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OLENEKIAN (EARLY TRIASSIC) STRATIGRAPHY AND FOSSIL ASSEMBLAGES IN NORTHEASTERN VIETNAM

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Abstract

Reported herein are extensive data resulting from a through investigation of the stratigraphy and paleontology of the Olenekian Bac Thuy Formation (Lower Triassic) in Lang Son City and the surrounding Chi Lang District of northeastern Vietnam. The Bac Thuy Formation conformably overlies the siliciclastic sandstone and mudstone of the Induan to Olenekian Lang Son Formation (Lower Triassic) and is unconformably overlain by rhyolitic rocks of the Middle Triassic Khon Lang Formation. Commonly divided into three parts, the Bac Thuy Formation consists of a lower part comprised mainly of limestone and mudstone, a middle part characterized by organic-rich dark gray limestone and an upper part composed of thick mudstone, sandstone and limestone. Its depositional environment consists of tidal flat, wave-influenced carbonate platform, and slope and marginal basin plain deposits. The intervals of organic-rich dark gray limestone and mudstone intercalated in the succession of slope to marginal basin plane facies are characterized by monospecific fossil and ichno-fossil assemblages, which suggest anoxic to dysoxic conditions.

The Bac Thuy Formation is very fossiliferous. Various types of fossils, e.g. cephalopods, gastropods, bivalves and conodonts, are abundant throughout the sequence, whereas ostracods and radiolarians are present only in the middle part. Five distinct ammonoid faunas, the *Flemingites rursiradiatus* beds, *Urdyceras tulongensis* beds, *Owenites koeneni* beds, *Xenoceltites variocostatus* beds, *Tirolites* cf. *cassianus* beds and *Tirolites* sp. nov. beds, as well as three conodont zones, *Novispathodus* ex gr. *waageni* Zone, *Novispathodus pingdingshanensis* Zone and *Triassospathodus symmetricus* Zone are recognized in ascending order. Based on these ammonoid and conodont occurrences, the formation ranges in age from Middle Smithian (middle Early Olenekian) to Early Spathian (early Late Olenekian), and the Smithian/Spathian boundary occurs in the organic-rich dark gray mudstone in the middle part of the formation. Radiometric ages of zircons reveal that the age of the rhyolite in the basal part of the overlying Khon Lang Formation is 237.7±1.9 Ma, which infers a latest Ladinian to earliest Carnian age.

Ammonoid faunas exhibit a very strong relationship with other Tethyan faunas, but show a relatively weak relationship with faunas on opposite sides of the Panthalassa. In contrast, Lower Spathian bivalve occurrences demonstrate probable faunal exchanges between the Tethys and Panthalassa. The gastropod fauna is characterized only by larvae or early juveniles of taxa displaying a mostly planktotrophic type of development, which indicates an unfavourable benthic environment for gastropods. The radiolarian fauna dominated by entactinarians from the Upper Smithian includes a mixture of Paleozoic and Triassic types.

The ammonoid mode of occurrence suggests that while the supratidal to intertidal environment was uninhabitable, the majority of ammonoids probably lived in the subtidal flat to storm-wave-influenced shallow marine environment typical of a carbonate platform. After death their shells were transported from their biotope to the slope to marginal basin plane by gravity flow. Almost all bivalve species were also transported more or less from their original habitats to offshore environments. However, epifaunal *Crittendenia* and *Positra* probably inhabited the hemipelagic deposits of the slope and marginal basin plane environments, judging from their mode of fossil occurrence and shell preservation.

The limestone in the lower part of the Bac Thuy Formation contains many larval and/or juvenile shells of gastropods, whose external ornamentation is exceptionally well preserved. Acid treatment of this same limestone also produced many small ammonoid specimens free of obscuring matrix, thus permitting observation of the unique three-dimensional geometry of their internal features.

One hundred nineteen taxa (cephalopods: 42, gastropods: 8, bivalves: 5, conodonts: 46, ostracods: 6, radiorarians: 12) including seven new species (ammonoid: *Gaudemandites langsonensis*; radiolarians: *Multisphaera triassorobusta*, *Retentactinia*? *kycungensis*, *R.*? *parvisphaera*, *Plenoentactinia*? *terespongia*, *Paroertlispongus spinorientalis*, ostracoda: *Paracypris vietnamensis*) are described.

Key words: Ammonoids, Bac Thuy Formation, biostratigraphy, conodonts, Lower Triassic, northeastern Vietnam, Olenekian, Smithian, Spathian, stratigraphy

ベトナム北東部のオレネキアン階（下部三畳系）層序と化石群（重田康成・小松俊文・前川匠・Huyen Dang Tran 編）

ベトナム北東部のランソン市とチーラン地域周辺に分布するオレネキアン階（下部三畳系）バクトゥイ層について，層序学的研究と古生物学的研究を通して得られた様々な結果を報告する．バクトゥイ層は，インドゥアン階～オレネキアン階の珪砕屑性岩類（砂岩や泥岩）より成るランソン層に整合で重なり，中部三畳系コンラン層の流紋岩類に不整合で覆われる．バクトゥイ層は，主に石灰岩や泥岩によって形成される下部，有機物に富む暗灰色の石灰岩や泥岩で特徴づけられる中部，厚い泥岩，砂岩，石灰岩より成る上部に分けられ，干潟，波浪が卓越する炭酸塩プラットフォームの浅海相，陸棚斜面，海盆縁辺の堆積環境から成る．陸棚斜面相から海盆縁辺相に見られる有機物に富む暗灰色の石灰岩や泥岩は，単調な化石群や生痕化石群で特徴づけられ，無酸素から貧酸素の環境を示す．

バクトゥイ層からは，様々な化石が産出する．頭足類，巻貝類，二枚貝類，コノドント類は，全層準を通して豊富に産出するが，貝形虫類や放散虫類は中部のみから産出する．アンモノイド化石層は，下位から *Flemingites rursiradiatus* 層，*Urdyceras tulongensis* 層，*Owenites koeneni* 層，*Xenoceltites variocostatus* 層，*Tirolites* cf. *cassianus* 層，*Tirolites* sp. nov. 層の 5 層が認められた．またコノドント化石帯は，下位から *Novispathodus* ex gr. *waageni* 帯，*Novispathodus pingdingshanensis* 帯，*Triassospathodus symmetricus* 帯の 3 帯が認められた．これらの化石に基づくと，バクトゥイ層の年代は，スミシアン中期（オレネキアン前期の中頃）～スパシアン前期（オレネキアン後期の前半）で，スミシアン／スパシアン境界はバクトゥイ層中部の有機物に富む暗灰色泥岩中に位置する．コンラン層最下部の流紋岩中のジルコンの放射年代は，237.7 ± 1.9 Ma であり，ラディニアン末期あるいはカーニアン最初期を示す．

バクトゥイ層のアンモノイド化石群は，他のテチス域の化石群と強い関連性を示すが，パンサラッサ海両岸の化石群とは比較的関係性が弱い．一方，スパシアン階下部の二枚貝化石は，テチス域とパンサラッサ域の間での動物群の交流を示す．巻貝化石は，プランクトン栄養型の浮遊幼生あるいは稚貝のみが産出するが，これは海底が巻貝類には好ましくない環境であったことを意味する。スミシアン階上部の放散虫化石群は，Entactinaria 目が優占し，古生代型と三畳紀型の種群が混在する．

アンモノイド化石の産状から，潮上帯～潮間帯は，生息に不適な環境であり，アンモノイドの大部分は潮下帯～暴風時に波浪の影響を受ける浅海の炭酸塩プラットフォームに生息していたと考えられる．バクトゥイ層のアンモノイドの多くは，死後，その殻が重力流により生息域から陸棚斜面や海盆縁辺に運搬されたものである．二枚貝類の多くも生息域から沖合環境へ殻が運搬されたと考えられるが，産状や殻の保存状態から判断して，表在性の *Crittendenia* や *Bositra* は陸棚斜面や海盆縁辺で生息していたと思われる．

バクトゥイ層下部の石灰岩には，表面装飾が例外的に保存良好な巻貝類の幼生や稚貝の殻が多数含まれている．また，酸処理により殻内部の充填物が除去され内部形態の三次元構造が観察可能となった多数の微小なアンモノイド化石を得ることができる．

本論文では，7 新種（アンモノイド類：*Gaudemandites langsonensis*，放散虫類：*Multisphaera triassorobusta*, *Retentactinia*? *kycungensis*, *R*.? *parvisphaera*, *Plenoentactinia*? *terespongia*, *Paroertlispongus spinorientalis*，貝形虫類：*Paracypris vietnamensis*）を含む 119 分類群（アンモノイド類：42，巻貝類：8，二枚貝類：5，コノドント類：46，貝形類：6，放散虫類：12）を記載した．

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小松俊文・Huu Nguyen Dinh・Phong Nguyen Duc・Alexander Nützel・
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Introduction

(by Y. Shigeta, T. Komatsu, H. T. Dang, T. Maekawa, O. Takahashi, G. Tanaka and Y. Tsutsumi)

Lower Triassic marine deposits, widely distributed in northeastern Vietnam, have attracted the attention of many scientists beginning with the early work of pioneering French geologists and paleontologists. During the early twentieth century, Jean-Baptiste-Henri Counillon (1860–1923) and Henri Mansuy (1857–1937) collected various types of Lower Triassic molluscan fossils in Lang Son Province, and Mansuy (1908) is credited with being the first worker to describe ammonoids from the area. Furthermore, the 1908 work of Mansuy represents the first description of Triassic ammonoids from the country of Vietnam. Then in 1940, Professor Josué Heilmann Hoffet (1901–1945), while working at the University of Indochina, (established in 1906, now the Vietnam National University, Hanoi), collected ammonoids from limestone beds, approximately 24 km southeast of Lang Son City.

During the late twentieth century, Vietnamese paleontologists began investigating the Lower Triassic outcrops in Lang Son Province and eventually described the ammonoids, bivalves and conodonts they collected. In 1977, Nguyen Dinh Huu described several important age diagnostic Olenekian ammonoids from the Na Trang area, near Lang Son City. Then, in 1980 Vu Khuc erected the Bac Thuy Formation for the numerous carbonate beds in Lang Son Province and later he also described several Olenekian ammonoids from the Bac Thuy and Na Trang areas (Vu Khuc, 1984, 1991). During the period from 1988 to 2005, Dr. Dang Tran Huyen and Nguyen Dinh Huu conducted an extensive study of the paleontology and stratigraphy of the formation (Dang and Nguyen K. Q., 2000; Dang and Nguyen, D. H., 2005; Dang, 2006). Dr. Bui Duc Thang studied conodonts from the formation and reported typical Smithian (= Early Olenekian) conodont assemblages (Bui, 1989). Taken together, these studies reveal that the Lower Triassic of northeastern Vietnam yields numerous well-preserved fossils from various horizons within a relatively complete biostratigraphic sequence.

Similar fossiliferous Lower Triassic deposits also crop out in South China, and these outcrops have been extensively studied by various authors beginning with the pioneer works of Chao (1950, 1959) who first documented the occurrence of rich Early Triassic ammonoid faunas in northwestern Guangxi. More recently, Lehrmann *et al*. (2001, 2003, 2007a, b) and Galfetti *et al.* (2008) conducted detailed studies of the lithofacies and depositional environments of the Lower Triassic in this area. Brayard and Bucher (2008) and Brühwiler *et al*. (2008) recognized several Griesbachian to Smithian-aged ammonoid faunas in northwestern Guangxi and constructed a new, very high resolution biostratigraphical zonation, portions of which can be correlated with various Tethyan localities as well as certain faunal horizons in the eastern Panthalassic basins. Kaim *et al.* (2010) discovered and described a well-preserved Greisbachian gastropod fauna, and Goudemand *et al.* (2012) described early Triassic conodont clusters from the area. Chen *et al.* (2013) reported on the size variation of conodonts in sediments representing the Smithian/Spathian boundary. These studies have contributed significantly to achieving an improved understanding of the environment and dynamics of the biotic recovery after the end-Permian mass extinction.

In order to better understand the regional correlation and reconstruction of Early Triassic depositional environments, tectonics, biofacies and marine ecosystems in northeastern Vietnam, Japanese and Vietnamese workers in 2005 organized a joint working group under the leadership of Dr. Toshifumi Komatsu. During the period from 2006 to 2012, various members of the group conducted several scientific expeditions to Lang Son Province (Fig.

Fig. 1. Photographs of the Geologic Museum in Hanoi and major members of the Japanese-Vietnamese Joint Resaearch Group. 1, Geologic Museum (Bao Tang Dia Chat) in Hanoi, Vietnam. Numerous specimens of Lower Triassic megafossils collected by Vu Khuc and Huu Nguyen Dinh from the Bac Thuy Formation are reposited here. 2, Dr. Huyen Dang Tran, Tien Dinh Cong and Dr. Toshifumi Komatsu. 3, Phuong Nguyen Duc (driver), Huu Nguyen Dinh, Takumi Maekawa, Dr. Yasunari Shigeta and Dr. Huyen Dang Tran at the Bac Thuy Railway Station. 4, Phong Nguyen Duc.

1), where they investigated all geological and paleontological aspects of the extensive outcrops including lithostratigraphy, biostratigraphy, isotope stratigraphy, sedimentology, paleobiology, and systematic paleontology.

These studies have resulted in several reports, some of which are preliminary in nature. They include descriptions of several Olenekian bivalves (e.g., *Crittendenia*) by Komatsu *et al*. (2013), and Komatsu *et al.* (2014) have reported that the depositional environment of the Bac Thuy Formation consists mainly of intertidal, wave and storm dominated shallow marine, slope, and marginal basin plain deposits. Komatsu *et al*. (2011) and Maekawa *et al*. (2012) have presented preliminary reports in regular meeting of the Palaeontological Society of Japan regarding the Smithian to Spathian conodont, bivalve, and ammonoid assemblages. In order to document the enormous amount of resultant data concerning the Lower Triassic in northeastern Vietnam, a decision was made to publish a monograph with financial support from the National Museum of Nature and Science with Dr. Yasunari Shigeta as chief editor. This volume includes a systematic paleontology section for the cephalopods, bivalves, gastropods, conodonts, ostracods and radiolarians collected from the Bac Thuy Formation, as well as a description of the formation's sedimentary environments and that of the upper part of the underlying Lang Son Formation. Also included is a section dealing with the zircon geochronology of the overlying Khon Lang Formation.

Research methods

Fossil-bearing rock samples were collected following a careful bed-by-bed approach with special attention devoted to taphonomic considerations. Megafossils were recovered from host rocks in the laboratory by use of air tool and/or air abrasion equipment. Silicon casts were made of specimens consisting only of outer molds. Over 100 limestone samples have been examined in an effort to investigate microfossils. Conodonts and micro gastropods were removed by applying 5–8% acetic acid to approximately 0.5 to 2 kg sample, then sieving residues (0.177 mm and 1 mm screens) and washing in water. Radiolarians were extracted by applying 5% hydrochloric acid to 0.5 kg samples for 24 hours, then sieving residues (0.300 mm and 0.075 mm screens) and washing in water. Ostracods were removed by applying 5% acetic acid for two weeks, then washing in water.

During field work, facies analyses of the beds were performed based on lithology, sedimentary structures, grain size, paleocurrent data, and fossil content in order to reconstruct depositional environments. In the laboratory, we observed the detailed sedimentary structures and fabrics of block samples and also prepared thin sections for petrographic analysis and observation of microfossils. Sedimentological terminology follows that of Tucker and Wright (1990), Tucker (1991), Reading and Collinson (1996), Mulder and Alexander (2001), and Mulder (2011).

Radiometric ages of rhyolite samples were obtained by zircon U-Pb dating using a Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) unit installed at the National Museum of Nature and Science, Tsukuba. Procedures for sample preparation and their subsequent analyses for zircon are the same as those described by Tsutsumi *et al.* (2012). The quadrupole ICP-MS is an Agilent 7700x, and the laser ablation system is an ESI NWR213. A spot size of 25 μm and laser power 4–5 J/cm^2 were adopted. He gas was used as the carrier gas instead of Ar gas to enhance a higher transport efficiency of ablated materials (e.g. Eggins *et al*., 1998). Common Pb corrections for the concordia diagrams as well as for each age were made using ^{208}Pb and ^{207}Pb, respectively (Williams, 1998), on the basis of the model for common Pb compositions proposed by Stacey and Kramers (1975). The pooled ages presented in this

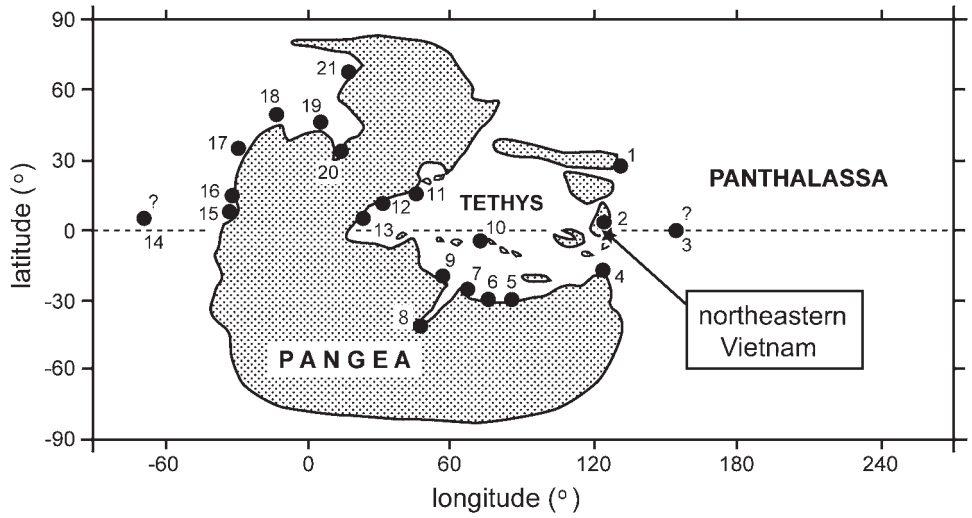


Fig. 2. Paleogeographical map of the Early Triassic showing the position of northeastern Vietnam and other areas. Paleomaps modified after Péron *et al*., 2005, Brayard *et al*., 2006 and Brayard *et al*., 2009. 1: South Primorye, 2: South China, 3: Kamura, Taho and Iwai limestones (Japan), 4: Timor, 5: South Tibet, 6: Spiti, 7: Salt Range, 8: Madagascar, 9: Oman, 10: Afghanistan, 11: Caucasus, 12: Chios, 13: Albania, 14: Chulitna (Alaska), 15: Nevada, 16: Idaho/Utah, 17: British Columbia, 18: Ellesmere Island, 19: Spitsbergen, 20: Greenland, 21: Olenek River area.

study were calculated using the Isoplot/Ex software (Ludwig, 2003).

