaensis* and *Pleuromyia hidensis*) have been recognized in the Qihulin (the first three) and Yunshan (all four) formations (Fig. 3, A) (Sha & Hirano, 2012; section 2.1.1). The Qihulin and Yunshan formations have been respectively dated as mainly Barremian and Aptian based on the index bivalves *Aucellina*, *Filosina* and *Thracia* (Fig. 3, A), and ammonites (Sha, 1990, 1991, 1992a, 1992b, 1992c, 2002, 2007a, 2012; Sha & Fürsich, 1993a, 1994; Sha et al., 1994, 2000, 2002, 2003, 2007a, 2008, 2009; Futakami et al., 1995). Kusuhashi et al. (2006) obtained a zircon U-Pb age of 129.8 ± 0.7 Ma from the tuff beds of the Mitarai Formation (Fig. 2, E), indicating an early Barremian age, which is within the time range of the bivalves. The Mitarai Formation is, therefore, Barremian in age, corresponding to the Barremian Qihulin Formation of the Longzhaogou Group (Fig. 2, A) in eastern Heilongjiang.

The Otaniyama Formation/Gomishima Conglo-

merate Member rests conformably on the Mitarai Formation and mainly comprises arkosic sandstone, frequently intercalated in the thin mudstone layers. In the eastern part of the region, thin layers of alternating sandstone and mudstone, muddy sandstone, and granule conglomerate are intercalated in the upper part of the formation, and a conglomerate bed consists of clasts ranging in size from boulder to granule (Gomishima Conglomerate Member) in the extreme western part of the region (Matsukawa et al., 2006). This formation yields marine, brackish-water and freshwater molluscs, such as belemnites (Belemnitida), bivalve mytilids, *Isognomon* sp., *Entolium inequivalve*, ostracids, exogyriids, *Nakamuraia* (= *Nagdongia*) sp., *Myrenea* (*Mesocorbicula*) *tetoriensis*, *Tetoria* (*Tetoria*) *yokoyamai* (Fig. 3, E), gastropods, charophytes (Matsukawa & Nakada, 1999; Matsukawa et al., 2006), and dinosaur footprints (Kusuhashi, 2002).

All the recognizable molluscan species, *Entolium inequivalve*, *Myrenea* (*Mesocorbicula*) *tetoriensis* and *Tetoria* (*Tetoria*) *yokoyamai*, range up from the underlying Ushimaru and Mitarai formations. The Otaniyama Formation should thus be regarded as Barremian, in common with the Mitarai Formation, hence younger than Valanginian–Hauterivian (Matsuka & Ido, 1993; Matsukawa et al., 2006; Matsukawa & Fukui, 2009; Lockley et al., 2012). It can also be correlated with the Qihulin Formation (Fig. 2, A).

The Okurodani/Kuwajima Formation rests conformably on the Otaniyama Formation and consists of alternating mudstone and sandstone, fine-grained sandstone, muddy sandstone, and thin black mudstone (Okurodani Formation) or predominantly alternating mudstone and sandstone (Kuwajima Formation) (mainly in western part of the region), and intercalated with tuff layers (Kusuhashi et al., 2006). It contains terrestrial plants, molluscs, insects, fish, amphibians, reptiles, dinosaurs and mammals. The molluscs consist of fresh-to brackish-water bivalves including *Modiolus* sp., ostracids, *Unio ogamigoensis* (= *Unio? ogamigoensis*), *Nakamuraia chingshanensis* (= *Nagdongia soni*), *Nipponoia tetoriensis*, *Batissa antiqua* (= "*Batissa antiqua*"), *Myrenea* (*Mesocorbicula*) *tetoriensis*, *Tetoria* (*Tetoria*) *yokoyamai* and *Sphaerium* (*S.*) *coreanicum*, and gastropods including *Viviparus onogensis* and *Mi-*

cromelania? katoensis (Fig. 3, E) (Matsukawa and Nakada, 1999; Matsukawa et al., 2006).

