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Crittendenia (Bivalvia) from the Lower Triassic (Olenekian) Bac Thuy Formation, An Chau Basin, Northern Vietnam

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Abstract. Well preserved molluscan fossils of Olenekian age (Early Triassic) were obtained from the upper part of the Bac Thuy Formation in Lang Son City, northern Vietnam. We report here an ammonoid, *Xenoceltites variocostatus* Brayard and Bucher, and describe two bivalve species, *Crittendenia australasiatica* (Krumbeck) and *Crittendenia langsonensis* sp. nov. *Xenoceltites variocostatus* is a characteristic species of the uppermost Smithian *Anasibirites* ammonoid zone and the earliest Spathian *Tirolites* ammonoid zone. *Crittendenia australasiatica* and *C. langsonensis* may thus be significant diagnostic species suggesting a middle Olenekian age. In addition, these occurrences demonstrate a probable faunal exchange between the eastern Tethys and eastern Panthalassa during the Olenekian, because many species of *Crittendenia* have been reported from Asia and from Panthalassic basins in the United States.

Key words: Bac Thuy Formation, biostratigraphy, *Crittendenia*, Lower Triassic, Northern Vietnam

Introduction

The Lower Triassic Bac Thuy Formation, consisting of carbonate and siliciclastic rocks, is widely distributed in Lang Son Province, northern Vietnam (Figure 1). Its stratigraphy and paleontology have been studied by Vu Khuc *et al*. (1965), Thang (1989), Vu Khuc (1991), Dang and Nguyen K. Q. (2000), and Dang and Nguyen D. H. (2005) in the stratotype area in Bac Thuy, Chi Lang District, Lang Son Province. Limestone in Chi Lang District yields abundant lower Olenekian (Smithian) conodonts and ammonoids (Vu Khuc *et al*., 1965; Thang, 1989; Vu Khuc, 1991), but in our study area in northern Lang Son City, the geological age and paleontological aspects of the Bac Thuy Formation remain largely unexplored.

We collected abundant, well preserved molluscan fossils, including ammonoids, nautiloids, and bivalves, from the Bac Thuy Formation in Lang Son City, including some *Crittendenia* bivalve species, which were abundant in limestone, calcareous nodules, and dark gray shale. The molluscan fossils included some genera and species diagnostic of Olenekian age. Here, we report on the ammonoids from the formation and describe two bivalves, including a new species. We infer the ranges and distributions of these *Crittendenia* species from occurrences of the ammonoids. In addition, we report the modes of fossil occurrence and shell preservation in detail. Finally, we discuss the age of the Bac Thuy Formation in Lang Son City and the age distribution of *Crittendenia*.

Geological setting

The Lower Triassic (Olenekian) Bac Thuy Formation is composed mainly of limestone breccia, limestone, marl, calcareous sandstone, and shale (Figures 2, 3). The formation conformably overlies the Lower Triassic (Induan to Olenekian) Lang Son Formation, which is characterized by siliciclastic storm- and wave-dominated shelf facies (Komatsu and Dang, 2007; Komatsu *et al*., 2008, 2010), and is in turn overlain by volcanic rocks of the Middle Triassic (Anisian) Khon Lang Formation (Dang, 2006).

In the stratotype area, the limestone yields abundant

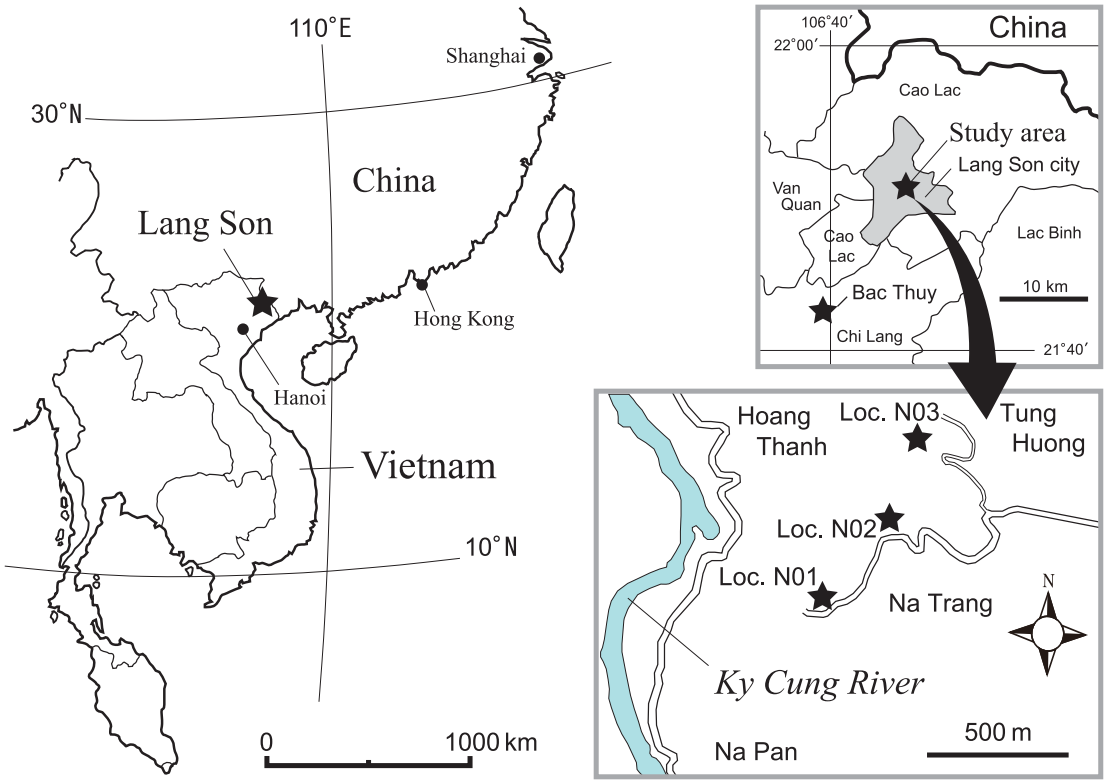


Figure 1. Map showing the study area in Lang Son City, Lang Son Province, northern Vietnam. Fossil localities (N01–03-09; 21°51.27′N, 106°44.21′E) are situated on the western part of Na Trang village.