Repository of specimens

All fossils and rock samples collected during our field work were transported from Vietnam to Japan with permission from the Vietnamese Government and other concerned authorities. All cephalopod, gastropod, ostracod and conodont specimens are reposited at the National Museum of Nature and Science, Tsukuba. Bivalves are stored in the Faculty of Science, Kumamoto University, Kumamoto, and radiolarian specimens are stored at Tokyo Gakugei University, Koganei.

Paleogeographical and geological setting
(by T. Komatsu, Y. Shigeta and H. T. Dang)

Tectonic activity of South China and Indochina blocks that probably began in the late Paleozoic continued throughout the Early to Middle Triassic (Metcalfe, 1998, 2009; Lepvrier *et al*., 2004; Nakano *et al*., 2008, 2010). According to Metcalfe (2009), the South China block originally rifted and separated from the northern margin of Gondwanaland in the Devonian and drifted northward in the Triassic. The Indochina craton was deeply subducted beneath the South China craton in the Early Triassic (Nakano *et al*., 2010).

In the Early Triassic, the Nanpanjiang and An Chau basins were widely exposed on the South China block (Enos *et al*., 2006; Lehrmann *et al*., 2007a, b; Galfetti *et al*., 2008; Komatsu *et al*., 2014). The Nanpanjiang basin is a vast, shallow to deep marine embayment in the southern part of the South China block. During the late Permian to Early Triassic, it was located in the eastern Tethys seaway near the equator (Metcalfe, 1998, 2009). The An Chau basin in Vietnam, which is located in the southern part of the South China block (Fig. 2), was continuous with the southeastern Nanpanjiang basin during the Triassic.

In the southwestern part of Guangxi Province, south China, the Nanpanjiang basin sur-

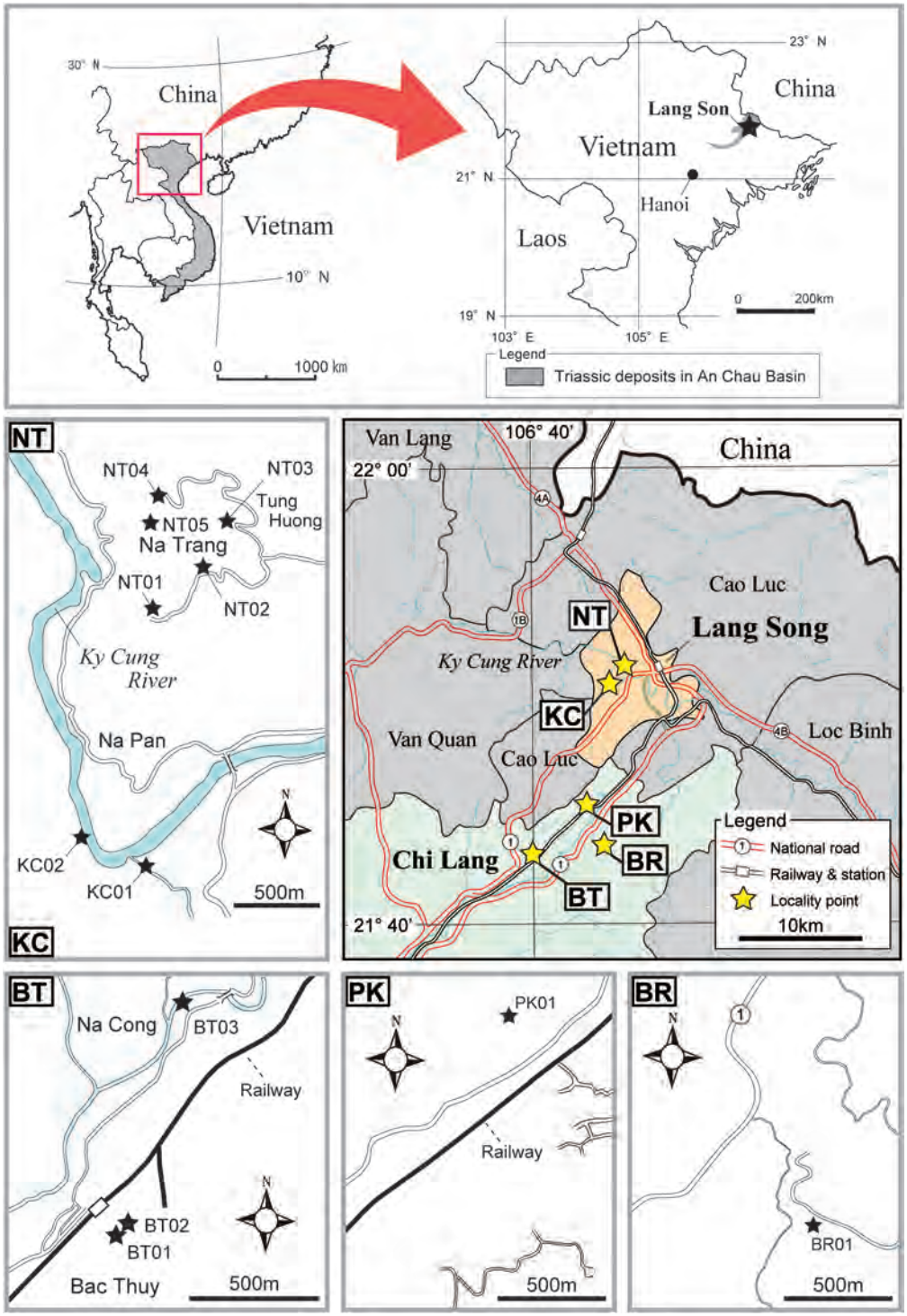


Fig. 3. Map showing the study area and An Chau basin in Lang Son Province, northeastern Vietnam. Studied sections (BT, KC, NT, PK and BR) are located in the central part of Lang Son Province.

rounds several large, isolated platforms, including the Chongzuo-Pingguo and Debao platforms (Lehrmann *et al*., 2007a, b). In the Chongzuo area of southwestern Guangxi Province, the Early Triassic Nanpanjiang basin is filled with mudstone and debris flow deposits of the Induan to Olenekian Luolou Formation and with isolated shallow marine platform deposits of the Induan Majiaoling and Induan to Olenekian Beisi formations (Lehrmann *et al*., 2007a, b). In Vietnam, the Early Triassic An Chau basin is filled mainly with marine deposits of the Lower Triassic Lang Son and Bac Thuy formations and the Middle Triassic volcanic rocks of the Khon Lang Formation. Komatsu *et al.* (2014) reported the Olenekian Bac Thuy Formation is lithologically equivalent to the Luolou Formation in the Nanpanjiang basin.

According to Lehrmann *et al*. (2007b), who examined long-term subsidence patterns during the Proterozoic to Triassic, the Yangtze platform and other, isolated platforms—including the Chongzuo-Pingguo platform and the Great Bank of Guizhou—were characterized by high subsidence and sedimentation rates during the Olenekian to Anisian in the Chongzuo area; peak subsidence rates occurred earlier in the southern basin (i.e., in the Pingguo and Chongzuo areas) than in the northern basin. During the Olenekian to Anisian, in the Nanpanjiang basin the huge accommodation space was filled with carbonate and siliciclastic gravity flow deposits. However, the timing and source area of the siliciclastic gravity flows in the southern Nanpanjiang basin are poorly understood, although Enos *et al.* (2006) suggested that the Middle Triassic turbidites originated from the east in association with the Jiangnan uplift in the northern basin.

In contrast, Lower Triassic siliciclastic sediments are common in the shallow to deep marine facies in the An Chau basin (Komatsu and Dang, 2007; Komatsu *et al.*, 2010, 2014). According to Komatsu *et al*. (2014), thick siliciclastic slump deposits accumulated in a slope environment are intercalated within the upper part of the Induan to early Olenekian Lang Son Formation. Many turbidite beds consisting of siliciclastics are embedded in the Olenekian Bac Thuy Formation. Climbing-ripple and current-ripple laminations in high- and low-density marginal basin turbidites indicate eastward, northeastward, and southeastward paleocurrent directions in the Bac Thuy Formation (Komatsu *et al*., 2014). These observations suggest that the Lower Triassic siliciclastic sediments in the southern Nanpanjiang basin originated mainly from the shelf in the An Chau basin or from a landmass in northern Vietnam. Moreover, it seems that the landmass was distributed in the western margin of the An Chau basin.

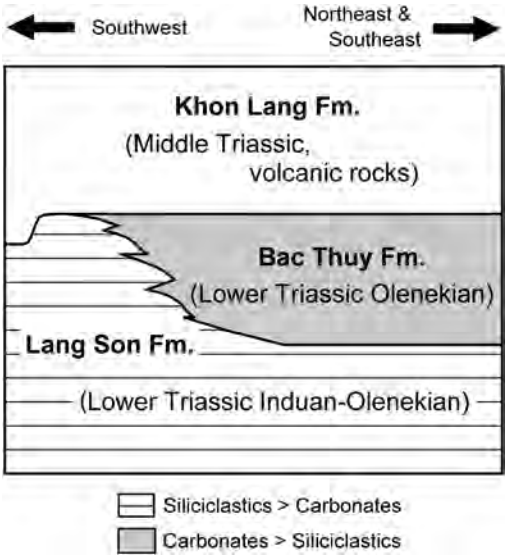


Fig. 4. Stratigraphic subdivisions of the Lower Triassic System in An Chau basin, northeastern Vietnam. The Olenekian Bac Thuy Formation consists of carbonates and siliciclastics.

Stratigraphy of the Bac Thuy Formation

(by T. Komatsu, T. Maekawa and Y. Shigeta)

The Bac Thuy Formation was established by Vu Khuc (1980), and its stratotype is locat-

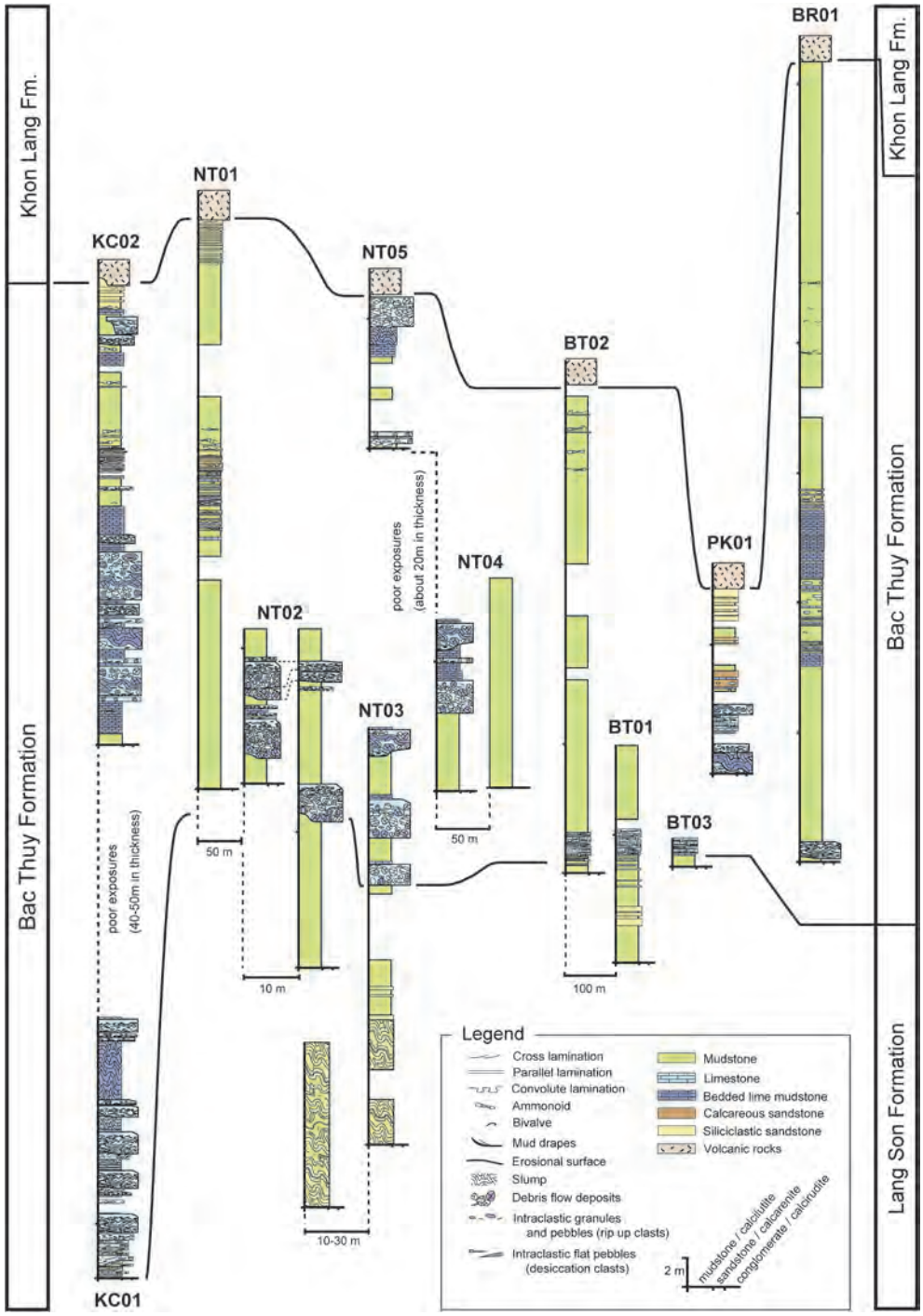


Fig. 5. Columnar sections of the Lang Son (upper part) and Bac Thuy formations in the central part of Lang Son Province.

ed near the Bac Thuy railway station in the Bac Thuy area (BT), Chi Lang District, Lang Son Province. It is also well exposed in the Pac Khanh (PK), Ban Ru (BR), Na Trang (NT) and Ky Cung River (KC) areas, in the central part of Lang Son Province (Fig. 3). The formation conformably overlies the Lower Triassic (Induan to Olenekian) Lang Son Formation, which consists mainly of siliciclastic sandstone and mudstone in the Na Trang, Bac Thuy and Ban Ru areas, and it is unconformably overlain by the Middle Triassic Khon Lang Formation, which consists predominately of rhyolitic rocks in these areas (Fig. 4). The Bac Thuy Formation is generally divided into three parts, namely a lower part consisting mainly of limestone and mudstone, a middle part characterized by organic-rich dark gray limestone and an upper part composed of thick mudstone, sandstone and limestone (Fig. 5).

Bac Thuy area

Exposures: Two sections, BT01 and BT02, near the Bac Thuy railway station (stratotype) and one section (BT03) at Na Cong, in Chi Lang District (Figs. 3, 5–11).

Thickness: 45 m at BT02 (Figs. 5, 8).

Lithology: The lowermost part of the Bac Thuy Formation (3 m thick) consists of a basal alternation of thin-bedded limestone and greenish gray mudstone that is overlain by 2 m thick interval of fossiliferous bedded limestone (Figs. 6, 9–11). This limestone bed interval, which contains abundant ammonoid shells and a thin slump bed, is also characterized by sutured stylolite (BT01–03). Although the middle part of the formation is not well exposed, the upper part is represented by a thick massive and dominant greenish-gray mudstone containing shelly sandstone layers.

Megafossils: The thin limestone beds of the basal limestone/greenish gray mudstone alternation and the lower part of the overlying fossiliferous limestone beds yield *Flemingites rursiradiatus* Chao, 1959, *Pseudaspidites muthianus* (Krafft and Diener, 1909), *Submeekoceras hsüyüchieni* (Chao, 1959) and *Jinyaceras* cf. *bellum* Brayard and Bucher, 2008. The middle part of the fossiliferous limestone beds intercalated with the thin slump bed contains *Urdyceras tulongensis* Brühwiler *et al*. 2010, *Ussuria kwangsiana* Chao, 1959, *Galfettites simplicitatis* Brayard and Bucher 2008, *Pseudaspidites muthianus*, *Submeekoceras hsüyüchieni*, *Jinyaceras* cf. *bellum*, *Parananites sinensis* (Chao, 1959) and *Aspenites acutus* Hyatt and Smith, 1905. *Owenites koeneni* Hyatt and Smith, 1905 is the characteristic ammonoid in the upper part of the 2 m thick fossiliferous limestone beds, but *Preflorianites radians* Chao, 1959, *Dieneroceras*? *goudemandi* (Brayard and Bucher, 2008), *Leyeceras rothi* Brayard and Bucher, 2008, *Parussuria compressa* (Hyatt and Smith, 1905), *Nammalites* sp. indet. and *Pseudosageceras multilobatum* Noetling, 1905a also occur in this interval. Megafossils are not found in the middle part of the formation. *Xenoceltites*? sp. indet., *Tirolites* sp. nov., *Columbites* sp. indet., *Yvesgalleticeras*? sp. indet. and *Eodanubites*? sp. indet. occur in the greenish-gray mudstone of the upper part. The bivalves, *Crittendenia australasiatica* (Krumbeck, 1924), "*Pseudomonotis*" *himaica* (Bittner, 1899) and *Positra* sp. indet. are also commonly found in the upper part of the formation.