It is difficult to determine the age of the Okurodani Formation based on the molluscan assemblage, because *Myrenea* (*Mesocorbicula*) *tetoriensis* and *Tetoria* (*Tetoria*) *yokoyamai* extend down into the Hauterivian Ushimaru Formation (Fig. 3, E), and *Unio ogamigoensis*, *Viviparus onogensis* and *Batissa? antiqua* have also been recorded from the Hauterivian–early Barremian Tatsukawa and Ryoseki formations of the Monobegawa Group (Fig. 3, F) in the Tokushima–Monobe areas of Shikoku, Outer Zone, SW Japan (Tashiro & Okuhira, 1993; Kozai & Ishida, 2003; Kozai et al., 2005, 2012). In addition, reports of other taxa elsewhere include aff. *Unio ogamigoensis* from the Aptian Chengzihe Formation of the Jixi Group (Fig. 3, B) of eastern Heilongjiang, cf. *Viviparus onogensis* from the mainly Hauterivian Myogog Formation of the Gyeongsang Basin (Fig. 3, D) (Yang, 1984; Park et al., 2003), and the Jiufotang and Fuxin formations of the Jehol Group (Fig. 3, C) in western Liaoning, *Micromelania? katoensis* from the Aptian–Albian Nakdong and Hasandong formations of SE Korea (e.g., Park et al., 2003) and *Sphaerium* (*S.*) *coreanicum* from the Albian Xiachengzi/Houshigou Formation of the Huashan Group (Fig. 3, B) in eastern Heilongjiang.

However, the youngest U-Pb age from the tuff beds of the Okurodani Formation is 117.5 ± 0.7 Ma (Fig. 2, E) (Kusuhashi et al., 2006), which is almost the same as that of the Nakdong Formation (118 Ma) (Fig. 2, D) in SE Korea and similar to that of Jiufotang Formation (120.3–122.1 Ma) (Fig. 2, C) in NE China, all of which are within the Aptian. In particular, the trigonoidid *Nakamuraia chingshanensis* (= *Nagdongia soni*) and *Nipponoia* have been recorded from the Okurodani, Nakdong, and Jiufotang and Fuxin formations (Fig. 3, C, D, E). Consequently, both fossils and radioisotopic ages indicate that the Okurodani Formation corresponds to the Nakdong Formation (Fig. 2, D) in SE Korea and the Chengzihe Formation of the Jixi Group (Fig. 2, B), and the Jiufotang and Fuxin formations of the Jehol Group (Fig. 2, C) in NE China, dated as Aptian.

The Amagodani Formation rests conformably on

the Akurodani Formation and is mainly composed of coarse-grained arkosic sandstone and thin-bedded conglomerate consisting of orthoquartzite pebble to granule conglomerates (Matsukawa & Nakada, 1999; Matsukawa et al., 2006).

The Okura Formation consists of pebble to boulder conglomerates and arkosic coarse-grained sandstone (Matsukawa & Nakada, 1999; Matsukawa et al. 2006). It conformably rests on (Matsukawa & Nakada, 1999; Matsukawa et al. 2006) or disconformably or unconformably overlies the Amagodani Formation (Kusuhashi et al., 2002).

The Bessandani Formation conformably overlies the Okura Formation and comprises alternating sandstone and mudstone yielding spores including *Cicatricosisporites* and coarse-grained arkosic sandstone (Matsukawa & Nakada, 1999; Matsukawa et al., 2006). It is unconformably overlain by the Nohi Rhyolite and locally (e.g., in the eastern part of the Shokawa area) the Makido mafic complex occurs between them (Kamiya & Harayama, 1982; Kusuhashi et al., 2006). The Nohi Rhyolite Rb-Sr, FT and chemical Th-U-total Pb isochron method (CHIME) ages are 70~90 Ma (Fig. 2, E), approximately corresponding to the Late Cretaceous Turonian–Maastrichtian ages, and the acceptable biotite K-Ar ages of the Makido Mafic complex are 100 ± 3 Ma and 90.7 ± 2.8 Ma, approximately corresponding to Cenomanian–Turonian Stages (Fig. 2, E) (Kusuhashi et al., 2006).

No index fossils have been recorded from the three formations or the Akawa Subgroup, but considering the age of the underlying Okurodani Formation, 117.5 ± 0.7 Ma, which corresponds to the Aptian, and less than 100 Ma for the overlying Nohi Rhyolite, corresponding to the Late Cretaceous, the Akawa Subgroup can be regarded as Albian.

2.5 Monobegawa Group of the Tokushima and Monobe areas of Shikoku, Outer Zone of SW Japan

The Monobegawa Group occurs mainly in the Tokushima area of east Shikoku and the Monobe area of the Kochi Prefecture, central Shikoku, Outer Zone of SW Japan (Fig. 1, F) (Kozai & Ishida, 2003; Kozai et al., 2005, 2012, this issue). In the Monobe area, the group comprises, in ascending order, the Ryoseki,

