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The Cenozoic on-shore basins of Northern Vietnam: Biostratigraphy, vertebrate and invertebrate faunas

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ABSTRACT

A first account of paleontological data from three Cenozoic on-shore basins in Northern Vietnam, i.e. the Na Duong, Cao Bang, and Hang Mon basins, reveals a rich fossil fauna and flora of supposed Oligocene age, offering a great potential for taxonomic, paleoenvironmental, and paleobiogeographic studies. Two excavation campaigns unearthed well-preserved fossil remains of mammals, crocodiles, at least six turtle species, some 20 fish taxa, some other 20 mollusc species, and different plant remains. The majority of these taxa are regarded as new to science. However, close affinities to modern faunas of northern Southeast Asia demonstrate the importance of these fossils for an evaluation of the biological history of this modern biodiversity hot spot. Moreover, the fossil assemblages may help to disentangle the intricate Cenozoic tectonic evolution of Southeast Asia by application of paleobiogeographic modelling. Finally, the discovery of complex paleo-food-webs and the presence of several taxa indicative of certain ecological conditions provide a solid base for autecologic, synecologic and paleoclimatic studies. The potential biostratigraphic value of the macrofauna has to be demonstrated yet, as evolutionary concepts for most of the respective groups have not been proposed to date.

1. Introduction

Today, the Indochina region represents one of the global hotspots in biodiversity, especially with regard to continental flora and fauna. Geographically situated at the southeastern margin of the continent, along the transition between the tropical and subtropical climate zones, Vietnam applicably contributes to this diversity, as it owns various unique but often critically endangered terrestrial and freshwater ecosystems. Most of them are yet poorly studied, which is underlined by the occurrence of more than 100 vertebrate species that have been described as new during the past 15 years (Sterling et al., 2006). Moreover, research on the evolution of these ecosystems, which are tightly bound to the Cenozoic geodynamic history of Southeast Asia, is still in its infancy.

Herein we present the first results of joint German–Vietnamese paleontological expeditions to three of the major Cenozoic basins in Northern Vietnam during the years of 2008 and 2009. These field campaigns revealed a rich, diverse, and largely well-preserved plant, invertebrate, and vertebrate fossil record. A significant collection of fossils is currently under study, aiming at a detailed taxonomical and paleoecological evaluation. Preliminary results already demonstrate the great scientific potential of the Cenozoic fossil record of Northern Vietnam for the understanding of biostratigraphy, biogeography, and ecosystem development in Southeast Asia and beyond.

2. Geologic overview

Tectonically, Northern Vietnam is positioned at the boundary between the Indochina and Southern China microplates. According to Tapponier et al. (1990), Leloup et al. (1995), and Morley (2002) the Indian–Asian collision during the Eocene caused the southeastward extrusion of Indochina along a continental transform plate boundary, creating the more than 1.000 km stretching, NW–SE trending, left-lateral shearing Red River Fault Zone (RRFZ) (for a disparate model see Searle, 2006).

Resulting from the tectonic movements, several deep strike-slip basins evolved along the fault, which are filled with up to 6 km of sediments in on-shore basins (e.g. Lo basin, Wysocka and

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Świerczewska, 2003) and up to 17 km of Cenozoic sediments in offshore basins (Yinggehai–Song Hong basin; Clift and Sun, 2006). The strike-slip motion along the RRFZ occurred after initial extension in the Late Eocene (Clift and Sun, 2006) mostly during the Oligocene and Early Miocene (34–17 Ma: Gilley et al., 2003; 30–16 Ma: Zhu et al., 2009), coinciding with the spreading of the South China Sea (32–15.5 Ma: Zhen et al., 2006). Initial uplift and basin inversion was diachronous and started during the Late Oligocene in the northwestern part of the RRFZ (Clift et al., 2006) and during the Middle Miocene in the southeast (Clift and Sun, 2006; Zhu et al., 2009).

Parallel to the RRFZ several major and minor fault zones have developed, whose timing is less constrained. We currently investigate three pull-apart basins (Fig. 1) associated with the Cao Bang – Tien Yen fault (NE of the RRFZ) and the Son La fault zone (SW to the RRFZ).

The Cao Bang – Tien Yen fault, for which Pubellier et al. (2003) suggested comparable tectonic history to the RRFZ, is 230 km long and parallels the RRFZ by 160 km. Along this structure, three fault-controlled basins occur (Wysocka, 2009): the Cao Bang basin (in the NW), the That Khe basin (in the central part; not studied), and the Na Duong basin (in the SE, Fig. 1). The Son La fault zone is composed of several parallel faults (see Zuchiewicz et al., 2004: Fig. 2) and formed two relatively small Cenozoic basins, of which the Hang Mon basin is the more important one with regard to vertebrate paleontology.

3. Results

3.1. The Na Duong basin

According to borehole data, the Cenozoic sediments of the Na Duong basin are up to 570 m thick and rest on Triassic and Cretaceous terrigenous siliciclastics (Fig. 2; Wysocka, 2009). The sedimentary succession exposed in the Na Duong coal mine (Figs. 3 and 4A; coordinates: N21°42.2, E106°58.6) comprises 165 m of lacustrine sediments belonging to the Na Duong and Rinh Chua Formations (sensu Thuy, 2001).