Microfossils: Microfossils are abundant in the 2 m thick fossiliferous limestone bed interval in the lower part of the formation, but the basal thin limestone/mudstone alternation yields only poorly preserved microfossils. Conodonts, including *Novispathodus* ex gr. *waageni* (Sweet, 1970b), *Conservatella conservativa* (Müller, 1956), *Discretella discreta* (Müller, 1956), and *D. robustus* (Wang and Wang, 1976) are commonly found throughout the fossiliferous limestone interval. In particular, the lower part of this interval is especially rich, yielding various species of conodonts such as *Eurygnathodus costatus* Staesche,

Fig. 6. Basal part of the Bac Thuy Formation in BT01, which conformably overlies the Lang Son Formation.

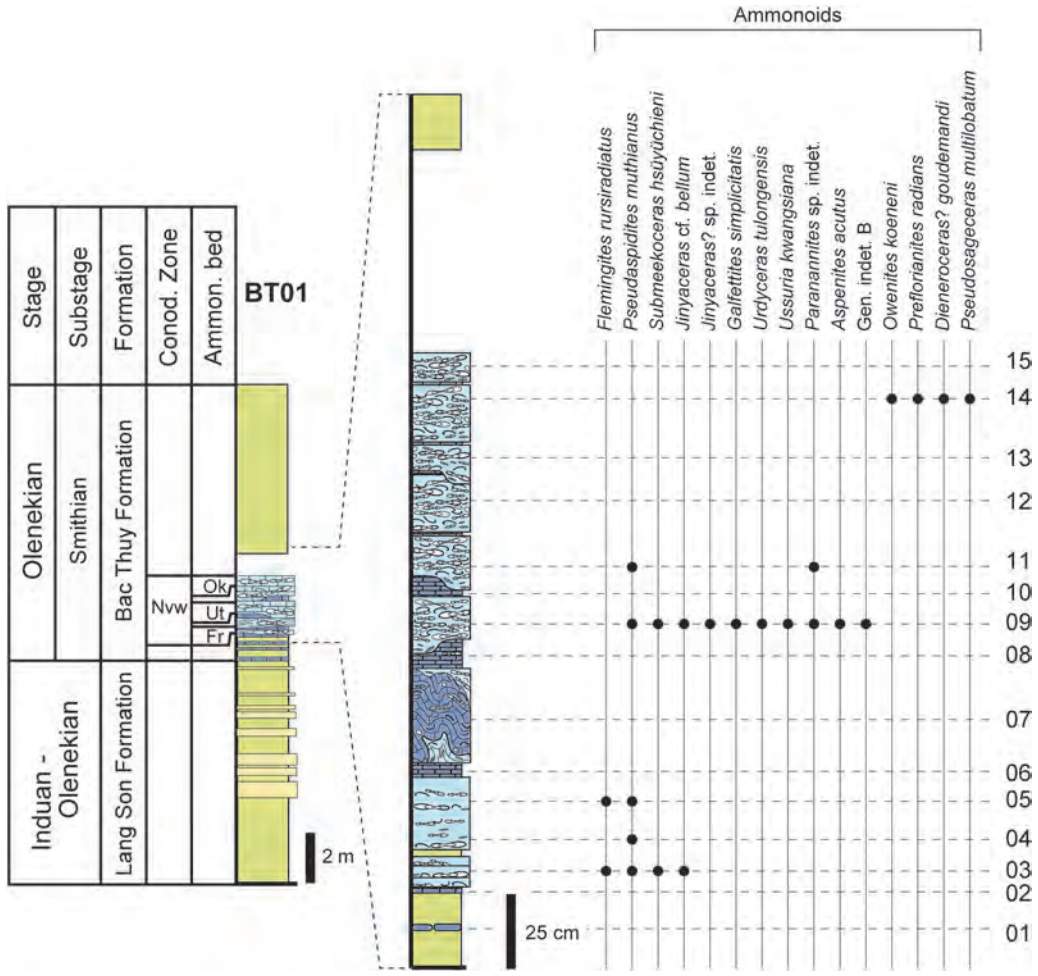
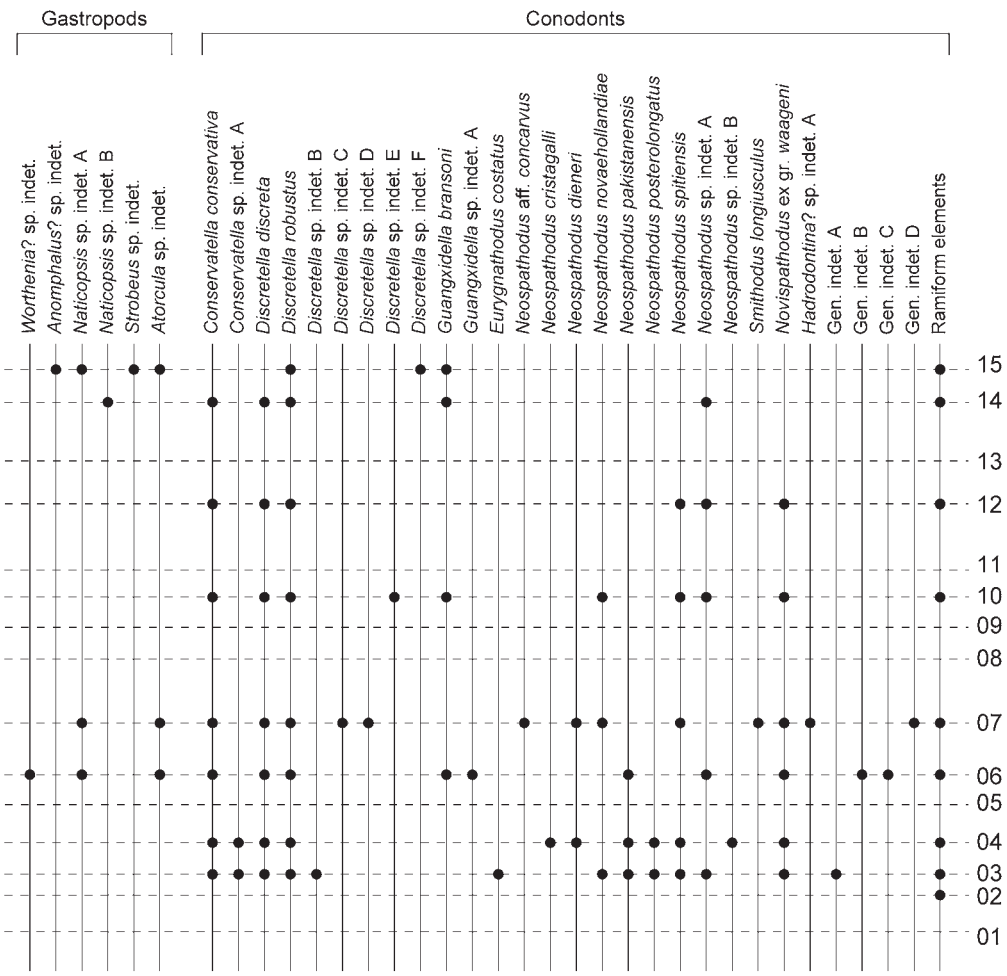


Fig. 7. Distribution of ammonoid, gastropod, and conodont taxa in BT01. Legend is shown in Fig. 5. Nvw: *Novispathodus* ex gr. *waageni* Zone, Fr: *Flemingites rursiradiatus* beds, Ut: *Urdyceras tulongensis* beds, Ok: *Owenites koeneni* beds.


Gastropods
Conodonts
Worthenia? sp. indet.
Anomphalus? sp. indet.
Naticopsis sp. indet. A
Naticopsis sp. indet. B
Strobeus sp. indet.
Atorcula sp. indet.
Conservatella conservativa
Conservatella sp. indet. A
Discretella discreta
Discretella robustus
Discretella sp. indet. B
Discretella sp. indet. C
Discretella sp. indet. D
Discretella sp. indet. E
Discretella sp. indet. F
Guangxidella bransoni
Guangxidella sp. indet. A
Eurygnathodus costatus
Neospathodus aff. concarvus
Neospathodus cristagalli
Neospathodus dieneri
Neospathodus novaehollandiae
Neospathodus pakistanensis
Neospathodus posterolongatus
Neospathodus spitiensis
Neospathodus sp. indet. A
Neospathodus sp. indet. B
Smithodus longiusculus
Novispathodus ex gr. waageni
Hadrodontina? sp. indet. A
Gen. indet. A
Gen. indet. B
Gen. indet. C
Gen. indet. D
Ramiform elements
15
14
13
12
11
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07
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03
02
01

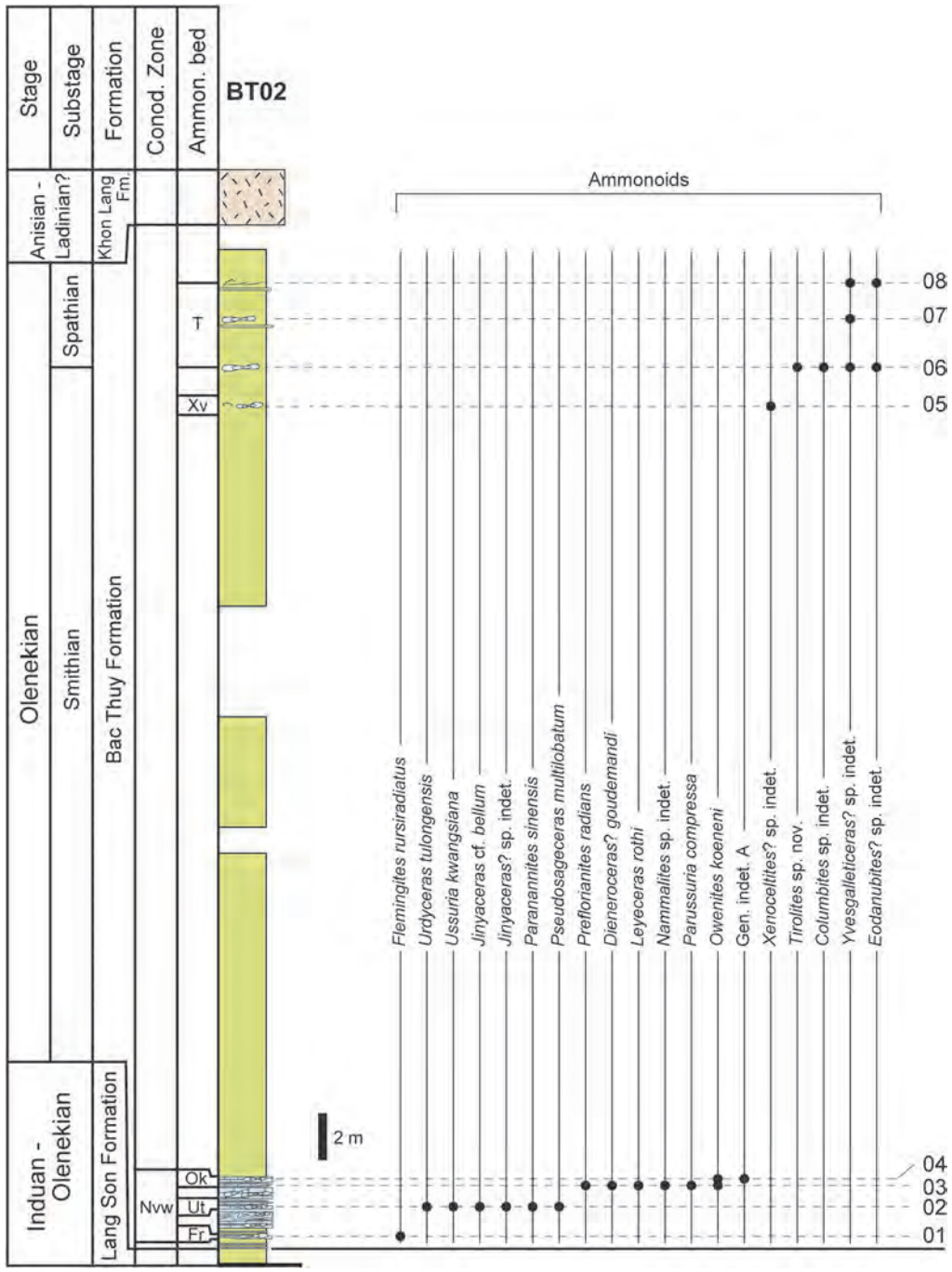
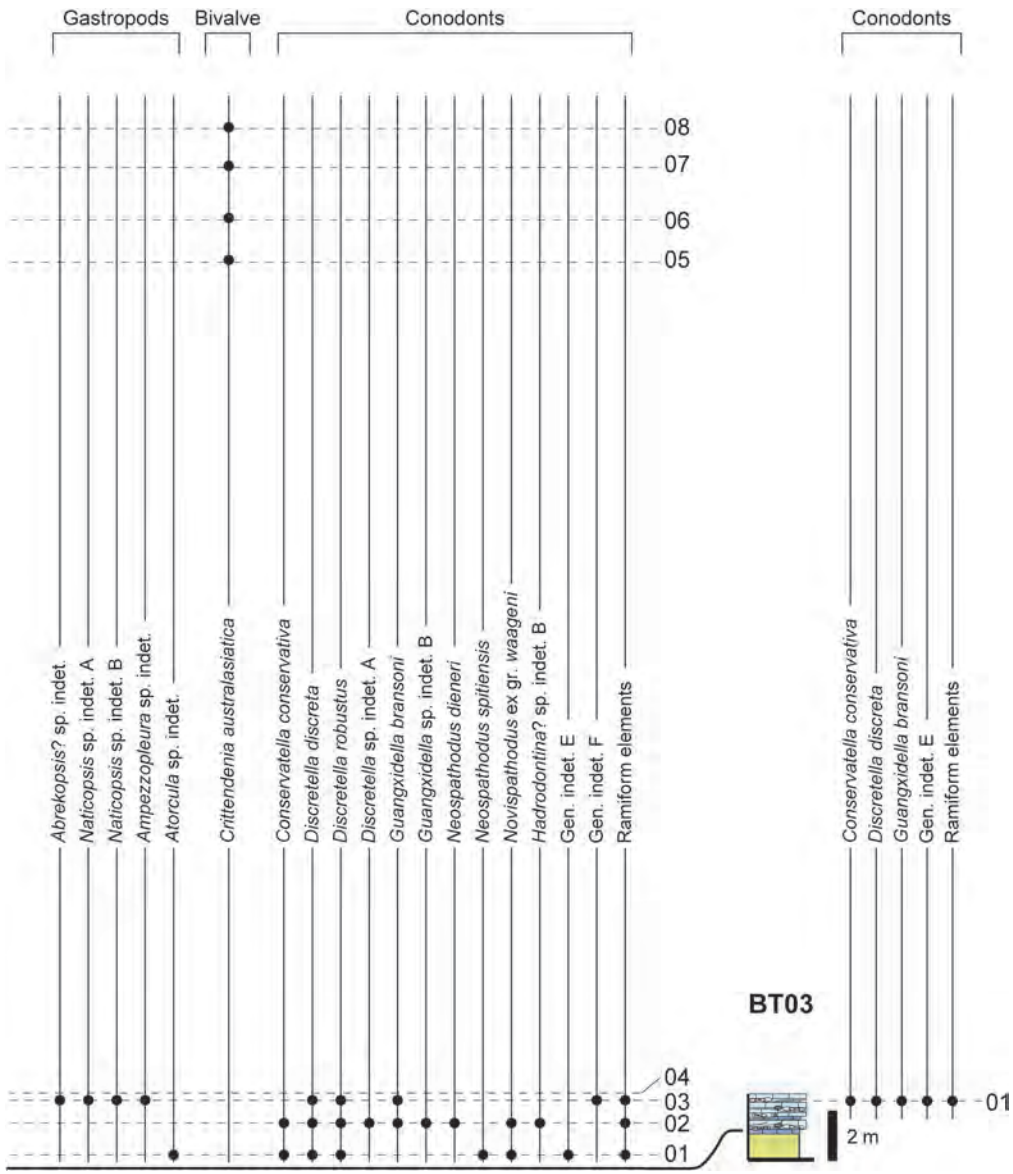


Fig. 8. Distribution of ammonoid, gastropod, bivalve, and conodont taxa in BT02. Legend is shown in Fig. 5. Nvw: *Novispathodus* ex gr. *waageni* Zone, Fr: *Flemingites rursiradiatus* beds, Ut: *Urdyceras tulongensis* beds, Ok: *Owenites koeneni* beds, Xv: *Xenoceltites variocostatus* beds, T: *Tirolites* sp. nov. beds.