Monobe, Yunoki and Hibihara formations, and in the Tokushima area, it is composed of, in ascending order, the Tatsukawa, Lower Hanoura (containing the Hiura Facies), Upper Hanoura, Hoji and Fujikawa formations (Fig. 2, F). Although the formation names of the group differs in the two areas, according to Kozai & Ishida (2003, Fig. 4), and Kozai et al. (2005, Fig. 3, 2012, Fig. 3), the Tatsukawa Formation corresponds to the Ryoseki Formation, the Lower Hanoura Formation to the Monobe Formation, the Hiura Facies of the Lower Hanoura Formation to the Yunoki Formation, the Upper Hanoura Formation to the lowermost part of the Hibihara Formation, the Hoji Formation to the lower part of the Hibihara Formation, and the Fujikawa Formation to the upper part of the Hibihara Formation (Fig. 2, F). The contacts between all of these formations of the Monobegawa Group are conformable, but the group rests unconformably on Permian accretionary complexes (PAC) (Fig. 2, F) (Kozai & Ishida, 2003; Kozai et al., 2005, 2012) and is overlain by alternating sandstone and mudstone in both the Tokushima and the Monobe areas (Kozai & Ishida, 2003). The rocks and fossil associations/assemblages of the formations are summarized below following Kozai & Ishida (2003), Kozai et al. (2005, 2012) and Tashiro & Okuhira (1993).

The Tatsukawa and Ryoseki formations are dominated by reddish conglomerates intercalated with reddish mudstone in their lower parts. Their upper parts consist of grey conglomerate, fine-grained sandstone and dark grey mudstone. The two formations yield the same non-marine molluscan assemblage, including brackish-water *Costocyrena otsukai*, *Hayamina naumanni*, *H. bungoensis*, *Isodomella shiroiensis* and *Myrene (Mesocorbicula) tetoriensis*, and freshwater *Batissa? antiqua*, *Trigonioides (Wakinoa) tetoriensis*, *Unio ogamigoensis*, and *Viviparus onogoensis*. They have been assigned a Hauterivian–early Barremian age because they are overlain by the Barremian Lower Hanoura and Monobe formations, which contain Barremian ammonites and radiolarians.

The Lower Hanoura and Monobe formations consist of conglomerate, sandstone and mudstone. They contain abundant marine molluscs, including *Crioceratites a siaticum*, *Olcostephanus can doceroides*, *Pul-*

chellia ishido ensis, *Shastrioceras nipponicum* and *Yabea shinanoensis*, and a radiolarian assemblage of *Archaeodictyomitra pseudoscalaris*, all indicating a Barremian age.

The Hiura Facies and the Yunoki Formation consist of dark grey muddy sandstone, black mudstone, grey sandstone, conglomerate, and some intercalations of acidic tuff and black shale in their upper parts. They contain plant fragments, radiolarians and molluscs including brackish-water bivalves such as *Costocyrena radiatostrata*, *Hayamina matsukawai* and *Pulsidis tashiroi*. The fauna of the formations is regarded as late Barremian.

The Upper Hanoura Formation and lowermost part of the Hibihara Formation consist of conglomerates, sandstones and mudstones, intercalated with black shale. The lower parts yield abundant brackish-water bivalves, including *Costocyrena minor*, *Hayamina solida* and *Pulsidis rostrata*. The black shale of the upper part contains the Aptian ammonite *Chelonicerases* sp. and a *Stichomitra communis* radiolarian assemblage.

The Hoji Formation and the lower part of the Hibihara Formation consist of conglomerates and sandstones, with some intercalations of mudstone and acidic tuff in their upper parts. The sandstone yields abundant marine molluscs, including the middle Aptian ammonites *Parahoplites* sp. and *Chelonicerases* (*Chelonicerases*) aff. *cornuelianus*, and the bivalves *Nipponitrigonia sakamotoensis* and *Pterotrigonia pocilliformis*.

The Fujikawa Formation and the upper part of the Hibihara Formation comprise thick black shales and alternating sandstone and shale, yielding rare fossils, such as the molluscs *Eodouvilleiceras* sp., *Portlandia sanchuensis* and *Inoceramus angulicus*, and a radiolarian assemblage of *Pseudodictyomitra pentacolaensis*, which together indicate a late Albian age.

All the formations of the Monobegawa Group are well dated by marine fossils, particularly by ammonites and radiolarians. Among them, the Tatsukawa and Ryoseki formations correspond to the Myogog Formation of SE Korea (Fig. 2, D), because of the presence of *Viviparus onogoensis* in all of the formations (Kozai et al., 2005).

By correlating between marine and non-marine

successions on the basis of especially the occurrence of marine and non-marine molluscs (Fig. 3), together with the radiometric dating (Fig. 2), an Early Cretaceous stratigraphic correlation between eastern Heilongjiang and western Liaoning in NE China, the Gyeongsang Basin in SE Korea, the Makito/Shokawa area of northern Gifu, Inner Zone, and the Tokushima–Monobe areas of Shikoku, Outer Zone, SW Japan has been possible, as shown in Figure 2.