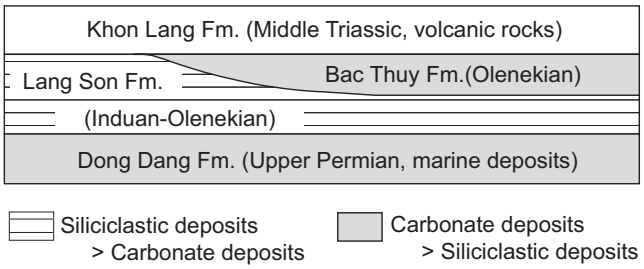


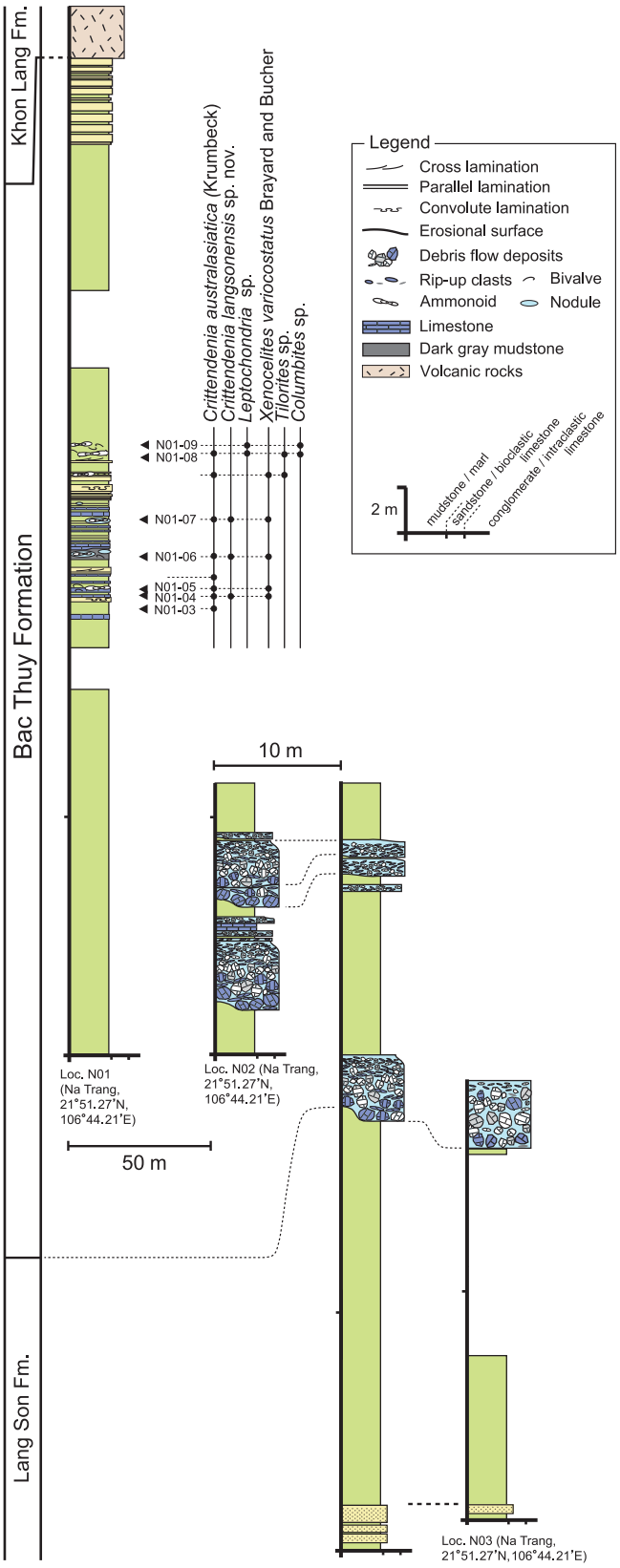
Figure 2. Stratigraphic divisions in the Lower Triassic System in the An Chau Basin, northern Vietnam. The Lang Son Formation is dominated by siliciclastics. The Olenekian Bac Thuy Formation is mainly composed of carbonates andsiliciclastics. Note the top part of the Lang Son Formation is Induan or Olenekian.

early Olenekian (Smithian) ammonoids such as *Flemingites*, *Owenites*, and *Paranorites* (Vu Khuc *et al*., 1965; Vu Khuc, 1991, 2000; Vu Khuc and Dang, 1998; Dang, 2006). Thang (1989) reported Olenekian conodont assemblages characterized by *Neospathodus dieneri*, *N. waageni*, and *N. homeri* from marl and bioclastic limestone also yielding many ammonoids in the stratotype area.

Dang (2006), who studied the geological setting, lithostratigraphic units, and characteristic molluscan fossils of the Bac Thuy Formation in the Lang Son area, reported that the formation is widely distributed there, with a total thickness that sometimes exceeds 185 m, though the thickness of the formation in the stratotype area in Bac Thuy, Chi Lang District, is only about 40 m.

In our study area, Tung Huong and Na Trang villages, northern Lang Son City, the Bac Thuy Formation is about 70 m thick and consists mainly of limestone, marl, and shale. Vu Khuc (2000) and Dang (2006) reported that the upper part of the Bac Thuy Formation in Na Trang village yields the late Olenekian (Spathian) ammonoids *Columbites* cf. *parisianus* and *Tirolites* aff. *armatus*, and the bivalves *Entolium discites microtis* and *Gervillia modiola*. Carbonate lenses (from about 30 m to several hundred meters in width), composed of whitish gray limestone, bedded marl, and thick limestone breccia (about 1–5 m thick) commonly intercalate the formation (Figure 3). The thick limestone breccia contains intraformational tabular limestone pebbles and boulders, limestone blocks, and slump bedding consisting of marl beds.