Gastropods
Bivalve
Conodonts
Conodonts
Abrekopsis? sp. indet.
Naticopsis sp. indet. A
Naticopsis sp. indet. B
Ampezzopleura sp. indet.
Atorcula sp. indet.
Crittendenia australasiatica
Conservatella conservativa
Discretella discreta
Discretella robustus
Discretella sp. indet. A
Guangxidella bransoni
Guangxidella sp. indet. B
Neospathodus dieneri
Neospathodus spitiensis
Novispathodus ex gr. waageni
Hadrodontina? sp. indet. B
Gen. indet. E
Gen. indet. F
Ramiform elements
Conservatella conservativa
Discretella discreta
Guangxidella bransoni
Gen. indet. E
Ramiform elements
08
07
06
05
04
03
02
01
01
BT03
2 m

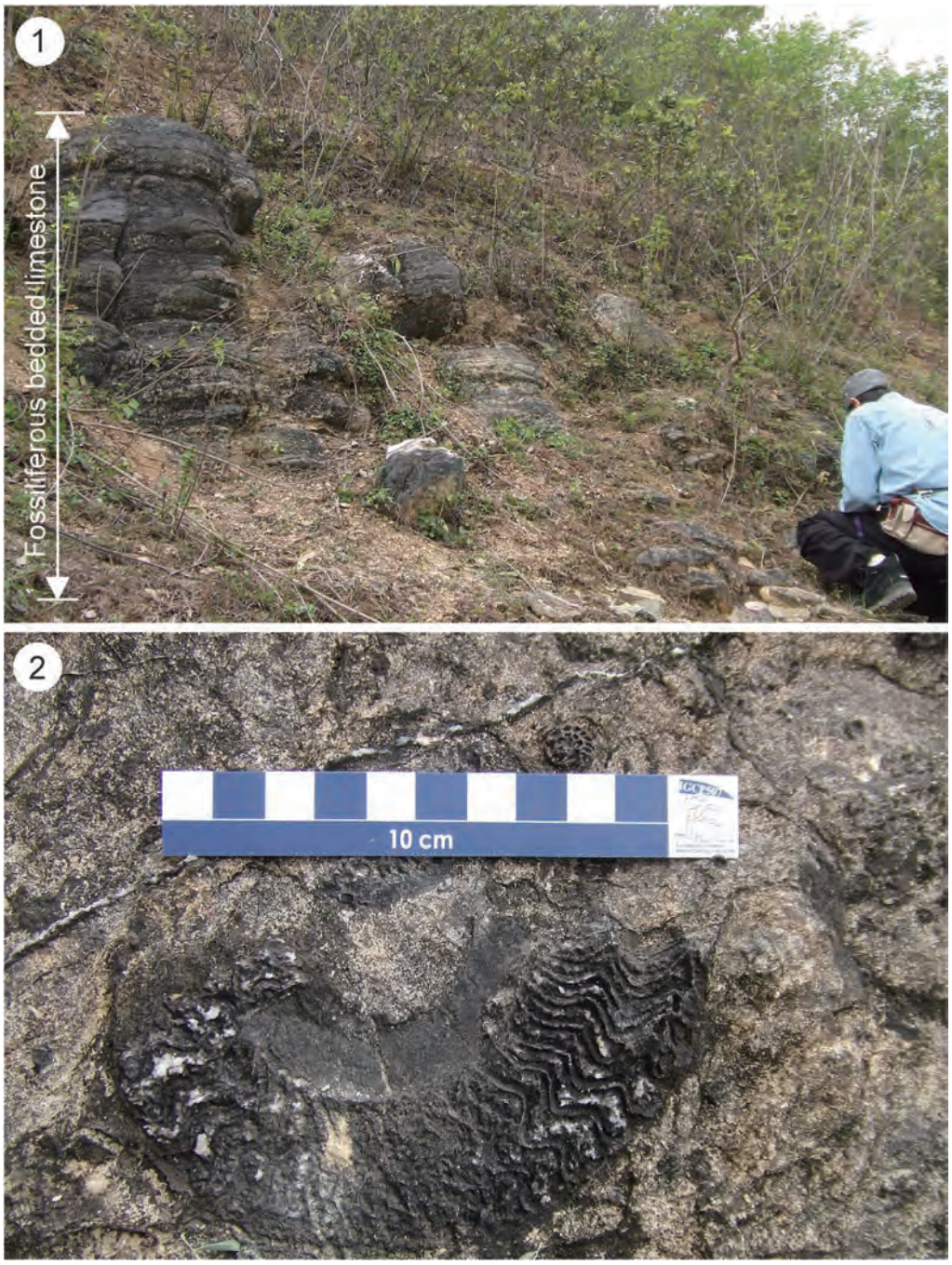


Fig. 9. Alternating thin-bedded limestone and mudstone and 2 m thick fossiliferous bedded limestone interval in the basal part of the BacThuy Formation in BT01. 1, 2 m thick bedded limestone interval containing abundant ammonoids, gastropods and conodonts. 2, Bedding plane in the 2 m thick fossiliferous bedded limestone interval at BT01-09. Many ammonoid sections are visible.

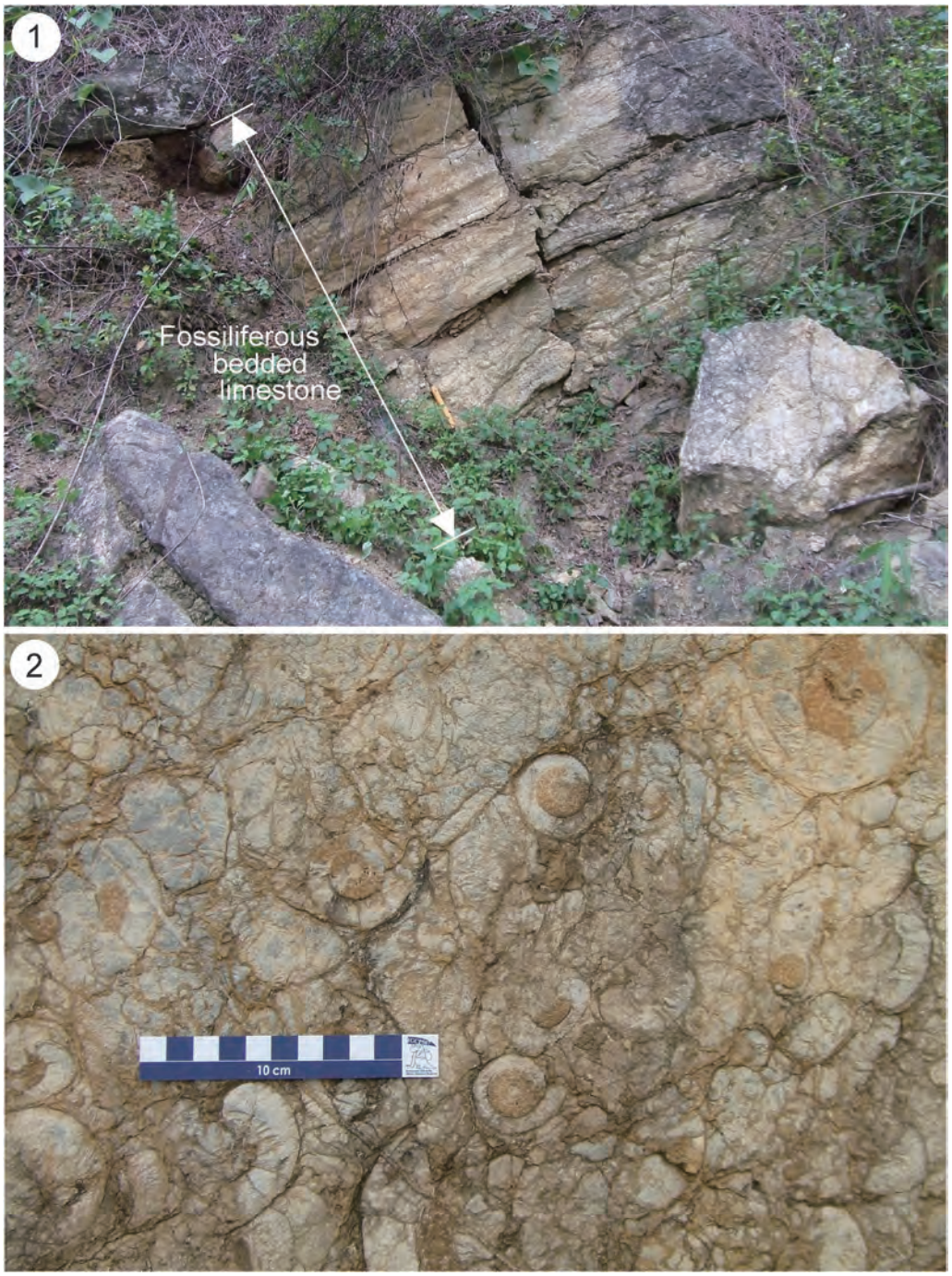


Fig. 10. 1, 2 m thick fossiliferous bedded limestone interval containing abundant ammonoids in the basal part of the Bac Thuy Formation in BT03. Scale is 20 cm. 2, Bedding plane in the ammonoid supported shell-concentration in the 2 m thick fossiliferous bedded limestone interval.

Fig. 11. Bedding plane in the ammonoid supported shell-concentration in the 2 m thick fossiliferous bedded limestone interval in the basal part of the Bac Thuy Formation in BT03. *Owenites koeneni* and *Preflorianites radians* occur abundantly in the ammonoid supported shell-concentration.

1964, *Neospathodus* aff. *concavus* Zhao and Orchard, 2007, *Ns. cristagalli* (Huckriede, 1958), *Ns. dieneri* Sweet, 1970a, *Ns. novaehollandiae* McTavish, 1973, *Ns. pakistanensis* Sweet, 1970b, *Ns. posterolongatus* Zhao and Orchard, 2007 and *Ns. spitiensis* Goel, 1977.

The middle part of the limestone bed interval is intercalated with a slump bed containing the conodonts, *Ns. dieneri*, *Ns. novaehollandiae*, *Ns. spitiensis*, *Guangxidella bransoni* (Müller, 1956), *Smithodus longiusculus* (Buryi, 1979), and two species of *Hadrodontina*?, as well as the gastropods *Worhtenia*? sp. indet., *Atorcula* sp. indet. and *Naticopsis* sp. indet. A.

The upper part of the limestone bed interval yields the conodont *Guangxidella bransoni*, and the gastropods *Anomphalus*? sp. indet., *Abrekopsis* sp. indet., *Strobeus* sp. indet., *Ampezzopleura* sp. indet. *Atorcula* sp. indet. and *Naticopsis* sp. indet. A and B. Microfossils are not found in the middle and upper parts of the formation.

Ky Cung River

Exposures: Two sections, KC01, 02 along the Ky Cung River near Na Pan, in Lang Son City (Figs. 3, 5, 12–16)

Thickness: Greater than 100 m (Figs. 5, 12, 15).

Lithology: The lower part of the formation (95 m thick), which is poorly exposed in this area, consists of limestone breccias, bedded limestone, carbonate slump beds and greenish gray mudstone (Figs. 13, 14, 16). Embedded in the basal part at KC01 are 4 m thick typical shallow marine carbonates consisting of oolites, lenticular to wavy beddings, tidal bundles containing mud drapes and cross-stratified limestone. Thin bivalve shells and small ammonoids commonly occur in the oolitic limestone and cross-stratified limestone, and desiccation cracks are typically found in the lenticular to wavy bedding (Komatsu *et al.*, 2014). The middle part of the formation (3 m thick) is characterized by organic-rich dark gray thin-bedded limestone yielding abundant radiolarians and bivalves, and mudstone containing dark gray calcareous nodules. The upper part of the formation (12 m thick) consists of thick mudstone intercalated with limestone breccias, thin bedded limestone, thin turbidite beds and sandstone/mudstone alternations. Ammonoid and bivalve shell lag deposits, and cross- and parallel-laminations characterize the thin turbidite beds.

Megafossils: Ammonoids are common in the limestone breccias and bedded limestone in the lower part of the formation. *Owenites koeneni* and *Dieneroceras*? *goudemandi* are dominant, but other taxa are also found in two different horizons as follows: *Juvenites sinuosus* (Kiparisova, 1947), *Paranannites sinensis*, *Preflorianites radians*, *Leyeceras rothi*, *Anaflemingites hochulii* Brayard and Bucher, 2008, *Parussuria compressa* and *Aspenites acutus* in the lower portion, and *Guodunites monneti* Brayard and Bucher, 2008 in the upper portion. The organic-rich dark gray carbonate beds in the middle part of the formation contain the following megafossils: ammonoid–*Xenoceltites variocostatus* Brayard and Bucher, 2008 and bivalves–abundant *Crittendenia australasiatica*, rare *Crittendenia langsonensis* Komatsu and Dang, 2013 and *Bositra limbata* (Guo, 1985).

The upper part of the formation yields the bivalves–*Crittendenia australasiatica*, *Leptochondria bittneri* (Kiparisova, 1938), "*Pseudomonotis*" *himaica*, *Bositra limbata* and *Bositra* sp. indet. and ammonoids, whose shells form thin lenticular shell concentrations (Figs. 17–19). Ammonoid composition changes toward the upward sequence within the upper part of the formation. *Tirolites* cf. *cassianus* (Quenstedt, 1849) is common in the greenish-gray mudstone of the lower portion, while *Tirolites* sp. nov., *Columbites* sp. indet., *Yvesgalleticeras*? sp. indet. are abundant in the middle portion. Also occurring in the middle portion are *Procarnites*? sp. indet., *Eodanubites*?

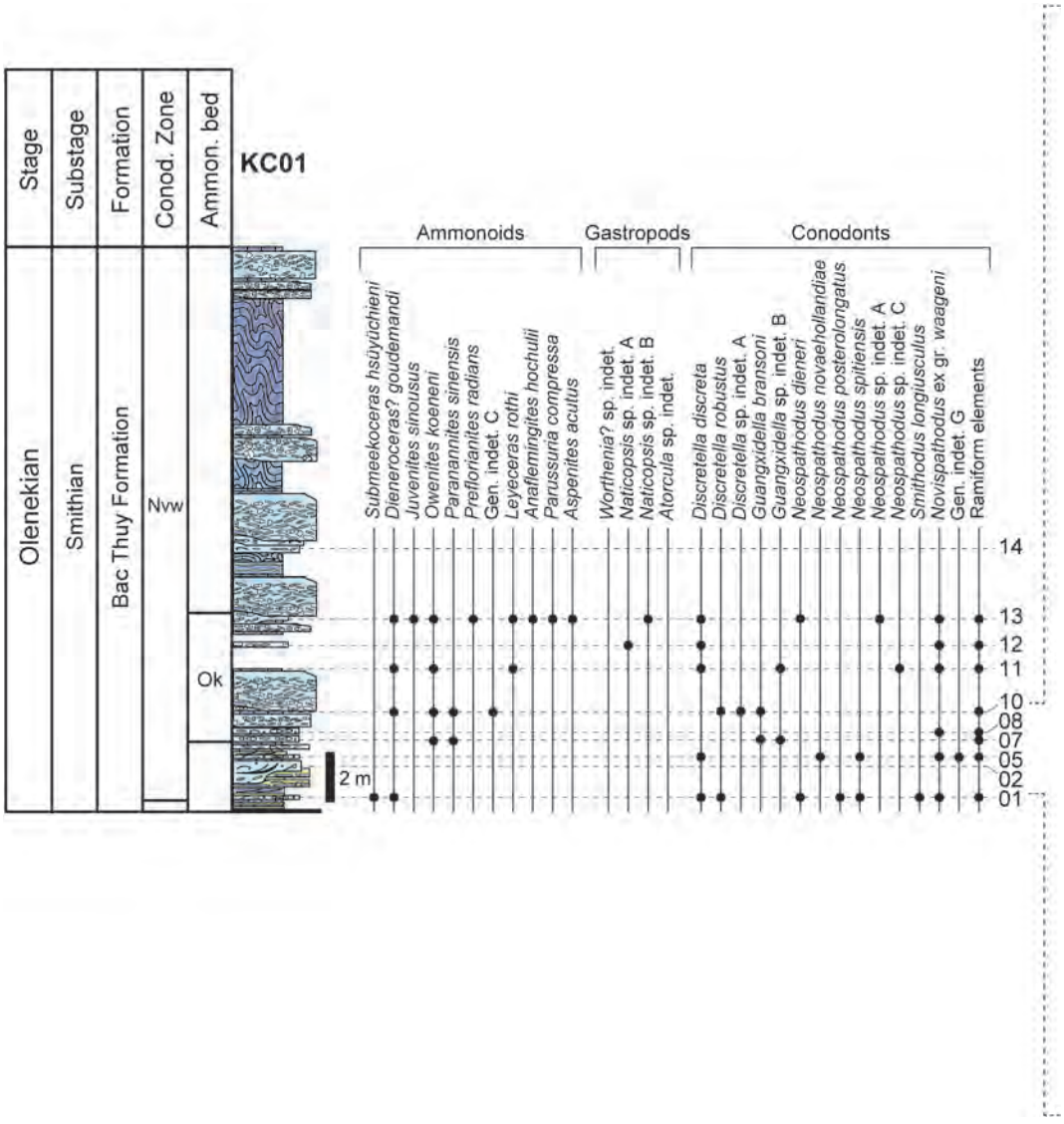
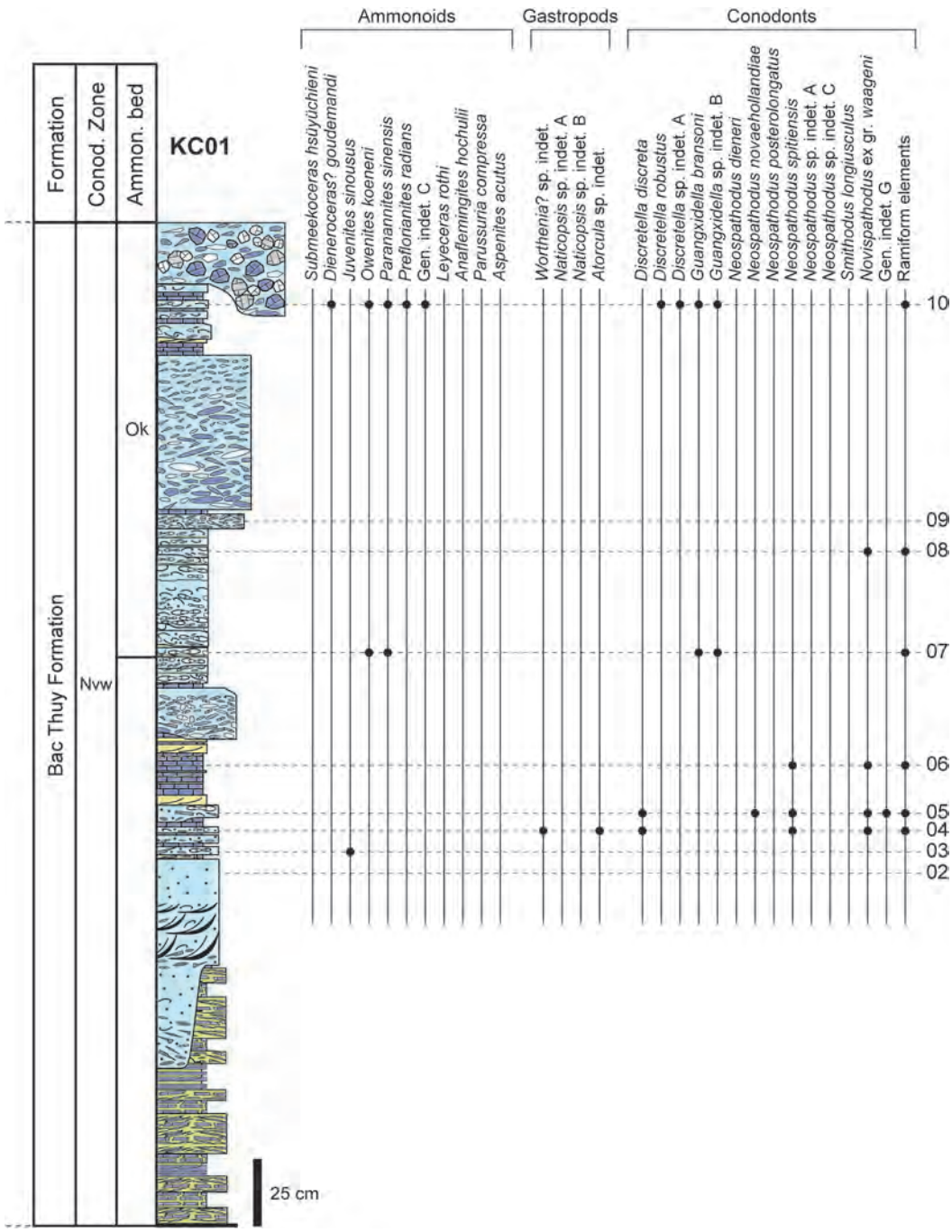