3 Non-marine molluscan biochronology

The geological ranges of the non-marine molluscs in the formations studied have been constrained by the correlations and radioisotopic ages derived from the volcanic rocks intercalated in the fossil-bearing strata (Fig. 4).

Cuniopsis kihongi, *Nakamuranaia leei* (= *Nagdongia leei*) and *Koreanaia cheongi* (*Bivalvia*) are recorded from the Myogog Formation of the Gyeongsang Basin (Fig. 3, D), and *Trigonioides* (*Wakinoa*) *tetoriensis* comes from the Tatsukawa and Ryoseki formations of the Monobegawa Group of the Tokushima–Monobe areas of Shikoku (Fig. 3, F). The Tatsukawa and Ryoseki formations are of Hauterivian–early Barremian age (Fig. 2, F) to judge from the overlying formations that yield Barremian molluscs and radiolarians (Tashiro & Okuhira, 1993; Kozai & Ishida, 2003; Kozai et al., 2005, 2012). The Myogog Formation is correlated with the Tatsukawa Formation and the coeval Ryoseki Formation by the presence of the common gastropod *Viviparus onogoensis* in all three formations (Fig. 3, D, F) (Kozai et al., 2005), demonstrating that the five molluscan taxa are as early as Hauterivian in age.

Among the four bivalves above, *Cuniopsis kihongi* and *Nakamuranaia leei* (= *Nagdongia leei*) have been only recorded from the Hauterivian–early Barremian Myogog Formation (Fig. 3, D) to date. *Trigonioides* (*Wakinoa*) *tetoriensis* has been regarded as a latest Hauterivian or early Barremian indicator (e.g., Tashiro & Okuhira, 1993), although it is also present in the Aptian–Albian Kitadani Formation of the Kitadani area of Fukui Prefecture, Inner Zone, SW Japan (Matsukawa & Ito, 1993; Kozai et al., 2005; Sha, 2007b). The forms of *Koreanaia cheongi* could be recognized

System	Stage	Time in Ma	Geological range		
Upper Cretaceous	Cenomanian	99.6			
	Albian	112.0			
Lower Cretaceous	Aptian	125.0	<i>U. longus</i>	<i>T. (W.) tamurai</i> <i>T. (T.) kodairai</i> <i>T. (T.) quadratus</i> <i>T. (T.) heilongjiangensis</i> <i>P. (P.) naklongensis</i> <i>P. (P.) okijuni</i> <i>S. (S.) subplanum</i> <i>S. (S.) sclonginense</i> <i>S. (S.) ebientaense</i> <i>Pis. (Pis.) cf. fujimense</i> <i>B. wakinoensis</i>	
	Barremian	130.0	<i>U. aff. obrutschewi</i> <i>M. islopensis, M. nagriensis</i> <i>N. qingshanensis</i> <i>K. bongkyuni</i> <i>Nip. roosekiana</i> <i>Nip. tetoriensis</i> <i>T. (W.) wakinoensis</i> <i>P. (P.) multiplicatus</i> <i>Ps. (Mar.) matsumotoi</i> <i>S. (S.) coreanicum</i> <i>S. (S.) sclonginense</i> <i>Sph. yixianensis</i> <i>Sch. antiquus</i> <i>V. keishonensis</i> <i>Mic. katoensis</i> <i>Bel. claviliteformis</i>		
	Hauterivian	133.9		<i>Ps. (S.) anderssoni</i> <i>Pis. (Pis.) liaoningense</i> <i>Myr. (Mes.) tetoriensis</i> <i>Tet. (Tet.) yokoyamai</i> <i>V. ongoensis</i> <i>Pr. vilimensis, Pr. gerassimovi</i>	
	Valanginian	140.2	<i>A. cf. quadrata, A. cf. ventricosa</i> <i>U. ogamigoensis</i> <i>C. kihongi</i> <i>N. leei</i> <i>K. cheongi</i> <i>Nip. shensis, Nip. yanjimensis, Nip. tetoriensis</i> <i>T. (W.) tetoriensis</i>		
	Berriasian	Berriasian	145.5	<i>A. cf. quadrata, A. cf. ventricosa</i> <i>U. ogamigoensis</i> <i>C. kihongi</i> <i>N. leei</i> <i>K. cheongi</i> <i>Nip. shensis, Nip. yanjimensis, Nip. tetoriensis</i> <i>T. (W.) tetoriensis</i>	
		Upper Volgian	145.5		

Fig. 4 The geological ranges of most of the Early Cretaceous non-marine molluscs of eastern Heilongjiang and western Liaoning, the Gyeongsang Basin, and the Makito/Shokawa area of northern Gifu and the Tokushima–Monobe areas of Shikoku