In the Permian to Triassic Nanpanjiang Basin, which is widely distributed on the South China Block in northern



Vietnam and southern China, several isolated carbonate platform to basin deposits have been reported by Enos *et al*. (1997), Lehrmann *et al*. (2001, 2003), Komatsu *et al*. (2004), and Galfetti *et al*. (2008). Thus, the carbonate facies of the Bac Thuy Formation, which are characterized by limestone breccias, also represent slope and marginal basin facies of isolated carbonate platforms.

Fossil localities and mode of occurrence of molluscan fossils

In the upper part of the Bac Thuy Formation, very fine sandstone, dark gray shale, fossiliferous dark gray limestone, and marl crop out around fossil locality (Loc.) N01 (21°51.27′N, 106°44.21′E), Na Trang village, Lang Son City (Figures 1–3). These fossiliferous carbonates and siliciclastics are covered by shale containing the late Olenekian (Spathian) ammonoids *Columbites* and *Tirolites* (Figure 3). The dark gray shale in the upper part of the formation commonly contains thin, calcareous, very fine sandstone layers, normal and inversely graded structures, and parallel, cross-, and convolute laminations. The shale and sandstone layers and beds yield abundant molluscan fossils and elongated spherical calcareous nodules (5–60 cm in length). Some of these calcareous nodules also contain well preserved molluscan fossils. The dark gray limestone also commonly yields bivalves and ammonoids, which may occur as minor shell concentrations or sporadically. Thin concentrations of mainly ammonoid and bivalve shells are commonly embedded in the limestone, calcareous nodules, and host shale rocks (Figures 4–8).

The minor shell concentrations are characteristically matrix-supported or shell-supported, and at localities N01–03-07 (Figures 3–6) in the upper part of the formation they are composed mainly of abundant shells of *Xenoceltites variocostatus* Brayard and Bucher (ammonoid), and *Crittendenia australasiatica* (Krumbeck) and *Crittendenia langsonensis* sp. nov. (bivalves), or of shell fragments. In the calcareous nodules, the remains of these molluscs are preserved as undeformed shells (3D-shells, Figures 6, 7A), and most phragmocone chambers inside the ammonoid shells are not crushed. Very thin and fragile convex bivalve shells are also well preserved. It is likely that these shells were preserved in the concretions during an early diagenetic stage and that compaction was prevented by the formation of the concretion (Briggs, 1990).

On the contrary, in the shale, convex shell remains and

Figure 3. Columnar sections showing occurrence of molluscan fossils in Tung Huong and Na Trang villages, Lang Son City, northern Vietnam. Bivalves and ammonoids are abundantly found at Locs. N01–03-09. See Figure 1 for localities.