Fig. 12. Distribution of ammonoid, gastropod, and conodont taxa in KC01. Legend is shown in Fig. 5. Nvw: *Novispathodus* ex gr. *waageni* Zone, Ok: *Owenites koeneni* beds.


Formation
Conod. Zone
Ammon. bed
KC01
Bac Thuy Formation
Nvw
Ok
25 cm
Ammonoids
Gastropods
Conodonts
Submeekoceras hsüyüchieni
Dieneroceras? goudemandi
Juvenites sinousus
Owenites koeneni
Paranannites sinensis
Prefloianites radians
Gen. indet. C
Leyeceras rothi
Anaflemingites hochulli
Parussuria compressa
Aspenites acutus
Worthenia? sp. indet.
Naticopsis sp. indet. A
Naticopsis sp. indet. B
Atorcula sp. indet.
Discretella discreta
Discretella robustus
Discretella sp. indet. A
Guangxidella bransoni
Guangxidella sp. indet. B
Neospathodus dieneri
Neospathodus novaehollandiae
Neospathodus posterolongatus
Neospathodus spitiensis
Neospathodus sp. indet. A
Neospathodus sp. indet. C
Smithodus longiusculus
Novispathodus ex gr. waageni
Gen. indet. G
Ramiform elements
10
09
08
07
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05
04
03
02

Fig. 13. Exposures of the lower part of the Bac Thuy Formation along a tributary of the Ky Cung River in KC01. 1, Limestone breccia, slump bed and bedded limestone. 2, Secondarily deformed bedded limestone (slump bedding).

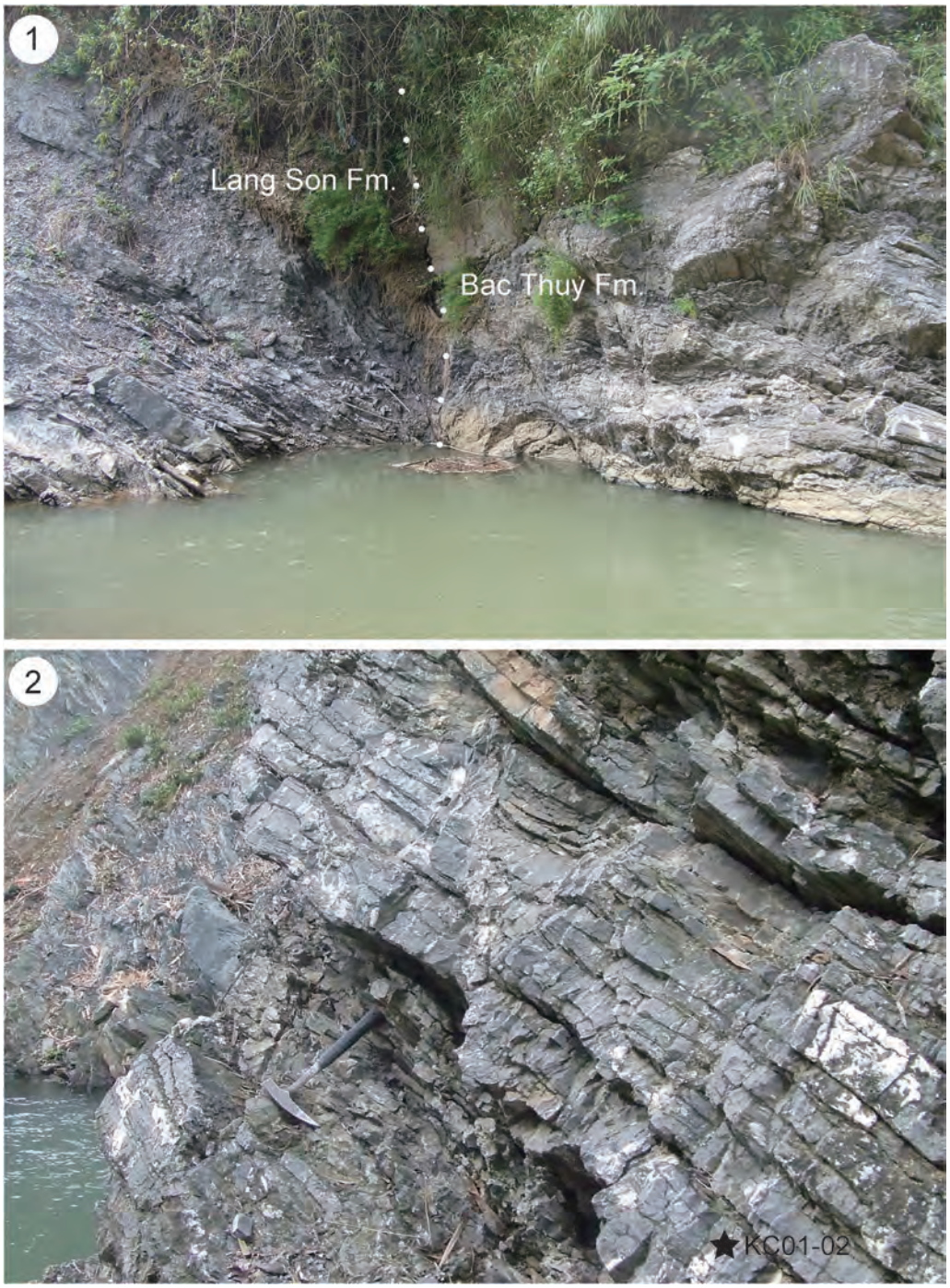


Fig. 14. Exposures of the lower part of the Bac Thuy Formation along a tributary of the Ky Cung River in KC01. 1, Outcrop showing the fault contact between shallow marine limestone of the Bac Thuy Formation and underlying Lang Son Formation in KC01. 2, Shallow marine carbonate lithofacies.

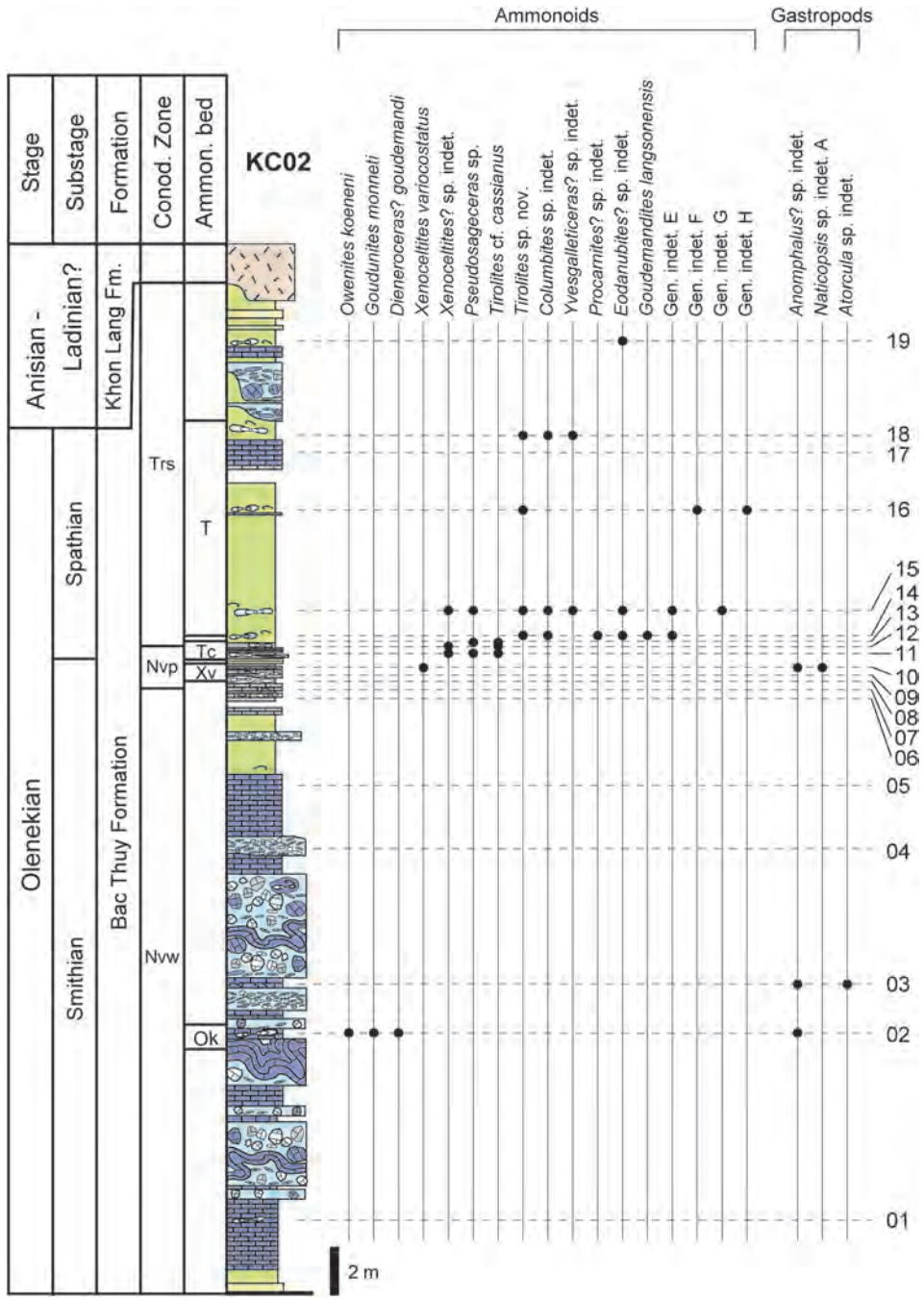
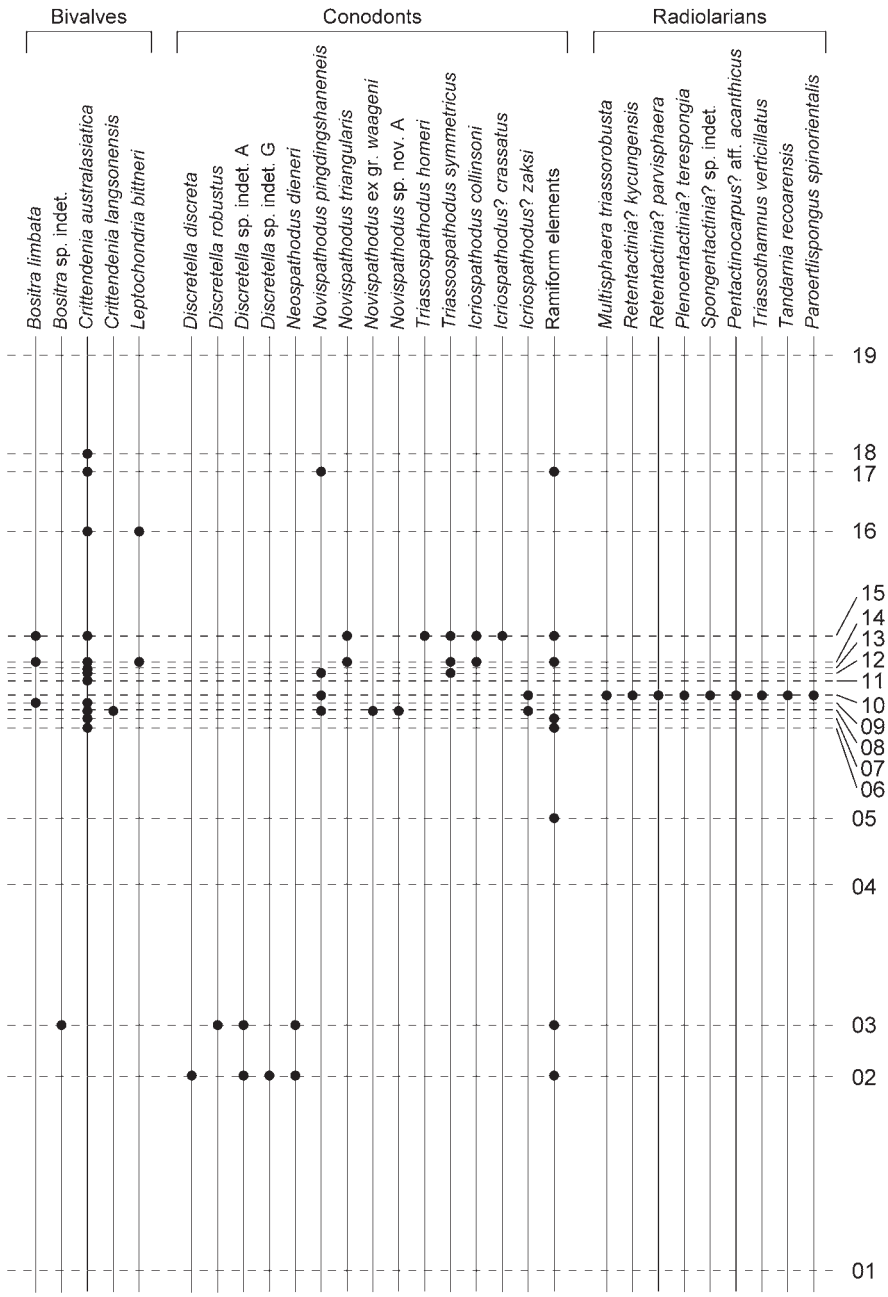


Fig. 15. Distribution of ammonoid, gastropod, bivalve, conodont, and radiolarian taxa in KC02. Legend is shown in Fig. 5. Nvw: *Novispathodus* ex gr. *waageni* Zone, Nvp: *Novispathodus pingdingshanensis* Zone, Trs: *Triassospathodus symmetricus* Zone, Ok: *Owenites koeneni* beds, Xv: *Xenoceltites variocostatus* beds, Tc: *Tirolites* cf. *cassianus* beds, T: *Tirolites* sp. nov. beds.