A. Arguniella; *B.* Brotiopsis; *Bel.* Bellamyia; *C.* Cuniopsis; *K.* Koreanaia; *M.* Margaritifera; *Mat.* Matsumotoina; *Mes.* Mesocorbicula; *Mic.* Micromelania; *Myr.* Myrene; *N.* Nakamuraia; *Nip.* Nipponaia; *P.* Plicatounio; *Pis.* Pisidium; *Pr.* Probaicalia; *Ps.* Pseudohyria; *S.* Sphaerium; *Sch.* Schistodesmus; *Sph.* Sphaerioides; *T.* Trigonioides; *Tet.* Tetoria; *U.* Unio; *V.* Viviparus; *W.* Wakinoa

in the Jinxin Formation of western Yunnan, southern China, and the Lengshuiwu Formation of Jiangxi, eastern China. The Jixing and Lengshuiwu formations have been regarded as Hauterivian in age (Sha, 2007b). *Cuniopsis kihongi*, *Nakamuraia leei* (= *Nagdongia leei*), *Koreanaia cheongi* and *Trigonioides (Wakinoa) tetoriensis* could, therefore, be Hauterivian–early Barremian indicators locally, if not globally.

Viviparus ongoensis (Gastropoda) and *Unio ogamigoensis* (Bivalvia) are Hauterivian–Aptian in age, since they occur in the Hauterivian–early Barremian Tatsukawa and Ryoseki formations, which are overlain by the Barremian ammonite- and radiolarian-bearing strata in the Tokushima–Monobe areas of Shikoku (Fig. 3, F) (Tashiro & Okuhira, 1993; Kozai & Ishida, 2003; Kozai et al., 2005, 2012, this issue).

They also appear in the Okurodani Formation (Fig. 3, E) with a radioisotopic age of 117.5 Ma (Aptian) (Fig. 2, E) (Kusuhashi et al., 2006) in the area of Makito/Shokawa, and cf. *Viviparus ongoensis* and cf. *Unio ogamigoensis* have been respectively recorded in the Jiufotang and Fuxin formations (Fig. 3, C), confirmed as Aptian by radiometric dating (120.3–122.1 Ma) (Fig. 2, C) (He et al., 2004; Chang et al., 2009) and the Chengzihe Formation with typical Aptian marine bivalves (Fig. 3, B) (Sha et al., 1994, 2000, 2002, 2003, 2007, 2008, 2009; Sha, 2002, 2007a).

The bivalves *Myrene (Mesocorbicula) tetoriensis* and *Tetoria (Tetoria) yokoyamai* have been recorded from the Ushimaru, Otaniyama and Okurodani formations (Fig. 3, E). Both of the marine bivalves from these formations (Sha & Hirano, 2012; sections 2.1.1,

2.4) and the radioisotopic datings of 130.2 Ma (Hauterivian) for the Ushimaru Formation and 117.5 Ma (Aptian) for the Okurodani/Kuwajima Formation (Fig. 2, E) (Kusuhashi et al., 2006) indicate that the range of these two bivalve taxa is Hauterivian–Aptian.

The bivalves *Arguniella* cf. *quadrata*, *A.* cf. *venetricosa*, *Sphaerium* (*S.*) *anderssoni* (= *S.* (*S.*) *jehoense*) and *Pisidium* (*Pis.*) *lioaninense* and gastropods *Probaicalia viti mensis* and *Pr. gerassimovi* range from Hauterivian/Barremian to Aptian in age, because the radioisotopic ages of the volcanic rocks in the fossil-bearing strata concerned, the Yixian and Jiufotang formations (Fig. 2), are within the Hauterivian/Barremian–Aptian age-range of 125.7–133.6 Ma (Zhu et al., 2003, 2007; Yang et al., 2007; Yang & Li, 2008) to 120.3–122.1 Ma (He et al., 2004; Chang et al., 2009) (Fig. 2, C), and the *Arguniella*-bearing Chengzihe Formation contains typical Aptian marine bivalves (Fig. 3, B; section 2.1.2).