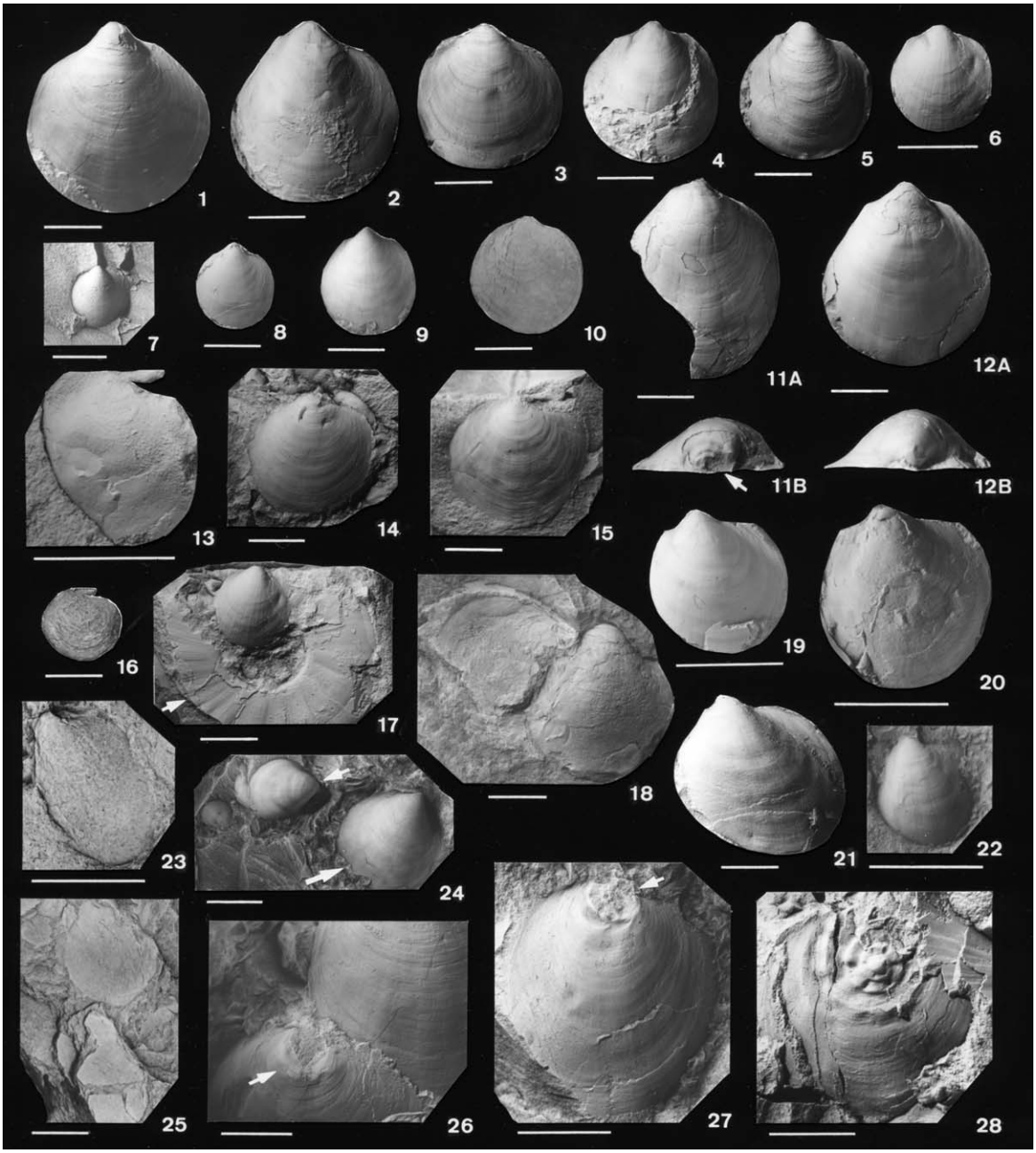


Figure 4. Molluscan fossils from the upper part of the Bac Thuy Formation, in Na Trang village, Lang Son City. **1–16**, *Crittendenia australasiatica* (Krumbeck). 1, left valve, KMSP-5100; 2, left valve, KMSP-5101; 3, left valve, KMSP-5102; 4, left valve, KMSP-5103; 5, left valve, KMSP-5104; 6, left valve, KMSP-5105; 7, left valve, KMSP-5106; 8, left valve, KMSP-5107; 9, left valve, KMSP-5108; 10, deformed left valve, KMSP-5109; 11, left valve, KMSP-5110; 11A, external view; 11B, dorsal view, umbonal area showing imprint of ammonoid (*Xenoceltites variocostatus* Brayard and Bucher) umbilicus (arrow); 12, left valve, KMSP-5111; 12A, external view; 12B, dorsal view; 13, internal cast of right valve, showing byssal notch and anterior auricle, KMSP-5112; 14, right valve, KMSP-5113; 15, right valve, KMSP-5114; 16, right valve KMSP-5115; **17**, ammonoid *Xenoceltites variocostatus* Brayard and Bucher (arrow) and *Crittendenia australasiatica* (Krumbeck), KMSP-5105; **18**, *Crittendenia australasiatica* (Krumbeck), right and left valves, showing anterior auricle, KMSP-5116; **19–23**, *Crittendenia langsonensis* sp. nov. 19, left valve, KMSP-5117 (paratype); 20, left valve, KMSP-5118 (paratype); 21, left valve, KMSP-5119 (holotype); 22, left valve, KMSP-5120 (paratype); 23, deformed left valve, showing obtuse anterior auricle, KMSP-5121; **24**, *Crittendenia langsonensis* sp. nov. (small arrow), KMSP-5125 and *Crittendenia australasiatica* (Krumbeck) (large arrow), KMSP-5108; **25**, shell concentrations composed of poorly preserved *Crittendenia* in mudstone, KMSP-5125; **26–28**, *Crittendenia australasiatica* (Krumbeck); 26, irregular attachment cicatrix on right valve (arrow), KMSP-5122; 27, umbonal area showing imprint of ammonoid umbilicus on right valve (arrow), KMSP-5123; 28, imprint of ammonoid (*Xenoceltites variocostatus* Brayard and Bucher) umbilicus below byssal notch of right valve, KMSP-5124. Scale bars indicate 1 cm.

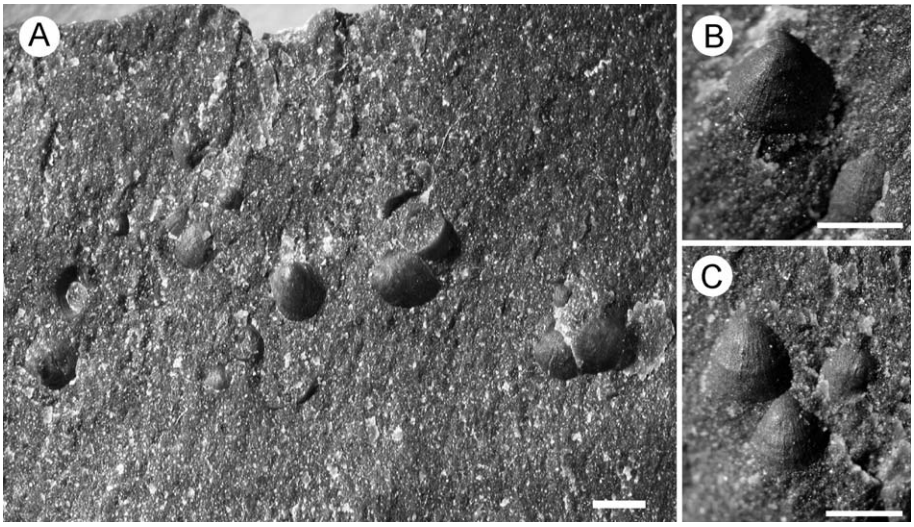


Figure 5. Juveniles of *Crittendenia australasiatica* (Krumbeck) from the upper part of the Bac Thuy Formation (Loc. N01-05). **A**, modes of occurrence; **B**, **C**, juvenile shells ornamented by clear radial thread. Scale bars represent 1 mm.

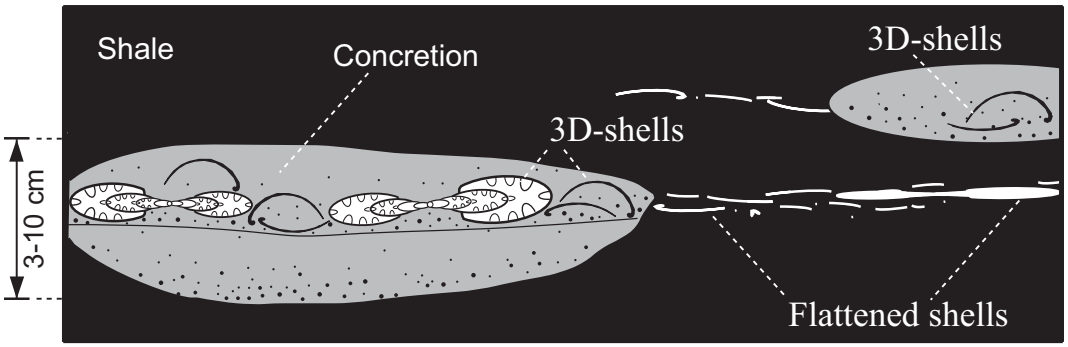


Figure 6. Schematic sketch of modes of fossil occurrence. Molluscan fossils are found abundantly in nodules and host shale. In the host shale, bivalves and ammonoids are completely flattened. Three-dimensional well preserved molluscs are obtained from calcareous nodules.