Bivalves
Conodonts
Radiolarians
Bositra limbata
Bositra sp. indet.
Crittendenia australasiatica
Crittendenia langsonensis
Leptochondria bittneri
Discretella discreta
Discretella robustus
Discretella sp. indet. A
Discretella sp. indet. G
Neospathodus dieneri
Novispathodus pingdingshanensis
Novispathodus triangularis
Novispathodus ex gr. waageni
Novispathodus sp. nov. A
Triassospathodus homeri
Triassospathodus symmetricus
Icriospathodus collinsoni
Icriospathodus? crassatus
Icriospathodus? zaksi
Ramiform elements
Multisphaera triassorobusta
Retentactinia? kycungensis
Retentactinia? parvisphaera
Plenoentactinia? terespongia
Spongentactinia? sp. indet.
Pentactinocarpus? aff. acanthicus
Triassothamnus verticillatus
Tandarnia recoarensis
Paroertlispongus spinorientalis
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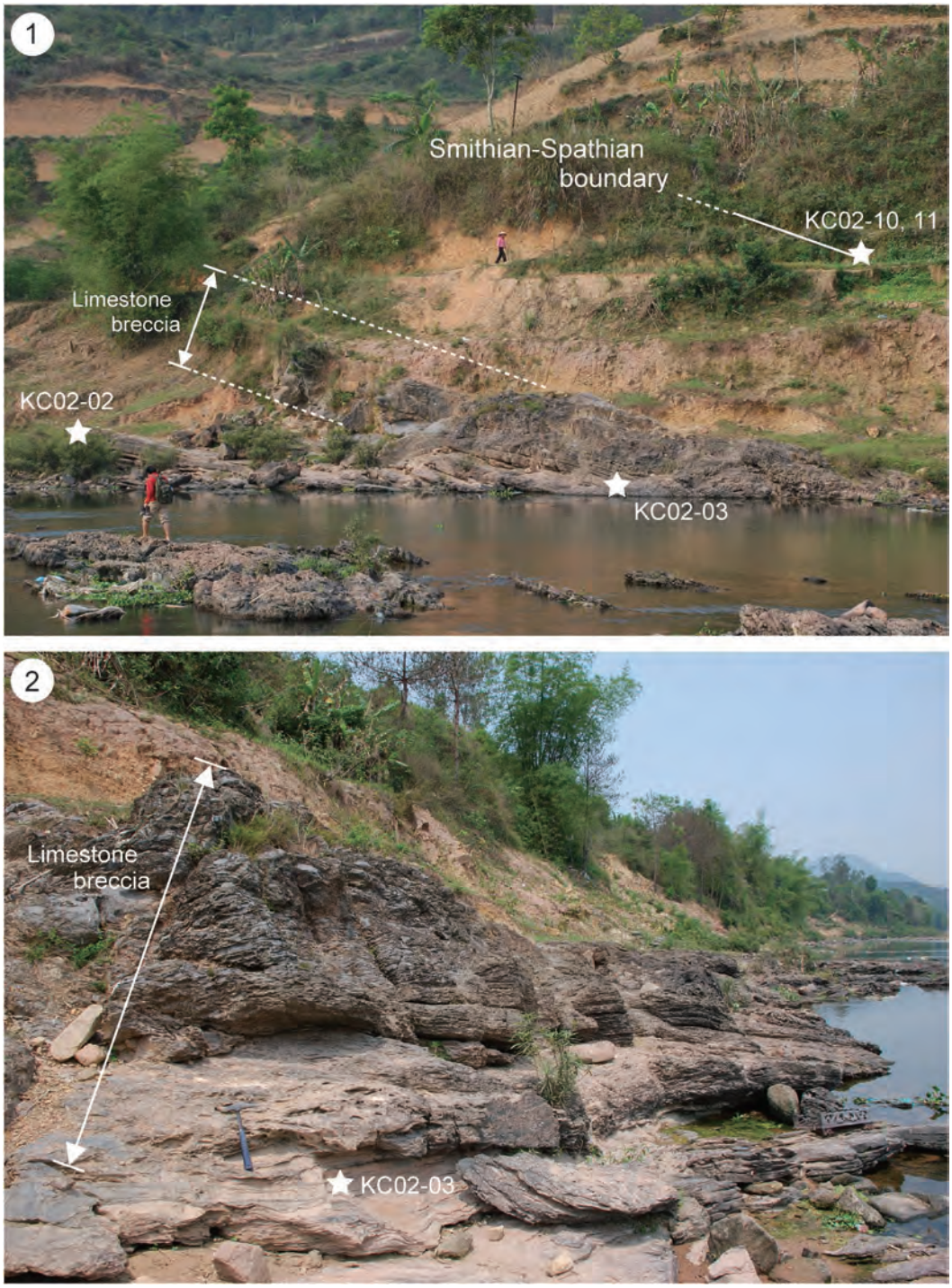

Fig. 16. Exposures of the lower and middle parts of the Bac Thuy Formation in KC02. 1, Limestone breccia, thin-bedded limestone and thick mudstone cropping out along the Ky Cung River. The Smithian/Spathian boundary is intercalated in alternating organic-rich dark gray bedded limestone and mudstone at KC02-10 and KC02-11. 2, Thick limestone breccia containing intraclasts composed mainly of oolitic and bioclastic shallow marine limestone and thin-bedded hemipelagic limestone.

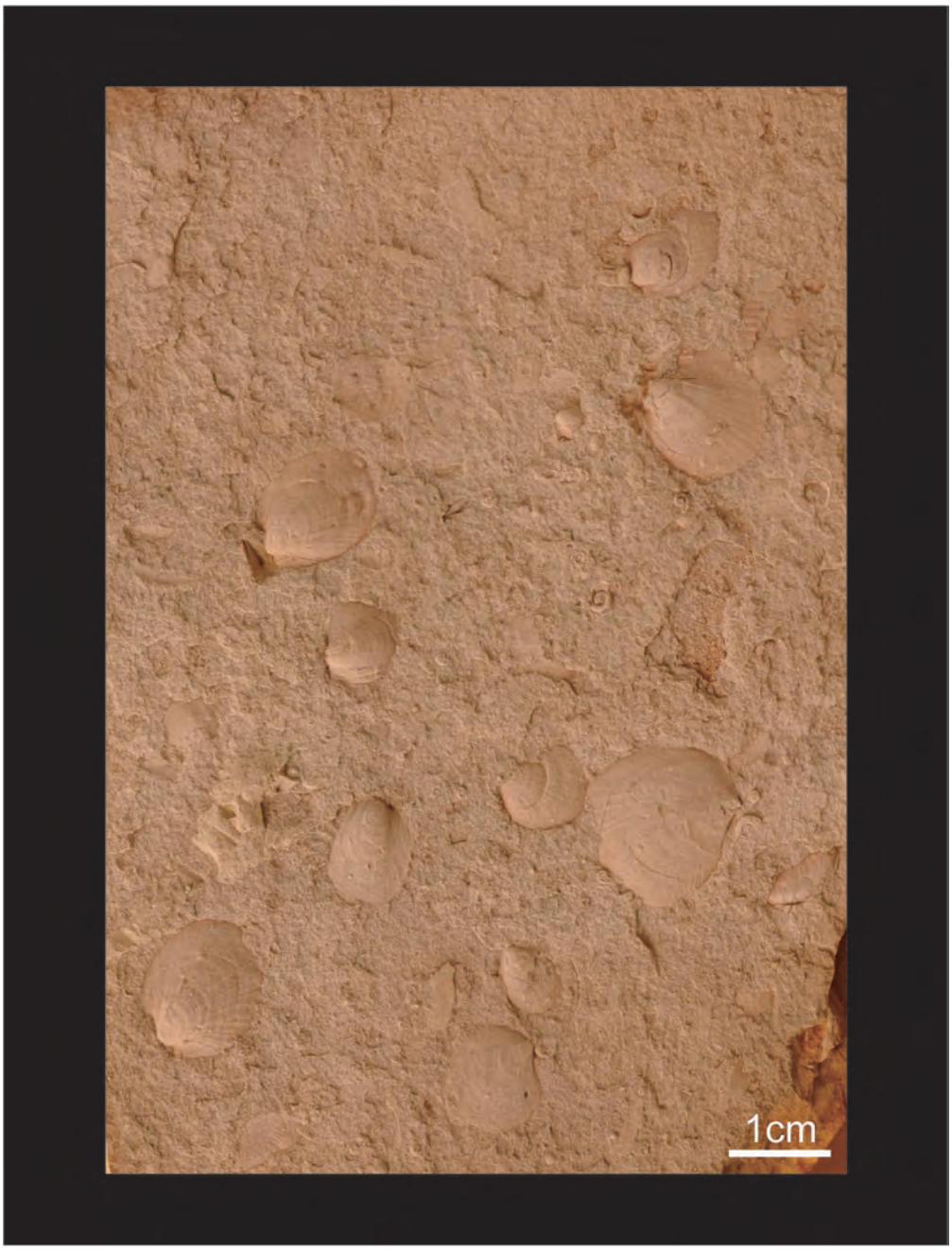

Fig. 17. Shell concentration (KMSP-5138) consisting of "*Pseudomonotis*" *himaica* and *Crittendenia australasiatica* in the Td division of a thin turbidite layer in thick hemipelagic mudstone at KC02-15. Disarticulated shells are scattered on the basal erosive surface of the low-density turbidite layer.

Fig. 18. Early Spathian ammonoids in a low-density turbidite layer from KC02-14.

Fig. 19. Early Spathian ammonoids in a low-density turbidite layer from KC02-14.

sp. indet. and *Goudemandites langsonensis* Shigeta and Nguyen sp. nov. Only rare specimens of *Eodanubites*? sp. indet. occur in the greenish-gray mudstone in the upper portion.

Microfossils: The bedded limestone in the lower part of the formation contains abundant microfossils as follows: conodonts–*Novispathodus* ex gr. *waageni*, *Ns. dieneri*, *Ns. novaehollandiae*, *Ns. posterolongatus*, *Ns. spitiensis*, *Discretella discreta*, *D. robustus*, *Guangxidella bransoni*, and *Smithodus longiusculus*, gastropods–*Worhtenia*? sp. indet., *Anomphalus*? sp. indet., *Atorcula* sp. indet. and *Naticopsis* sp. indet. A and B.

In the middle part of the formation, the dark gray thin-bedded limestone and calcareous nodules contain the following fossils: conodonts–*Novispathodus* ex gr. *waageni*, *Nv. pingdingshanensis* (Zhao and Orchard, 2007), *Nv*. sp. nov. A Goudemand and Orchard, 2012, and *Icriospathodus*? *zaksi* (Buryi, 1979), abundant radiolarians–*Multisphaera triassorobusta* Takahashi, sp. nov., *Retentactinia*? *kycungensis* Takahashi, sp. nov., *R. parvisphaera* Takahashi, sp. nov., *Plenoentactinia*? *terespongia* Takahashi, sp. nov., *Spongentactinia*? sp. indet., *Pentactinocarpus*? aff. *acanthicus* Dumitrica, 1978, *Triassothamnus verticillatus* (Dumitrica, 1978), *Tandarnia recoarensis* Dumitrica, 1982 and *Paroertlispongus spinorientalis* Takahashi, sp. nov., gastropod–*Anomphalus*? sp. indet.

In the upper part of the formation, the thin bedded limestone and thin layered shell concentrations contain conodonts as follows: abundant *Novispathodus triangularis* (Bender, 1970), *Triassospathodus homeri* (Bender, 1970), *T. symmetricus* (Orchard, 1995), *Icriospathodus collinsoni* (Solien, 1979), and rare *I.*? *crassatus* (Orchard, 1995) and *Nv. pingdingshanensis*.

Na Trang area

Exposures: Five sections, NT01–05 around Na Trang Village, in Lang Son City (Figs. 3, 5, 20–22)

Thickness: 50 m (Figs. 5, 21).

Lithology: The lower part of the formation (20–26 m thick, NT01–04) consists of thick greenish gray mudstone, limestone breccias and thin bedded limestone. The 0.2–4 m thick limestone breccias, characterized by structureless clast- or matrix supported textures, exhibit typical channel-like bodies. The middle part (6 m thick) is dominated by organic-rich dark gray thin-bedded limestone, mudstone and sandstone. Organic-rich dark gray calcareous nodules are abundant in the dark gray mudstone. These dark gray carbonates yield abundant radiolarians, and commonly contain monospecific ammonoids and bivalves. The sandstone is characterized by normal and inverse-grading, cross- and convolute-laminations. The upper part of the formation (18 m thick) is composed of thick greenish gray mudstone overlain by 3 m thick alternations of sandstone and mudstone (Fig. 22). The thick mudstone portion is commonly intercalated with thin shelly sandstone layers. The sandstone/mudstone alternations contain climbing ripples, parallel- and convolute-laminations. At NT05 the upper part is intercalated with limestone breccias and thin bedded limestone.

Megafossils: Fossils have not been found in the lower part of the formation, but the following megafossils have been collected from the organic-rich dark gray carbonates in the middle part: ammonoid–*Xenoceltites variocostatus*, nautiloid–*Trematoceras* sp. indet., and bivalves–abundant *Crittendenia australasiatica*, rare *Crittendenia langsonensis*, and a fragment of *Leptochondria bittneri*. The greenish-gray mudstone in the upper part contains the following ammonoids: *Tirolites* sp. nov., *Columbites* sp. indet. and *Eodanubites*? sp. indet., noutiloid–*Trematoceras* sp. indet., and the bivalves–*Crittendenia australasiatica*, *Leptochondria bittneri*, "*Pseudomonotis*" *himaica* and *Bositra* sp. indet.

Microfossils: In the middle part of the formation, the organic-rich dark gray thin-bedded

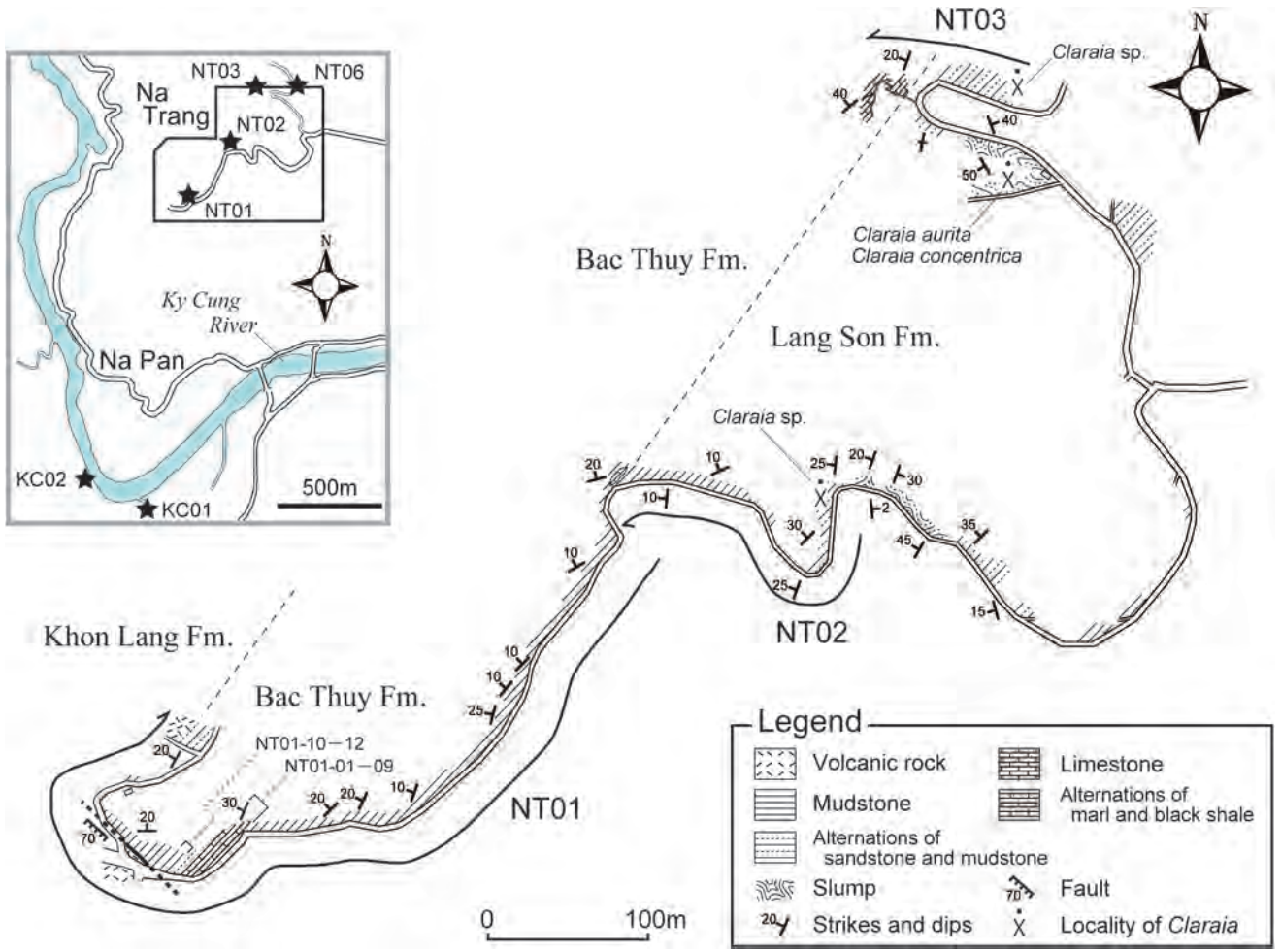

Fig. 20. Route map in the Na Trang area (NT01, 02, 03). The upper part of the Lang Son, Bac Thuy and Khon Lang formations are widely distributed in the area. The alternating organic-rich dark gray bedded limestone and mudstone contains abundant bivalves, ammonoids and radiolarians (NT01-01–09). The Spathian ammonoids, *Tirolites* and *Columbites*, are commonly found in thin turbidite layers (NT01-10, NT01-11).