The bivalves *Unio* aff. *obrutschewi*, *Margaritifera isfarensis* *M. tugriensis*, *Koreanaia bongkyuni*, *Nippononaia si nensis*, *Nip. yanjiensis*, *Nip. tetoriensis*, *Nip. ryosekiana*, *Trigonioides* (*Wakinoa*) *wakinoensis*, *Pseudohyria* (*Matsumotoina*) *matsumotoi*, *Sphaerium* (*S.*) *subplanum*, *Sphaerioides yi xianensis* and *Schistodesmus antiquus*, and the gastropod *Bellamyia clavilithiformis* are partly distributed in the Nakdong Formation of the Gyeongsang Basin (Fig. 3, D), partly in the Jiufotang and Fuxin formations of BF basins (Fig. 3, C), and partly in the Okurodani Formation in the Makito/Shokawa area (Fig. 3, E). All of these formations containing diverse fossil assemblages have been dated by non-marine to marine correlation of fossil occurrences and radiometrically as Aptian: Nakdong Formation, 118 Ma (Fig. 2, D) (Lee et al., 2010; Hong & Lee, 2012); Jiufotang Formation, 120.3–122.1 Ma (Fig. 2, C) (He et al., 2004; Chang et al., 2009); Okurodani Formation, 117.5 Ma (Fig. 2, E) (Kusuhashi et al., 2006).

The non-marine molluscs, particularly *Nippononaia si nensis*, *Nip. tetoriensis*, *Nip. ryosekiana* and *Trigonioides* (*Wakinoa*) *wakinoensis*, are widely distributed in Asia (Sha, 2007b, 2010) and, hence, are good indicators of the Aptian Stage, though *Nippononaia ryosekiana* possibly could extend up into the

Aptian–Albian Hasnadong Formation in the Gyeongsang Basin (Fig. 3, D) (Yang, 2002).

Nakamuraia chingshanensis (= *Nagdongia soni*), *Plicatounio* (*P.*) *multiplacatus* (= *P.* (*P.*) *yooni*), *Sphaerium* (*S.*) *coreanicum* (Bivalvia) and *Micromelania? katoensis* (Gastropoda) have all been recorded from the Nakdong, Hasandong and even Jinju formations of the Gyeongsang Basin (Fig. 3, D). All the taxa, except *P.* (*P.*) *multiplacatus*, have been recorded from the Okurodani Formation of the Makito/Shokawa area (Fig. 3, E), and *Nakamuraia chingshanensis* (= *Nagdongia soni*) and *Sphaerium* (*S.*) *coreanicum* have also been recorded, respectively, in the Jiufotang Formation of the BF basins (Fig. 3, C) and the Xianchengzi Formation of the JBM basins (Fig. 3, B). The radioisotopic ages of the detrital zircons in the Nakdong, Hasandong and Jinju formations range from 118 to 106 Ma (Fig. 2, D) (Lee et al., 2010; Hong & Lee, 2012), 117.5 Ma in the Okurodani Formation (Fig. 2, E) (Kusuhashi et al., 2006) and 120.3–122.1 Ma in the Jiufotang Formation (Fig. 2, C) (He et al., 2004; Chang et al., 2009), and the Xianchengzi Formation is Albian according to non-marine to marine correlation (Sha, 2002, 2007a; Sha et al., 2003, 2007, 2008, 2009). *Nakamuraia chingshanensis* (= *Nagdongia soni*), *Plicatounio* (*P.*) *multiplacatus* (= *P.* (*P.*) *yooni*), *Sphaerium* (*S.*) *coreanicum* and *Micromelania? katoensis* are, therefore, constrained as Aptian–Albian in age.

Trigonioides (*Wakinoa*) *tamurai*, *Trigonioides* (*T.*) *kodairai*, *T.* (*T.*) *quadratus* (= *T.* (*T.*) *jaehoi*), *Plicatounio* (*P.*) *naktongensis* are encountered in the Hasandong and Jinju formations, but *T.* (*T.*) *kodairai* and *P.* (*P.*) *naktongensis* first appear in the upper Nakdong Formation in the Gyeongsang Basin (Fig. 3, D), and *Unio longus* (= *U. heilongjiangensis*), *T.* (*T.*) *heilongjiangensis*, cf. *P.* (*P.*) *naktongensis* and *Sphaerium* (*S.*) *chintaoense* (= *S.* (*S.*) *yanbianense*) are recorded in the Xiachengzi Formation of the JBM basins (Fig. 3, C). The fossil-bearing strata indicate a late Aptian–Albian age in SE Korea, because the detrital zircon age range of the Naktong, Hasandong and Jinju formations is 118–106 Ma (Fig. 2, D) (Lee et al., 2010; Hong & Lee, 2012), and the Xiachengzi Formation is Albian on the basis of non-marine to marine correlation (Sha et al., 2003, 2007, 2008, 2009; Sha,

2007a). These molluscan fossils, especially *Unio longus* (= *U. heilongjiangensis*), *T. (T.) quadratus* (= *T. (T.) jaehoi*), *T. (T.) heilongjiangensis*, *P. (P.) naktongensis*, and *S. (S.) chintaense* (= *S. (S.) yanbianense*) are widely distributed in Asia (Sha et al., 2006; Sha, 2007b, 2010), implying that they are good indicators of late Aptian–Albian or Albian ages.