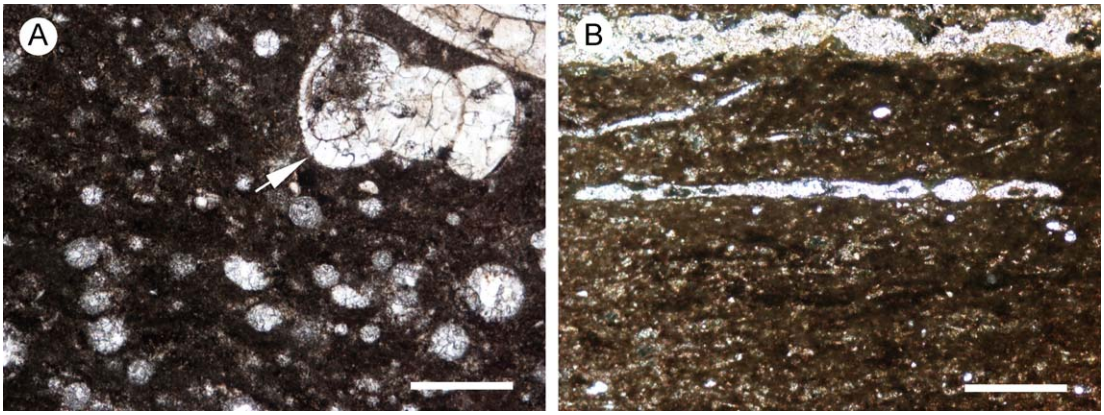


Figure 7. Photomicrographs of molluscan fossils in calcareous nodule (A) and shale (B) from the upper part of the Bac Thuy Formation (Loc. N01-06). **A**, well preserved juvenile ammonoid (arrow); **B**, flattened shells of molluscan fossils such as ammonoids and bivalves. Scale bars represent 0.5 mm.

faint ornamentations have been completely flattened by compaction and diagenetic processes (Figures 6, 7B), leaving only shell impressions. The surfaces of flattened shells commonly show secondary irregular, faint zigzag and branched lines (Figures 4.10, 4.16, 4.23, 4.25). These secondary characteristics may be due to cracks caused by the shells being crushed by the sediment overburden during the postmortem stage. Very similar cracks on the surfaces of paper shells such as *Claraia* and *Posidonia* can occasionally be seen in many previously published photographs of fossils (plates in Hsu, 1937; Li and Ding, 1981; Yin, 1985; Tong *et al*., 2006; Komatsu *et al*., 2006; He *et al*., 2007).

It is difficult to identify the flattened specimens from the shale. Unfortunately, in the Bac Thuy Formation, flattened bivalve shells of the orthogyrous species *Crittendenia australasiatica* appear quite similar to shells of some species of *Claraia* and *Posidonia* (e.g. *Posidonia circularis* Hsu, 1937) (Figure 4.10, 4.16), and a flattened left valve of the prosogyrous species *Crittendenia langsonensis* sp. nov. (Figure 4.23) resembles the shells of some species of *Guichiella* (Li and Ding, 1981, pl. 1, figs. 10, 25, 26) and pteriform shells.

Systematic paleontology

(by T. Komatsu and H. T. Dang)

Abbreviation of repository.—KMSP: Faculty of Science, Kumamoto University.

Order Pterioida Newell, 1965
Superfamily Pterinopectinacea, Newell, 1938
Family Pterinopectinidae, Newell, 1938
Subfamily Claraiinae Gavrilova, 1996
Genus *Crittendenia* Newell and Boyd, 1995

Type species.—*Crittendenia kummeli* Newell and Boyd, 1995

Remarks.—Holotype of the type species is a well preserved left valve collected from the Thaynes Formation at Crittenden Spring, near Long Canyon, northeastern Nevada, USA (Newell and Boyd, 1995). *Bittnericlaraia*, described by Gavrilova (1996), is a junior synonym of *Crittendenia* Newell and Boyd (1995) (Waterhouse, 2000). Waterhouse (2000) redid the diagnosis of *Crittendenia* and described some new species from Asia. The nature of the hinge and ligament areas is poorly known.

Crittendenia australasiatica (Krumbeck), 1924

Figures 4.1-4.18, 4.24, 4.26-4.28

Pseudomonotis australasiatica Krumbeck, 1924, pl. 8, figs. 8-10.
Pseudomonotis subconvexa Krumbeck, 1924, pl. 8, fig. 12a, b.

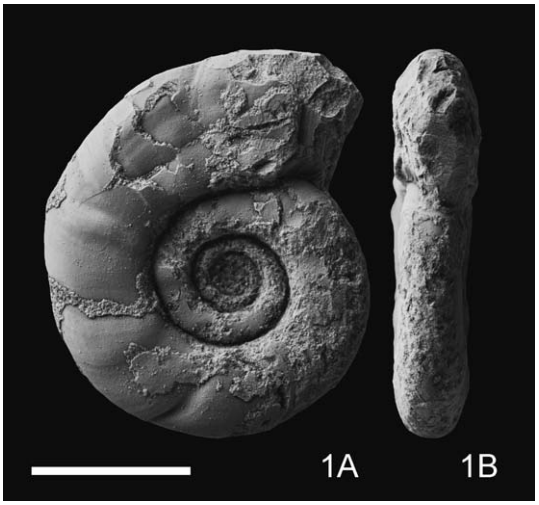


Figure 8. *Xenoceltites variocostatus* Brayard and Bucher, 2008, from the upper part of the Bac Thuy Formation (Loc. N01). **1A**, Lateral view; **1B**, apertural view. Scale bar represents 1 cm.