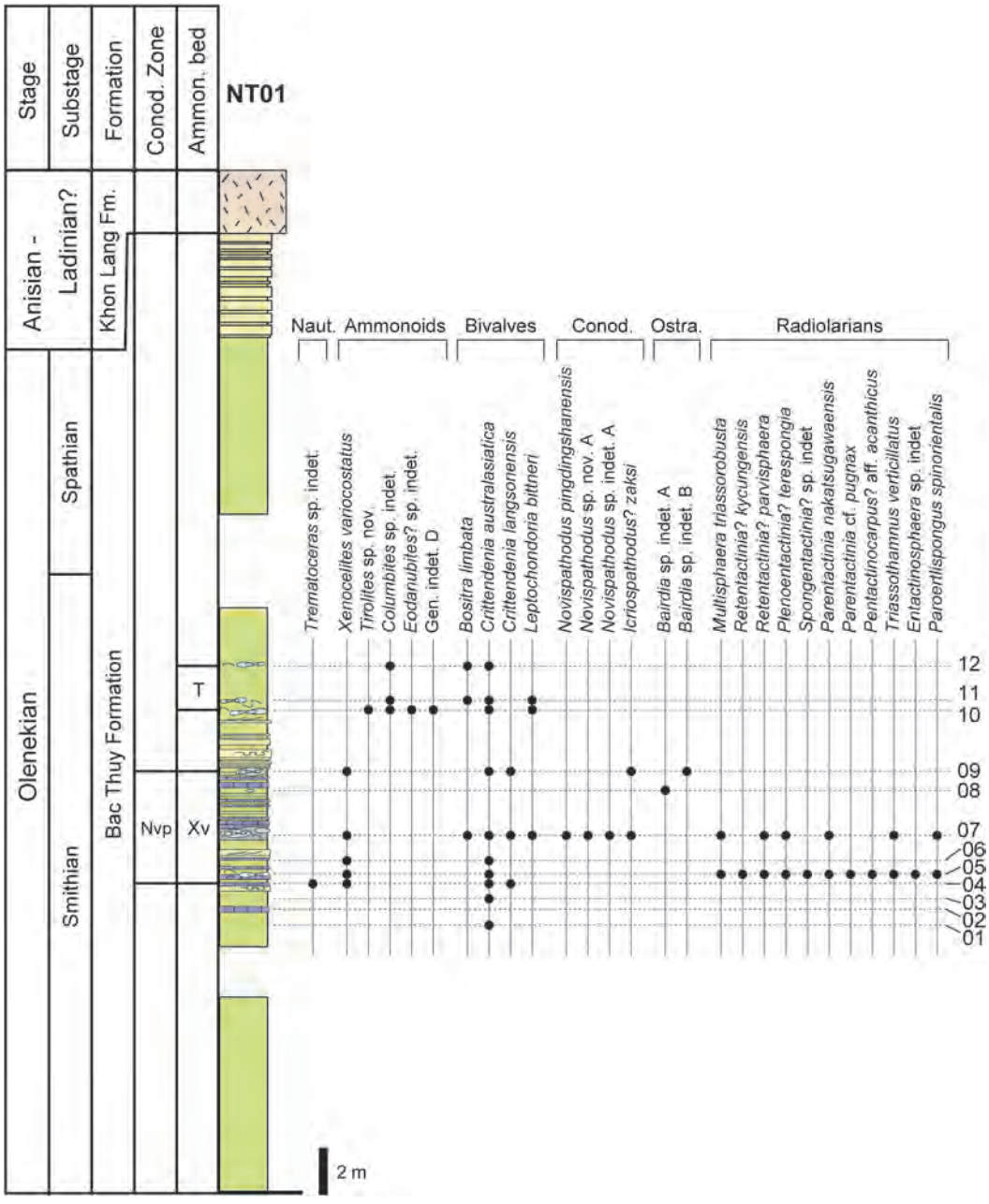

Fig. 21. Distribution of nautiloid, ammonoid, gastropod, bivalve, conodont, ostracoda and radiolarian taxa in NT01. Legend is shown in Fig. 5. Nvp: *Novispathodus pingdingshanensis* Zone, Xv: *Xenoceltites variocostatus* beds, T: *Tirolites* sp. nov. beds.

Fig. 22. Exposures of the upper part of the Bac Thuy Formation in NT01. 1, Hemipelagic mudstone intercalated with turbidite layers that contain abundant ammonoids and bivalves. 2. Outcrop showing unconformity between the Bac Thuy Formation consisting mainly of concentrated density flow to turbidity flow deposits and overlaying volcanic rocks of the Khon Lang Formation in NT01.

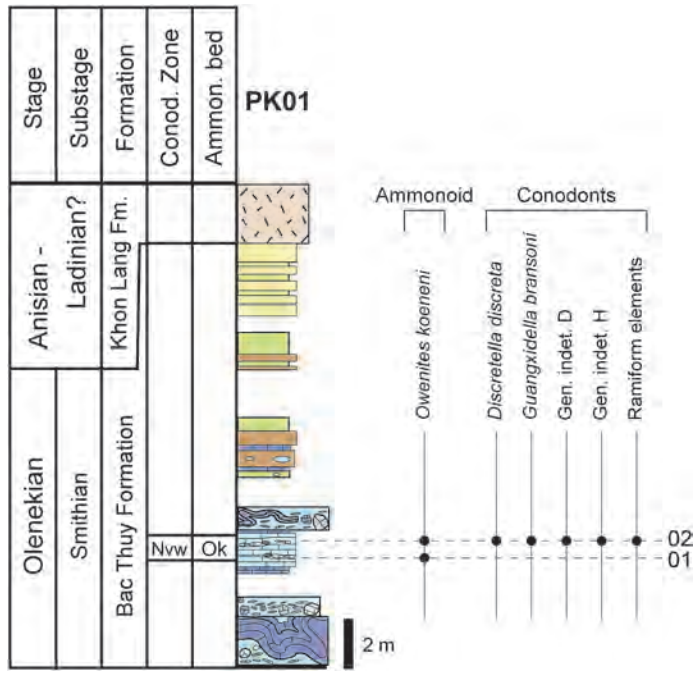

Fig. 23. Distribution of ammonoid and conodont taxa in PK01. Legend is shown in Fig. 5. Nvw: *Novispathodus* ex gr. *waageni* Zone, Ok: *Owenites koeneni* beds.

limestone contains rare conodonts–*Novispathodus pingdingshanensis*, *Novispathodus* sp. nov. A, and *Icriospathodus*? *zaksi*, abundant radiolarians–*Retentactinia*? *kycungensis* Takahashi, sp. nov., *Parentactinia nakatsugawaensis* Sashida, 1983, *P.* cf. *pugnax* Bumitrica, 1978, and *Paroertlispongus spinorientalis* Takahashi, sp. nov., and ostracods–two species of *Bairdia*.

Pac Khanh area

Exposures: One section, PK01, in Chi Lang District (Figs. 3, 5, 23, 24)

Thickness: Greater than 14 m (Figs. 5, 23).

Lithology: The lower part of the formation, which is poorly exposed in this area, consists mainly of limestone breccia, bedded limestone with abundant ammonoid shells, and greenish gray mudstone (Figs. 24). Ammonoid composition and mode of occurrence in the bedded limestone are quite similar to those of the ammonoids in the lower part of the Bac Thuy section stratotype. The middle part of the formation (2 m thick) is characterized by sandstone and dark gray mudstone containing organic-rich calcareous nodules. The upper part of the formation in the Pac Khanh section is distinguished by alternating sandstone and mudstone whose lithology resembles that of the uppermost Na Trang (NT01) and Ky Cung River (KC02) sections.

Megafossils: Because of the difficulty encountered in collecting macrofossils from the unusually hard limestone breccias and bedded limestone, only the ammonoid *Owenites koeneni* is recognized in the lower part of the formation. Megafossils have not been found in the middle and upper parts of the formation.

Microfossils: The conodonts, *Discretella discreta* and *Guangxidella bransoni* occur commonly in the bedded limestone in the lower part of the formation.

Fig. 24. Fossiliferous bedded limestone containing abundant ammonoids in the Bac Thuy Formation in PK01.

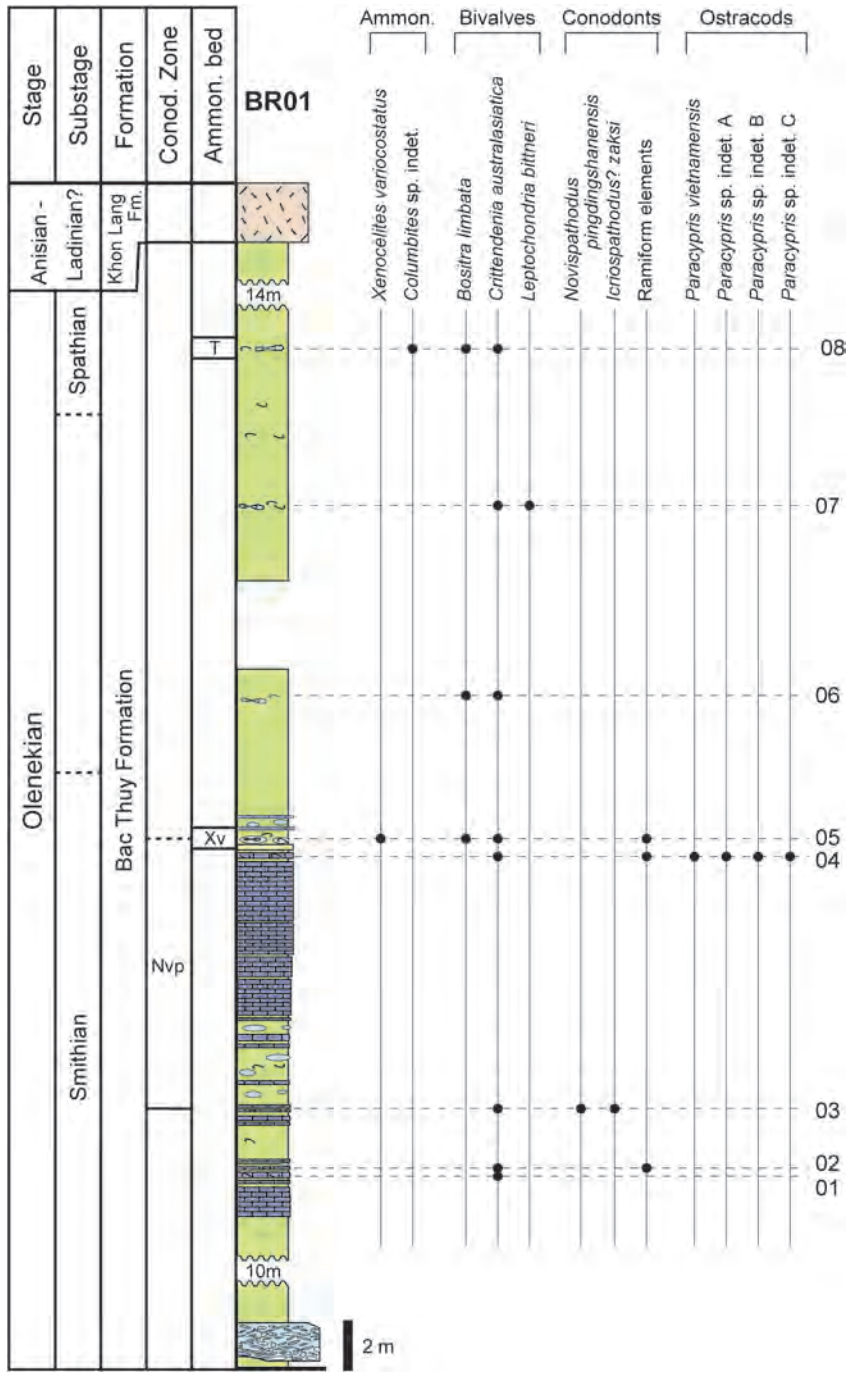

Fig. 25. Distribution of ammonoid, bivalve, conodont, and ostracoda taxa in BR01. Legend is shown in Fig. 5. Nvp: *Novispathodus pingdingshanensis* Zone, Xv: *Xenoceltites variocostatus* beds, T: *Tirolites* sp. nov. beds.

Ban Ru area

Exposures: One section, BR01, in Chi Lang District (Figs. 3, 5, 25)

Thickness: Greater than 185 m by Dang (2006). However, the lower part of the section was not closely examined (Figs. 5, 25).

Lithology: The lower part of the formation is composed mainly of mudstone, limestone breccias and bedded limestone, while the middle part of the formation (13 m thick) consists predominately of dark gray organic-rich thin-bedded limestone and mudstone containing dark gray calcareous nodules that commonly yield ostracods and bivalves. Lithologically, the middle part of the Ban Ru section closely resembles the middle parts of the Na Trang (NT01) and Ky Cung (KC02) sections. The upper part of the section (30 m thick), dominated by thick greenish gray mudstone, is lithologically similar to the upper parts of the Bac Thuy (BT02) and Na Trang (NT01) sections. Taken together, the thickness of the middle and upper parts of the Ban Ru (BR01) section exceeds 40 m, which is much thicker than the same intervals in the other section.

Megafossils: Megafossils have not been found in the lower part of the formation, but the ammonoid *Xenoceltites variocostatus* and bivalve *Crittendenia australasiatica* are quite common in the middle part. The upper part of the formation yields rare specimens of the ammonoid *Columbites* sp. indet., and bivalves *Crittendenia australasiatica*, *Bositra limbata* and "*Pseudomonotis*" *himaica*.

Microfossils: The organic-rich dark gray thim-bedded limestone in the middle part of the formation yields rare conodonts including *Novispathodus pingdingshanensis*, *Icriospathodus*? *zaksi*, as well as fragments of conodont elements. Also found are abundant ostracods, *Paracypris vietnamensis* Tanaka and Komatsu sp. nov. and *Paracypris* sp. A. Microfossils have not been found in the lower and upper parts of the formation.

Depositional environments of the Bac Thuy Formation

(by T. Komatsu, T. Maekawa, Y. Shigeta, H. T. Dang and P. D. Nguyen)

Depositional environments of the Triassic systems in the An Chau basin have been documented by Komatsu and Dang (2007), Komatsu *et al*. (2010) and Komatsu *et al*. (2014). The Olenekian stage in this basin, consisting of the upper part of the Lang Son and Bac Thuy formations, is composed of mixed carbonate and siliciclastic shallow marine to marginal basin deposits (Fig. 26). Dominated by siliciclastic facies, the upper part of Lang Son Formation is composed mainly of storm and wave-influenced shallow marine deposits, characterized by wave ripples and hummocky cross-stratification as well as slope deposits (Komatsu and Dang, 2007; Komatsu *et al.*, 2014). According to Komatsu *et al*. (2014), the Bac Thuy Formation consists of a tidal flat, wave-influenced carbonate platform, and slope and marginal basin plain deposits (Fig. 26). The lower part of Bac Thuy Formation is locally intercalated with tidal deposits and wave-influenced shallow marine carbonates at KC01 (Figs. 27–31). The tidal flat deposits are composed mainly of lenticular and wavy bedding with thin flat-bedded carbonates containing desiccation cracks (Fig. 27). Current ripples in the lenticular and wavy bedding exhibit bi-directional paleocurrents. These tidal deposits are intercalated with cross-stratified limestone characterized by tidal bundle carbonates containing mud drapes. The tidal bundles may have accumulated in response to migration of sand bars formed by tidal currents in intertidal to subtidal zones (Dalrymple, 1992, 2010). Desiccation cracks containing tepee structures are generally formed on the supratidal and upper intertidal zones in arid to semiarid environments (Wright 1990; Wright and Burchette, 1996; Pratt, 2010). The subtidal carbonates yield poorly preserved bivalves, ammonoids and conodonts (Figs. 28, 30, 31).

The shallow marine carbonates contain wave-ripples, low-angle cross-stratification (hummocky cross-stratification?, Fig. 29), ooids and abundant typical marine mollusks and microfossils (Figs. 29–31). The Smithian conodont, *Novispathodus waageni* (=*Neospathodus waageni*), is common in the shallow marine carbonates (Fig. 12). Marine molluscan fossil assemblages are characterized by abundant small bivalves and Smithian ammonoids such as *Owenites koeneni*. These thin bivalve shells typically show an edgewise arrangement (i.e., flat shells arranged perpendicular to the bedding, Kidwell *et al*., 1986) generated by strong wave currents (Fig. 31). Cyclic tidal deposits and wave-influenced shallow marine carbonates consist of typical retrogradational parasequence sets suggesting transgressive sequences (Komatsu *et al*., 2014). These tidal and wave influenced deposits were probably accumulated in a typical shallow marine environment on an isolated carbonate platform.

Slope and marginal basin-plain deposits, dominant in the upper part of Bac Thuy Formation, are widely distributed in Lang Son Province (BT02, KC02, NT01–05, PK01, BR01, in Figs. 32–35). These slope deposits are characterized by limestone breccias, high-density turbidites, slump beds and hemi-pelagic mudstone and limestone (Komatsu *et al*., 2014). Abundant concentrations of ammonoid shells, associated with limestone breccias or slump beds, are embedded in slope deposits (BT01–03, PK01).

Marginal basin-plain deposits consist of typical turbidite beds, minor limestone breccias and thick hemipelagic mudstone containing marl layers. These marl layers yield the Spathian ammonoids *Tirolites* and *Columbites*, the bivalve *Leptochondria bittneri* and conodonts *Triassospathodus* and *Icriospathodus*. The classical turbidite sets may represent frontal splay environments in the marginal basin plain. Clastics apparently were supplied from the west, hence the paleocurrent directions of the siliciclastic gravity flow deposits were approximately eastward (Komatsu *et al.*, 2014). These Olenekian carbonate and siliciclastic facies in the Bac Thuy Formation exhibit a typical transgressive succession.