Furthermore, *Thiara (Siragimelania) tateiwai* (Gastropoda) and *Trigonioides (T.) paucisulcatus* (Bivalvia), which have been recorded from the Jindong Formation in the Gyeongsang Basin (Fig. 2, D), have been confirmed as Cenomanian–Santonian based on the U–Pb zircon age from the tuff bed at the boundary between the Haman and Jindong formations (97–98 Ma), the K–Ar whole-rock age of the Chaeyaksan Andesite in the upper Jindong Formation (94 Ma) (Fig. 2, D) (Hong & Lee, 2012), and the determination of Cenomanian–Turonian based on non-marine and marine fossil correlation (Yang, 1978b; Sha, 2007b). In NE China and SW Japan, the non-marine molluscs, particularly the trigonioidid bivalves, were replaced by very different taxa after the Cenomanian (e.g., Sha, 2007b).

4 Palaeogeographic implications

The presence of a number of common non-marine, particularly freshwater Hauterivian–Albian molluscan taxa, such as *Unio oga migoensis*, *Nakamuraia chingshanensis* (= *Nagdongia soni*), *Koreanaia cheongi*, *Nipponoia*, *Trigonioides (Wakinoa) waki-noensis*, *Trigonioides (T.) quadratus* (= *T. (T.) jaehoi*), *Plicatounio (P.) naktongensis*, *Sphaerium (S.) coreanicum* and *Viviparus onogoensis* (Figs. 3, 4) in NE China, SE Korea and SW Japan, indicate that these regions were connected and that a single fluvial system drained them (Sha, 2010), allowing dispersal and exchange opportunities, particularly for the freshwater molluscs. However, the Lower Cretaceous of the Outer Zone, including the Tokushima–Monobe areas of Shikoku (Fig. 1, F), SW Japan, is dominated by marine deposits with intercalations of brackish-water and occasional freshwater beds (Kozai & Ishida 2003; Kozai et al., 2005, 2012), and in eastern Heilongjiang (Fig. 1, A, B) (Sha & Fürsich, 1993; Sha, 2002, 2007a; Sha et al., 2002, 2003, 2007, 2008, 2009) and the Tetori re-

gion, including the Makito/Shokawa area (Fig. 1, E) of the Inner Zone, SW Japan (Matsukawa & Ido, 1993; Matsukawa & Nakada, 1999; Fujita, 2003; Matsukawa et al., 2006), there are marine intercalations in the non-marine Early Cretaceous successions, as indicated by the marine fossils they contain (Fig. 3). These facts demonstrate that during the Hauterivian–Albian, the eastern part of the NE China–SE Korea–SW Japan landmass (i.e., the Outer Zone of SW Japan) facing the Palaeo-Pacific was topographically low and mainly occupied by the sea, and that there were some shallow, narrow embayment(s) along the line of the Makito/Shokawa area (Fig. 1, E)–YLPZ areas (Fig. 1, A)–JBM basins (Fig. 1, B)—that were subjected to marine transgressions (Sha, 1990, 2002, 2007; Sha et al., 1994, 2002, 2003, 2009).

The stratigraphic correlation framework for the three regions studied (Fig. 2) has clearly shown: 1) There commonly exists a large gap between? Valanginian/Hauterivian/Barremian and pre-Cretaceous strata, evidence of deposition of Jurassic (even Triassic)–Valanginian mostly being absent (Fig. 2, A, B, E, F) apart from some Tithonian–earliest Valanginian occurrences (Fig. 2, C, D). 2) All the Lower Cretaceous Hauterivian/Barremian (mostly)/Valanginian (?) (sometimes) strata unconformably overlie Triassic–Permian or even older rocks (Fig. 2, A, B, D, E, F), but in the BF basins (Fig. 2, C) the Valanginian probably rests disconformably on pre-Tithonian or older rocks.

Such long-lasting but varying absence of deposition and common unconformable contact relations between overlying and underlying strata (Fig. 2) demonstrate that (1) the NE China–SE Korea–SW Japan landmass was very probably a plateau that rose and fell and was subjected to long-term erosion as a result of orogeny and uplift, mostly before the Hauterivian/Barremian (Fig. 2, A, B, E, F) but probably prior to the Valanginian locally (Fig. 2, C, D). (2) Most of the basins did not develop until the Hauterivian/Barremian (134–126 Ma) (Fig. 2, A, B, E, F) during the peak destruction period (130–120 Ma) of the North China Craton (e.g., Zhu & Zheng, 2009). Although the BF and Gyeongsang basins probably began to develop in the Valanginian, there are unconformities between the

Hauterivian/Barremian and Valanginian (?) in the BF basins (Fig. 2, C) and within the Hauterivian and Barremian in the Gyeongsang Basin (Fig. 2, D), but this does not contradict the conclusion regarding the timing of the major development of the basins.