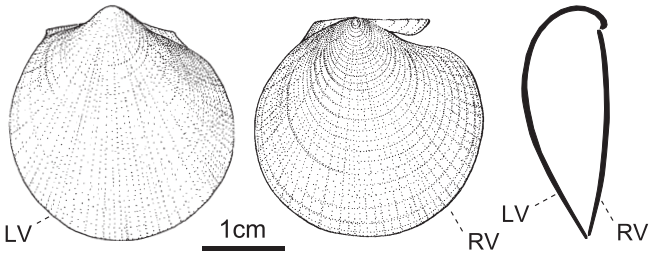


Figure 9. Sketch of *Crittendenia australasiatica* (Krumbeck). Abbreviations: LV, left valve; RV, right valve.

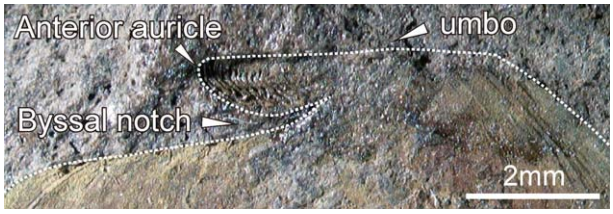


Figure 10. *Crittendenia langsonensis* sp. nov. Details of anterior auricle and byssal notch of external mould of right valve.

Materials.—Abundant well preserved left valves and several right valves obtained from calcareous nodules and limestone beds (KMSP5100-5115, 5122-5124). Overlapping solitary right and left valves found in a calcareous nodule (KMSP5116; Figure 4.18). Almost all specimens from the shale poorly preserved and completely flattened (KMSP5109, 5121; Figures 4.10, 4.25).

Description.—Shell moderate in size for genus,

inequivalve, orbicular or suborbicular in outline, length and height of shells subequal or slightly higher than length; test very thin; hinge line straight and moderately long for genus; strongly convex left valve, orthocline, anterior wing small without sinus, posterior wing also small and indistinguishable, ventral margins rounded, umbo protruded above hinge line, situated mostly central, umbonal angle about 90–120°, shell surface of left valve moderately smooth except for very weak concentric growth lines, irregularly faint radial threads, and ribs occasionally showing growth stops; slightly inflated right valve ornamented with irregular, very weak radial threads and growth lines, posterior wing not differentiated, anterior auricle small size for genus, surface of auricle smooth, narrow and moderately deep byssal notch conspicuous; dorsal area of right valve and umbonal area of left valve occasionally imprinted by the reflecting substrate, for example, an ammonoid umbilicus.

Discussion.—*C. australasiatica* from Timor is a typical orthocline species, and is ornamented by irregularly faint radial threads and ribs on both valves, though Krumbeck (1924) described and illustrated only left valves of this species. Juvenile shell surfaces are also ornamented with clear radial ribs and threads (Figure 5). Almost all species of *Crittendenia* are characterized by concentric growth lines or a smooth surface, and a few species with radial ornamentation are reported (Gavrilova, 1996; Waterhouse, 2000). The orthocline species *Crittendenia punjabiensis* (Wittenburg, 1909) from the Salt Range, Pakistan, *Crittendenia kummeli* Newell and Boyd, 1995, and *Crittendenia alta* Waterhouse, 2000 (=*Claraia decidens* of Nakazawa, 1977, 1981), are ornamented with only faint growth lines. In addition, *C. alta* is characterized by a moderately convex left valve, and *C. kummeli* shows a deep and very wide byssal notch on the right valve, different from *C. australasiatica*.

Crittendenia painkhandana (Bittner, 1899) from the western Himalaya and *Crittendenia nammalensis* Nakazawa, 1996 from the Mittiwali Formation, Salt Range, Pakistan, which are characterized by a prosogyrous umbo, are clearly distinguished from *C. australasiatica*. *Crittendenia decidens* (Bittner, 1899) (=*Claraia* (*Bittnericlaraia*) *decidens* of Gavrilova, 1996) is a prosocline to orthocline species with no radials, showing in addition a strongly prominent umbo, and thus is readily distinguished from *C. australasiatica*. *Crittendenia langpoensis* Waterhouse, 2000 from the Gungdang Formation in Nepal Himalaya is characterized by irregular concentric ribs and weakly prosocline or orthocline left valves.

In addition, *C. australasiatica* shows an important diagnostic character for the genus. Small attachment imprints are clearly marked on the umbonal area of the left valve and near the byssal notch of the right valve (Figures 4.11, 4.26–4.28). Some of the attachment imprints are coiled impressions of an ammonoid umbilicus, characterized by the conspicuous sinuous and prorsiradiate ribs of the juvenile stage of *Xenoceltites variocostatus*, which co-occurs with *C. australasiatica* (Figures 4.11B, 4.27–4.28). *Crittendenia* is interpreted as attached by the byssus to some hard object (e.g. rocks or shell remains), and apparently not cemented to the substrate. Probably its extremely thin shell at the early stage is easily impressed by a hard substrate. Recent byssate species of Mytilidae commonly inhabit hard substrates, specifically small depressions on rocks near a coastline (Cox, 1969), and recent shells of these epifaunal species are occasionally impressed clearly by substrate. *Crittendenia* seems to have lived in dense clumps attached by byssal threads in minor depressions on hard substrates such as the ammonoid umbilicus. Newell and Boyd (1995) described a *Crittendenia kummeli* specimen characterized by a coiled negative impression of an ammonoid umbilicus. In addition, they reported that some individuals of this species had been pseudoplanktonic, anchored tightly by the byssus to floating objects, while others were pseudopelagic on ammonoids.

Table 1. Measurements of *Crittendenia australasiatica* (Krumbeck).