The Smithian/Spathian boundary and latest Smithian anoxic to dysoxic facies, characterized by organic-rich dark gray bedded limestone and mudstone, are embedded in a succession ranging from slope to marginal basin-plain facies composed mainly of gravity flow and hemipelagic deposits (Komatsu *et al.*, 2014). The uppermost part of the organic-rich mudstone bed is intercalated with the Smithian/Spathian boundary as indicated by the first appearance of *Tilorites* cf. *cassianus* (KC02, NT01). The anoxic to dysoxic facies, composed of dark gray radiolarian and mollusk-shell bioclastic wackestone and dark gray mudstone, is characterized by rare bioturbation, small pyrite crystal aggregates and rich organic matter. The pyrite aggregates were possibly generated under anoxic sediments and/or under stagnant water conditions. The organic-rich dark gray mudstones contain weakly parallel and cross-laminations, and are intercalated with so-called high density turbidite beds characterized by massive, normal and inverse graded coarse grained calcareous sandstones (Fig. 34). Very small grazing traces (pascichnia), such as *Spirophycus* isp. and *Phycosiphon* isp. are commonly found in some layers (Fig. 29). These ichnofossil assemblages, dominated by pascichnia and characterized by low diversity and moderately high density, indicate opportunistic producers (Bromley, 1996). Ekdale and Mason (1988) proposed that pascichnia-dominated trace fossil assemblages were formed under less oxygenated conditions than domichnia-dominated assemblages, suggesting anoxic to dysoxic conditions.

The organic-rich carbonates and mudstone yield abundant low-diversity molluscan fossils and microfossils. Microfossil assemblages are mainly composed of spheroidal radiolarians

	Sedimentary environments		Lithology	Characteristic sedimentary structures, clasts, and fossils
Shallow carbonate platform	Tidal deposits	Intertidal -supratidal flat	Lenticular, wavy, and thin flat-bedded carbonates (wackestone, lime mudstone, and dolomite) and mudstone	• Current ripples and cross-lamination indicating bidirectional paleocurrents.
			Intraclastic rudstone and floatstone containing dolomite clasts (secondarily deformed or reworked deposits)	• Tepee structures and desiccation cracks. • Imbrications and flat pebbles and cobbles containing upside-down geopetal structures.
		Subtidal -intertidal flat	Intraclastic, oolitic, and bioclastic limestone (rudstone and floatstone)	• Cross-stratification, with mud drapes and reactivation surfaces. • Poorly preserved bivalve shells.
	Subtidal flat to wave-influenced shallow marine deposits		Alternating limestone (bioclastic, oolitic, and intraclastic floatstone and wackestone) and marl (wackestone and lime mudstone)	(Limestone) • Normal grading and structureless. • Abundant well-preserved marine mollusks. (Marl) •Weak lamination.
	Transgressive lag deposits		Intraclastic limestone (rudstone)	• Normal grading and structureless. • Poorly preserved molluscan shells.
Slope to marginal basin plain	Debris flow deposits		Limestone breccia (intraclastic floatstone and rudstone)	• Matrix- or clast-supported. • Structurless (chaotic). • Large intraclastic limestone clasts and slump beds.
	Concentrated density flow to turbidity flow deposits Hemipelagic siliciclastic deposits		Alternating siliciclastic sandstone and mudstone	(Sandstone) • Normal grading, weakly parallel lamination, and climbing ripples, or structureless. (Mudstone) •Weak parallel lamination and weak bioturbation, or structureless.
	Concentrated density flow deposits Hemipelagic calcareous deposits		Alternating limestone (bioclastic and intraclastic floatstone and rudstone) and marl (wackestone and lime mudstone)	(Limestone) • Normally graded shell concentrations, structureless, with ammonoid imbrication. • Abundant molluscan fossils, microfossils, and intraclastic marl clasts (rip-up clasts). (Marl) •Weak bioturbation and structureless. •Common molluscan fossils and microfossils.
	Turbidity flow deposits Hemipelagic siliciclastic deposits		Organic-rich dark gray limestone (wackestone) and mudstone containing marl layers	(Limestone) •Parallel lamination and cross-lamination, or structureless. •Common molluscan fossils, and microfossils. (Mudstone) •Weak parallel lamination, or structureless. •Common microfossils and calcareous nodules.
	Hemipelagic calcareous deposits		Bedded marl (wackestone and lime mudstone) containing mudstone layers	•Weak parallel lamination and weak bioturbation, or structureless. •Common microfossils and rare bivalves.
	Hemipelagic siliciclastic deposits Turbidity flow deposits		Thick mudstone intercalated by sandstone and wackestone layers	(Mudstone) •Weak parallel lamination and weak bioturbation, or structureless. (Sandstone) • Cross-lamination and current ripple lamination.
	Slump deposits originating from hemipelagic calcareous deposits		Secondarily deformed marl beds	•Folded and deformed beds.
	Slump deposits originating from shelf deposits in the Lang Son Fm.		Secondarily deformed alternating siliciclastic sandstone and mudstone	

Fig. 26. Sedimentary facies and depositional environments. Modified from Komatsu *et al.* (2014).

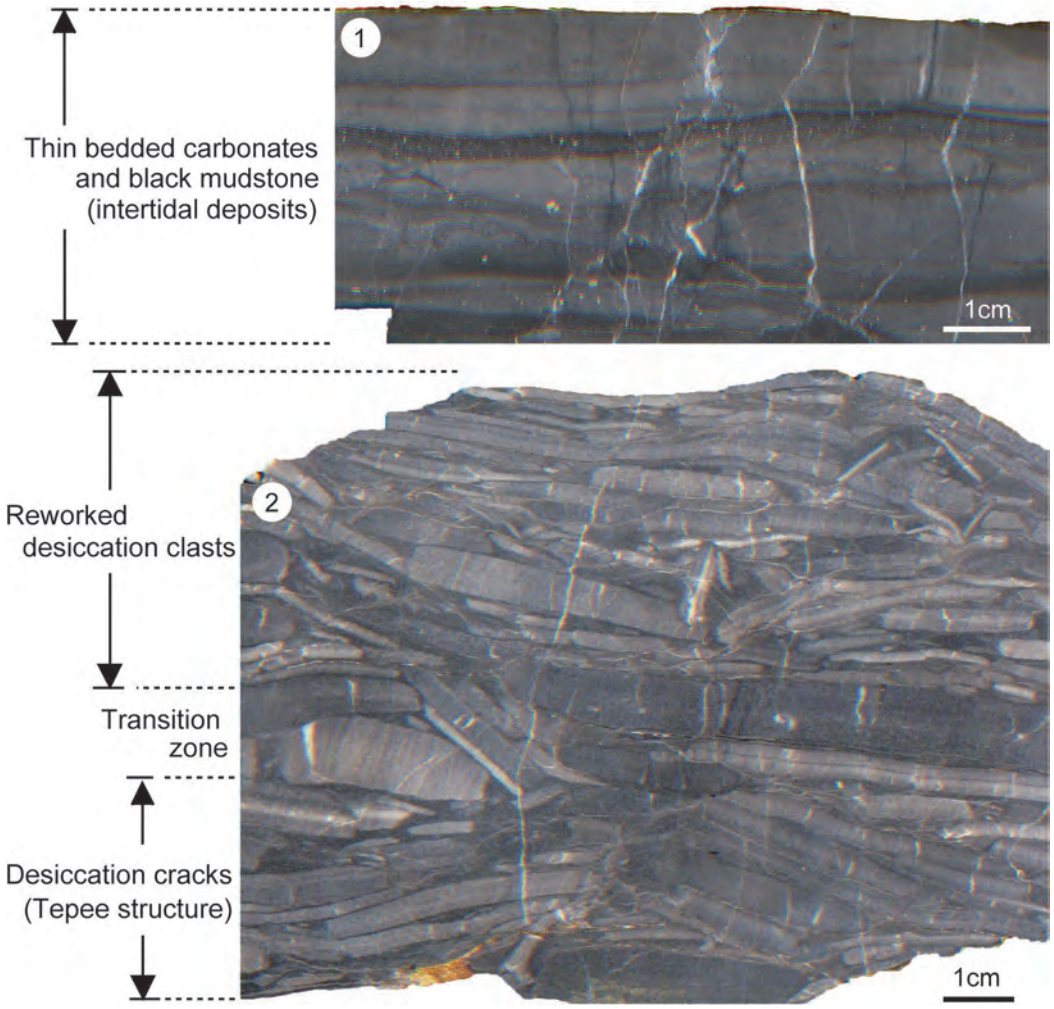

Fig. 27. Vertical cross sections of slabs from KC01. These deposits are interpreted to have accumulated in a tidal flat environment (Komatsu *et al*., 2014). 1, Alternating thin flat-bedded limestone and mudstone. 2, Intraclastic limestone containing tepee structures and desiccation cracks. Upper part of the slab is characterized by reworked desiccation clasts.

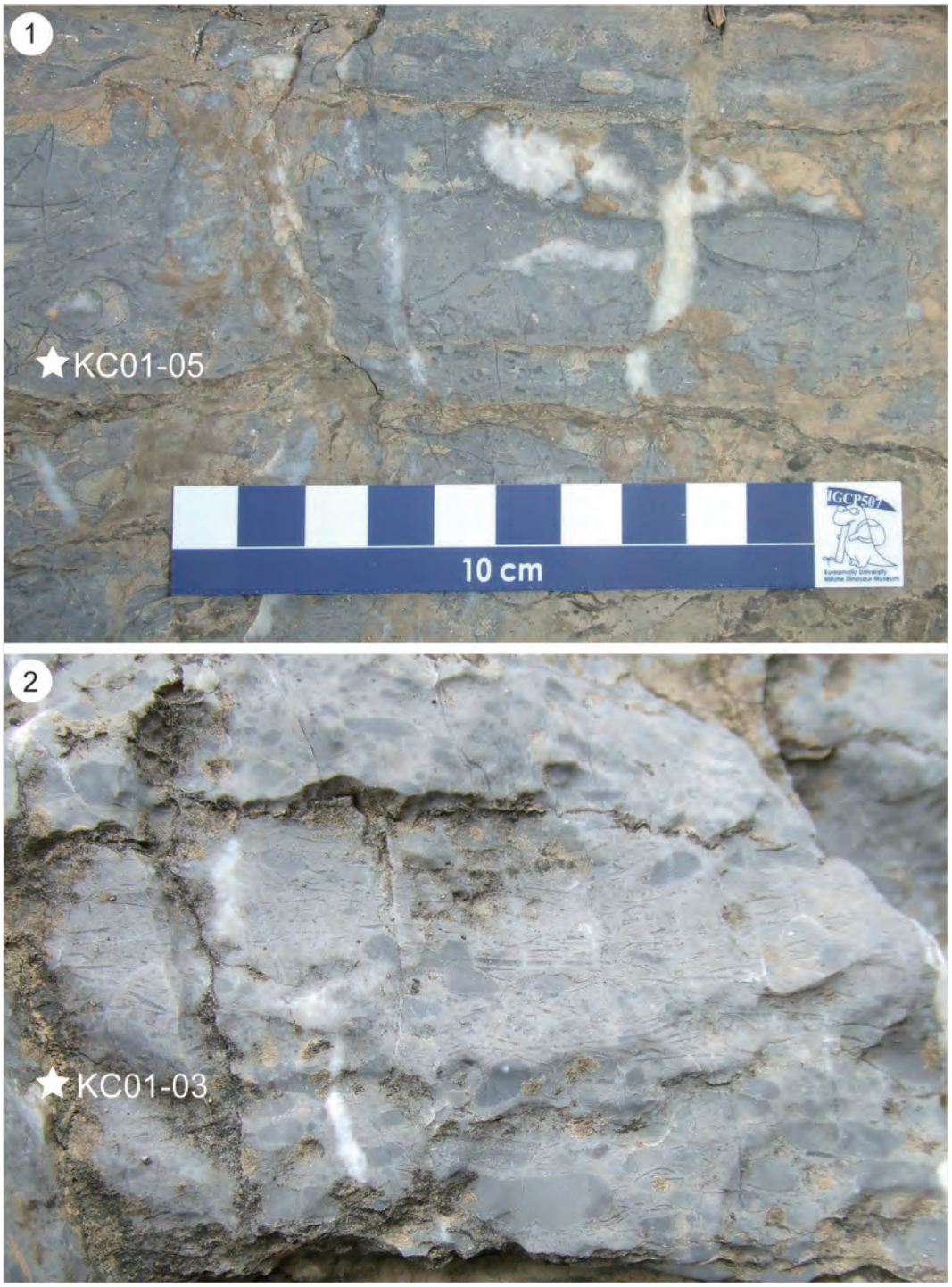

Fig. 28. Shallow marine carbonate lithofacies in KC01. 1, Bioclastic, oolitic and intraclastic limestone containing abundant thin-shelled bivalves and ammonoids at KC01-05. 2, Bioclastic, oolitic and intraclastic limestone at KC01-03.

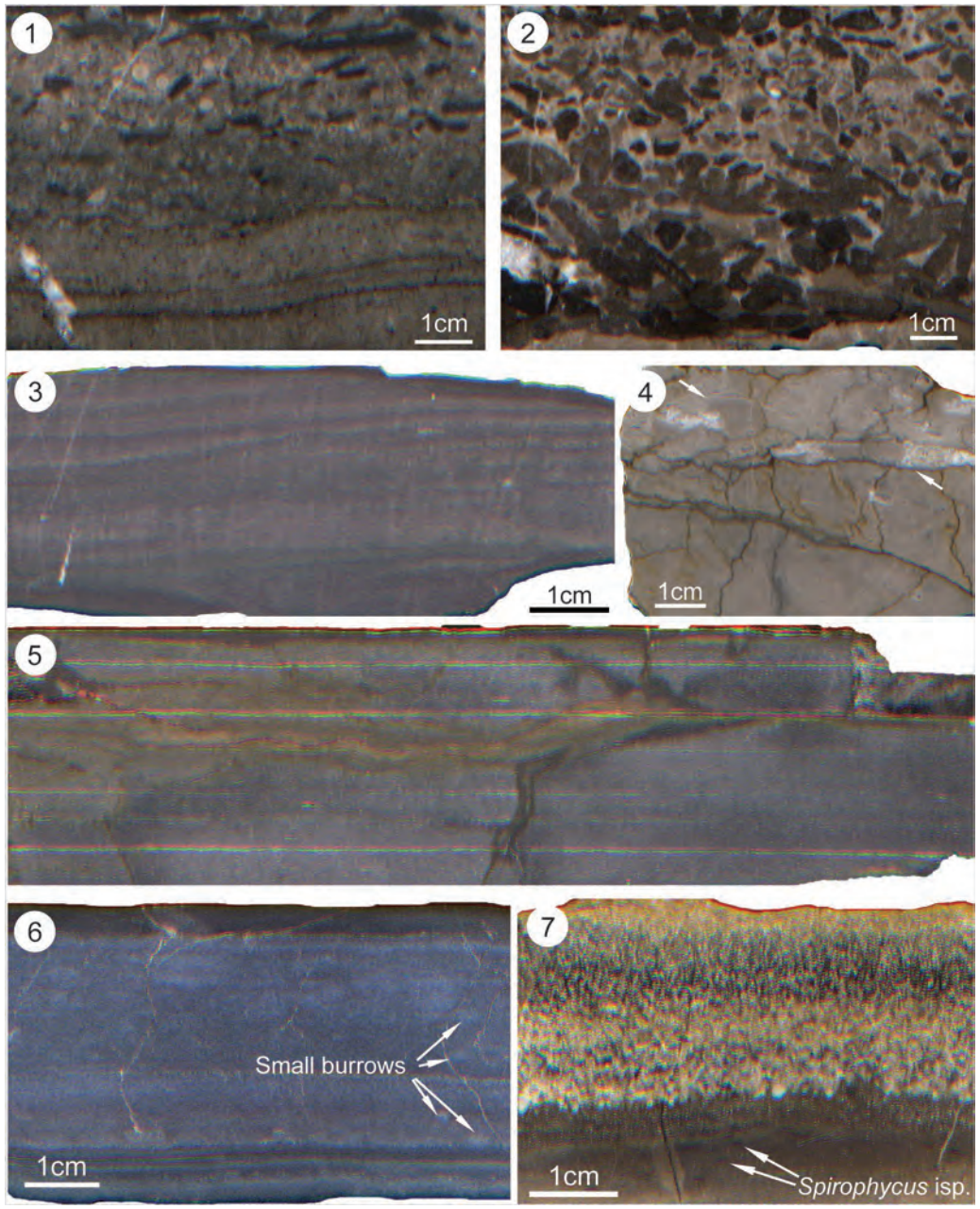

Fig. 29. 1–3, Vertical cross sections of shallow marine limestone slabs from KC01. 1, Intraclastic, oolitic, and bioclastic limestone from KC01-03. 2, Intraclastic limestone showing normal grading from KC01-09. 3, Low-angle cross-stratified limestone (hummocky cross-stratified limestone?) from KC01-05. 4, Vertical cross section of hemipelagic limestone slab from PK01. Bioclastic limestone contains ammonoid (arrows) and bivalve shells. The ammonoid shells show geopetal structures. 5, Laminated organic-rich dark gray mudstone from NT01. 6, Laminated organic-rich dark gray limestone containing small burrows in KC02 overlying well-laminated organic-rich black lime mudstone. 7, Calcareous sandstone showing normal grading and weakly bioturbated organic-rich, black lime mudstone containing tiny ichnofossils, *Spirophycus* isp. in NT01.