Furthermore, all of the Cretaceous basins are orientated subparallel to the NE- to NNE-trending fault zones (Fig. 1), and the Early Cretaceous strata are intercalated with volcanic rock beds including lavas and tuffs, which are sometimes fairly thick. This implies that the development of the Cretaceous basins and violent volcanic activity were controlled by the faults (Sha, 2007a), and particularly tectonic movements along the northwestern margin of the Paleo-Pacific and the Tan–Lu fault system, which were associated with frequent and intensive volcanic eruptions and some marine transgressions (Sha et al., 2008).

5 Conclusions

Stratigraphically, mostly Valanginian–Jurassic and even older strata (Fig. 2, A, B, E, F) but sometimes Tithonian–earliest Valanginian and even older deposits (Fig. 2, C, D), are absent from the areas studied. The well-known coal-bearing Longzhaogou and Jixi groups and the Jehol Biota/Fauna-bearing Jehol Group of NE China are all Hauterivian/Barremian–Aptian age, and the overlying Huashan Group and Sunjiawan Formation are Albian. In SE Korea, the Sindong Group and the Hayang Group except for the Jindong Formation are Aptian–Albian, and the Myogog Formation unconformably underlying the Sindong Group is mainly Hauterivian. The Tetori Group in the Makito/Shokawa area of the Inner Zone, and the Monobegawa Group in the Tokushima–Monobe areas of the Outer Zone of SW Japan are both Hauterivian–Albian (Fig. 2).

Biochronologically, *Cuniopsis ki hongii*, *Nakamuranaia leei* (= *Nagdongia leei*), *Koreanaia cheongi* and *Trigonioides (Wakinoa) tetoriensis* are Hauterivian–early Barremian in age. *Viviparus onogoensis*, *Unio ogami goensis*, *Myrene (Mesocorbicula) tetoriensis* and *Tetoria (Tet.) yokoyami* range from Hauterivian to Aptian. *Arguniella cf. quadrata*, *A. cf. ventricosa*, and *Sphaerium (S.) anderssoni* (= *S. (S.) jeholense*), and *Probaicalia vitimensis* and *Pr. gerassi-*

movi range from Hauterivian/Barremian to Aptian. *Nakamuranaia chi ngshanensis* (= *Nagdongia soni*), *Plicatounio (P.) multiplicatus* (= *P. (P.) yooni*), *Sphaerium (S.) coreanicum* and *Micromelania? katoensis* are Aptian–Albian. *Nippononaia sinensis*, *Nip. tetoriensis*, *Nip. ryoseki ana* and *T. (W.) wakinoensis* are good indicators of the Aptian. *T. (T.) quadratus* (= *T. (T.) jaehoi*), *T. (T.) heilongjiangensis*, *P. (P.) naktongensis*, *Unio longus* (= *U. heilongjiangensis*) and *S. (S.) chintaense* (= *S. (S.) yanbianense*) are good indicators of late Aptian–Albian or Albian (Fig. 4).

Palaeogeographically, during the middle and late Early Cretaceous, SW Japan was attached to NE China and SE Korea, and these areas were drained by a single fluvial system. Topographically, however, the eastern part of the NE China–SE Korea–SW Japan landmass, i.e., the Outer Zone of SW Japan facing the Palaeo-Pacific (Fig. 1), was low and mainly occupied by the sea in Hauterivian–Albian times, and there were some shallow and narrow embayment(s) that were subjected to marine transgressions in the areas of Makito/Shokawa (Fig. 1, E) and eastern Heilongjiang (Fig. 2, A, B). Before the Valanginian, and particularly before the Hauterivian/Barremian, the NE China–SE Korea–SW Japan landmass was a plateau that was affected by uplift and subsidence associated with orogeny, which led to widespread and long-lasting erosion (Fig. 2). The non-marine Cretaceous basins, containing violently eruptive volcanic rocks, including lavas and tuffs, oriented subparallel to the NE- to NNE-trending fault zones (Fig. 1), mostly did not develop until the Hauterivian/Barremian, but were possibly initiated a little earlier (during the Valanginian) in some areas (134–126 Ma) (Fig. 2), within the peak time (130–120 Ma) of destruction of the North China Craton (e.g., Zhu & Zhen, 2009). They were controlled by faults (Sha, 2007a) and particularly tectonic movements associated with violent volcanic eruptions and local transgressions along the northwestern margin of the Palaeo-Pacific and along the Tan–Lu fault system (Sha et al., 2008).

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