Specimen	Length	Height	Thickness	Valve
KMSP5100	33.1 mm	34.4 mm	11.8 mm	Left
KMSP5101	28.9 mm	31.2 mm	8.8 mm	Left
KMSP5102	26.1 mm	26.2 mm	8.5 mm	Left
KMSP5111	29.1 mm	32.0 mm	9.5 mm	Left
KMSP5113	22.4 mm	20.7 mm	3.7 mm	Right
KMSP5114	23.6 mm	22.1 mm	4.4 mm	Right

Occurrence.—*Crittendenia australasiatica* co-occurs with *C. langsonensis* sp. nov., *Leptochondria* sp., a late Smithian to an early Spathian ammonoid, *Xenoceltites variocostatus*, and the early Spathian ammonoids *Tirolites* sp. and *Columbites* sp. (Figure 3) from the upper part of the Bac Thuy Formation (Loc. N01).

Dimensions (in mm).—Table 1.

Crittendenia langsonensis sp. nov.

Figures 4.19–4.24, 10

Types.—Holotype, KMSP-5119; paratypes, KMSP-5117, 5118, 5120.

Type locality, horizon, and age.—Loc. N01, upper part of the Bac Thuy Formation, Olenekian (upper Smithian).

Etymology.—From Lang Son, city name at the type locality.

Table 2. Measurements of *Crittendenia langsonensis* sp. nov.

Specimen	Length	Height	Thickness	Valve
KMSP5119(Holotype)	27.5 mm^{+}	28.6 mm	7.8 mm	Left
KMSP5117(Paratype)	12.7 mm	13.5 mm	5.0 mm	Left
KMSP5120(Paratype)	8.9 mm	9.6 mm	3.5 mm	Left

Diagnosis.—Shell length slightly shorter than shell height; shell suborbicular in shape; shell surface moderately smooth except for weak radial threads and fine concentric growth lines; inflated, strongly prosogyrous shells, left anterior part forming a small distinguishable wing, umbo situated about 1/3–2/5 of the distance from the anterior margin; right valve moderately inflated, spatulate anterior auricle small size for genus, deep and narrow byssal notch.

Description.—Shells of average size for genus, inequivalve and inequilateral, prosocline, suborbicular in outline, slightly longer than high; test very thin; surface ornamented with growth lines and occasional irregularly faint radial threads representing growth stops; hinge line moderately long and straight; left valve inflated, strongly prosogyrous umbo protruded above hinge line, situated about 1/3–2/5 of the way from the anterior margin, umbonal angle about 95–105°; obtuse anterior left wing very small without sinus; posterior left wing inconspicuous, ventral margins rounded; right valve gently convex, unprotruded umbo; right spatulate small anterior auricle ornamented by fine clear ribs parallel to the anterior auricle end, byssal sinus; hinge unknown.

Discussion.—*Crittendenia langsonensis* sp. nov. is characterized as a prosocline species, and is ornamented with faint radial threads on the left valve. The typical orthocline species *C. punjabiensis, C. alta*, *C. kummeli*, and *C. australasiatica* are clearly distinguished from the present new species. Although *C. painkhandana* and *C. nammalensis* are typical prosocline species, the former is characterized by a strongly prominent umbo, and the latter has a more laterally elongate outline than *Crittendenia langsonensis* sp. nov. The umbonal area of *C. langpoensis* is much less prosocline than that of *C. langsonensis* sp. nov. In addition, the left valve of *C. langpoensis* is ornamented only by irregularly spaced, low concentric ribs. *C. decidens* (Bittner, 1899) shows a prominent umbo and no radial ornamentations and is thus readily distinguished from *C. langsonensis* sp. nov.

Dimensions (in mm).—Table 2.

Geologic age of the Bac Thuy Formation

The geologic age of the Bac Thuy Formation in the Lang Son area is determined by the occurrence of the ammonoids *Xenoceltites variocostatus, Tirolites* sp., and *Columbites* sp. *Xenoceltites variocostatus* is a significant age-diagnostic species, and was reported from the Luolou Formation, consisting mainly of outer platform facies, Guangxi, southern China (Brayard and Bucher, 2008). According to Brayard and Bucher (2008), this ammonoid species is characteristically found in the top part of the Smithian ammonoid zone in southern China. Specifically, *X. variocostatus* is abundant in the upper part of the *Anasibirites multiformis* beds.

In the stratotype area in Chi Lang, the Bac Thuy Formation is subdivided into lower and upper parts. The lower part is about 4 m thick and consists mainly of fossiliferous limestone containing many ammonoids, marl, and thin shale. The upper part of the formation is about 35 m thick and is predominantly composed of shale. The ammonoid assemblage from the limestone is composed mainly of several species of *Owenites* (Vu Khuc *et al*., 1965; Vu Khuc, 1991). According to Balini *et al*. (2010) and Brühwiler *et al*. (2012), an *Anasibirites* zone generally overlies the *Owenites* ammonoid zone. In southern China, the *Owenites koeneni* beds are older than the latest Smithian *Anasibirites multiformis* beds containing *X. variocostatus* (Brayard and Bucher, 2008).

In the Na Trang area, the top part of the Bac Thuy Formation commonly yields the ammonoids *Tirolites* sp. and *Columbites* sp., and rarely *X. variocostatus* from mudstone (Figure 3). Dang (2006) also reported *Columbites* cf. *parisianus* and *Tirolites* aff. *armatus* in the Na Trang area. The mudstones overlie dark gray carbonate and mudstone containing abundant *X. variocostatus* (Locs. N01–01-07). The ammonoids *Tirolites* and *Columbites* are critical indicators of the early Spathian (Balini *et al*., 2010). Therefore, in our study area, the Bac Thuy Formation includes at least the uppermost Smithian to lowermost Spathian ammonoid zones, and is composed mainly of strata younger than those in the formation's type section.

Range and distribution of *Crittendenia*

Most species of *Crittendenia* are commonly found in Olenekian marine deposits (Gavrilova, 1996; Waterhouse, 2000), though exceptionally *Pseudomonotis painkhandana* Bittner (= *Crittendenia painkhandana*) is described as coming from the Lower Induan "dark *Otoceras* beds" in Shalshal, western Himalaya (Bittner, 1899) and from the *Gyronites frequens* ammonoid zone of the Khangsar Formation, Manang, Nepal (Waterhouse, 2000). Olenekian to Anisian *Crittendenia langpoensis* is reported from the Langpo Member of the Gungdang Formation and from the *Paracrochordiceras anodosum* ammonoid zone, which is indicative of the lower Anisian, of the Phukung

Member, Manang, Nepal Himalaya (Waterhouse, 1996, 2000).

Crittendenia punjabiensis (Wittenburg, 1909) is commonly reported in Asia (Wittenburg, 1909; Waterhouse, 2000). Wittenburg (1909) described the species as *Pseudomonotis punjabiensis* from the "*Stephanites superbus* ammonoid zone" in Chhidru Nala, Salt Range, Pakistan. *Stephanites superbus* was obtained from the upper part (= Unit 4 of Pakistani-Japanese Research Group, 1985; Nakazawa, 1996) of the Mittiwali Member (Waterhouse, 2000). Unit 4 is composed of the *Meekoceras gracilitatus* and *Anasibirites pluriformis* ammonite zones, indicating the middle to upper Smithian (Nakazawa, 1996). Waterhouse (2000) reported *Crittendenia punjabiensis* from the Kone Member of the Gungdang Formation in Manang, Nepal, and from the Sungjar Formation in Dolpo, Nepal. In the Nepal Himalaya, *Crittendenia punjabiensis* occurs in the *Eophyllites giganteus* ammonoid zone, deemed to be Olenekian (Smithian?–Spathian) in age (Waterhouse, 1996, 2000).

Nakazawa (1977, 1981) reported *Claraia decidens* Bittner (= *Crittendenia decidens*) from the lower part (Bed 88) of Member H of the Khunamuh Formation, Guryul Ravine, Kashmir, India. Some specimens of *Crittendenia decidens* reported by Nakazawa (1977, 1981) were redescribed as *Crittendenia alta* Waterhouse by Waterhouse (2000). However, many specimens of *Crittendenia* collected by Nakazawa are stored in the Kyoto University Museum, and the registered shell concentration contains typical *Crittendenia decidens*. These species of *Crittendenia* come from the *Owenites-Kashmirites* ammonoid zone, indicating middle Smithian, in Kashmir.

Crittendenia nammalensis (Nakazawa), is found in the *Tirolites-Columbites* ammonoid zone of Unit 5 of the Mittiwali Formation. Waterhouse (2000) reported *Crittendenia nammalensis* and *Crittendenia langpoensis* from the *Keyserlingites costatus* ammonoid zone of the Gungdang Formation in Manang, Nepal. The *Keyserlingites costatus* ammonoid zone may correspond to the top of the Olenekian (Waterhouse, 1999) Recently, strongly prosocline *Crittendenia nammalensis* was treated as a synonym of *Eobuchia punjabensis* (Wittenburg) reported from the Spathian of the Nammal and Landu sections in the northern part of Pakistan (Wasmer *et al*., 2012), although the type species (= *Pseudomonotis punjabiensis* Wittenburg, 1909 = *Crittendenia punjabiensis* of Waterhouse, 2000) of *Eobuchia* is characterized by a typical orthocline shell.

In our study area, the latest Smithian to earliest Spathian ammonoid *X. variocostatus* co-occurs with *Crittendenia australasiatica* and *Crittendenia langsonensis* sp. nov. In addition, *Crittendenia australasiatica* is commonly associated with the earliest Spathian ammonoids *Tirolites* and *Columbites*. In our preliminary work at the Bac Thuy stratotype area, these species of *Crittendenia* are never found in the limestone containing abundant *Owenites koeneni*, which is assigned to the middle Smithian *Owenites* ammonoid zone (Komatsu *et al*., 2011). *Crittendenia* is absent from the Lower Triassic (Induan) and Middle Triassic bivalve assemblages in northern Vietnam (Vu Khuc, 1991, 2000; Dang, 2006; Komatsu *et al*., 2006, 2008, 2010; Komatsu and Dang, 2007).

Crittendenia is also reported from Panthalassic basins in the United States. *Crittendenia kummeli* Newell and Boyd occurs in the *Meekoceras* ammonoid zone (= *Meekoceras gracilitatis* Zone of Kummel and Steele, 1962; Jenks, 2007) of the Thaynes Formation at Crittenden Spring, near Long Canyon, northeastern Nevada (Newell and Boyd, 1995). The upper *Meekoceras gracilitatis* Zone is equivalent to the *Owenites* zone, which is indicative of the middle part of the Smithian (Balini *et al*., 2010).

Posenato *et al*. (2009) suggested that *Crittendenia* is absent from the Olenekian in the European Tethys. Therefore, the genus is found in the Lower Triassic Induan to Middle Triassic Anisian marine deposits in the eastern part of Tethys and in the Olenekian Panthalassa, although almost all species of *Crittendenia* have been reported from the Olenekian. These occurrences further demonstrate a probable faunal exchange between the eastern Tethys and the eastern Panthalassa during the Olenekian.

Conclusions

We have in the foregoing described two bivalve species, *Crittendenia australasiatica* and *Crittendenia langsonensis* sp. nov., and reported the occurrence of a late Smithian to early Spathian ammonoid *Xenoceltites variocostatus* from the upper part of the Bac Thuy Formation in the Lang Son area, northern Vietnam. This ammonoid and these bivalves are probably important as middle Olenekian age-diagnostic species.

Where the Bac Thuy Formation crops out along the Ky Cung River in the Lang Son area, it is much thicker than the type section of the formation (Dang, 2006). In a preliminary investigation of the formation along the Ky Cung River and in the type area, we have already found many conodonts, radiolarians, and bivalves, including *Crittendenia* and Smithian to Spathian ammonoids (Komatsu *et al*., 2011). These well preserved fossils and successive stratigraphic data will contribute significantly to our understanding of the biostratigraphy and paleobiogeography of the far eastern Tethys where it connects to the Panthalassic Ocean.

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