In the outcrop, the coal-bearing Na Duong Formation comprises the lower, ~130 m thick portion of the sequence and represents an alternation of thickly bedded lignites, lignitic marls, carbonate claystones, marls, marly siltstones, and fine- to middle-grained sandstones.

The sandstones appear as massive, laterally extending beds, are occasionally flaser bedded (Fig. 3, bed #67) and mostly unstratified. They commonly contain badly preserved macrofloral remains. The bases of the sand-stone beds are non-erosive.

Lignites are developed as stratified lignitic clays and marls or as massive and bright sub-bituminous lignite. Lignitic clays are rich in both nodular and disperse pyrite and markasite (Fig. 4C). Some lignite seams are underlain by thin yellowish-, greyish-, and brownish-mottled clay beds containing slickensides. The absence of rooting structures indicates allochthonous phytogenic deposits.

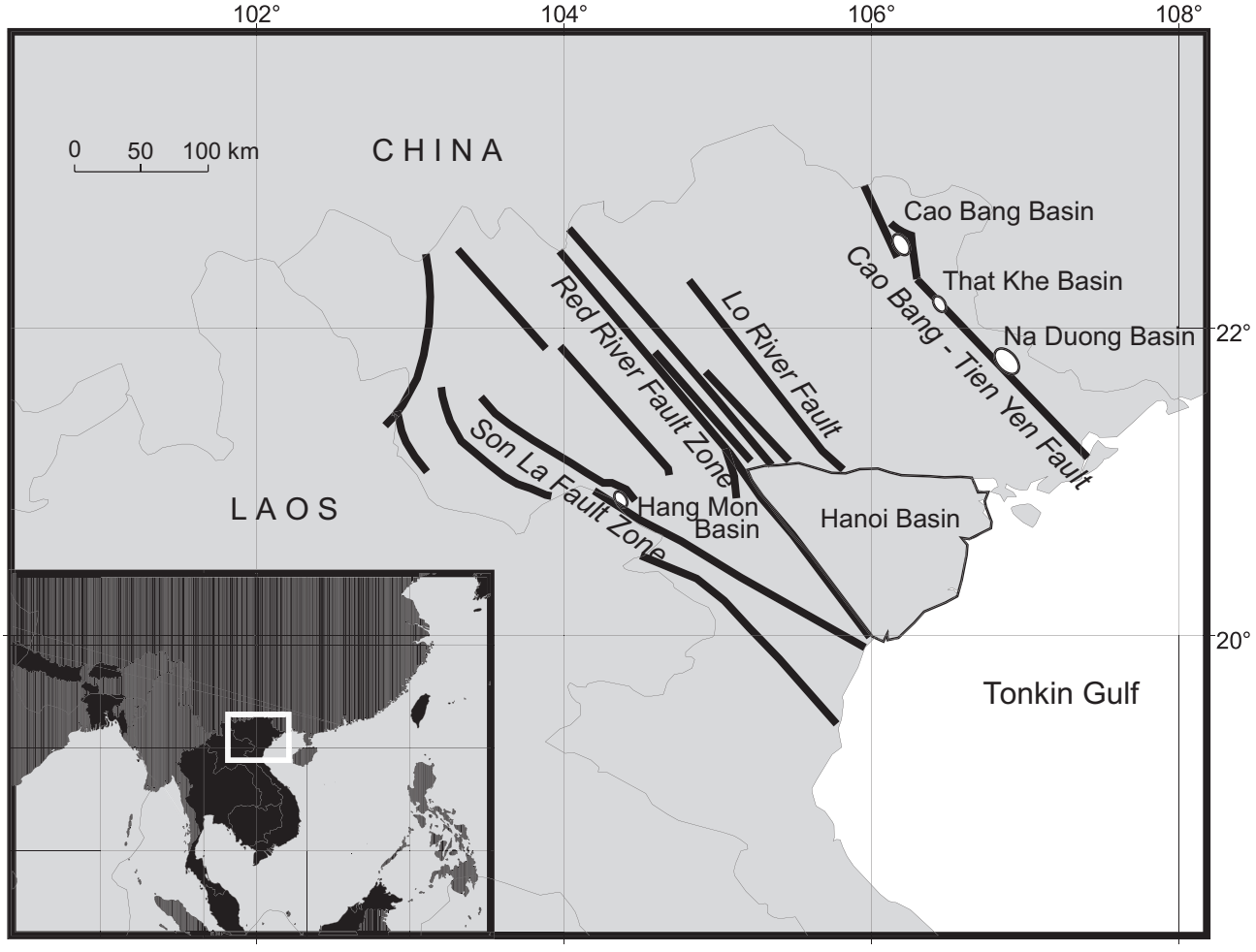

Fig. 1. Map of Northern Vietnam showing the major fault systems and the studied on-shore strike-slip basins (redrawn after Wysocka, 2009).

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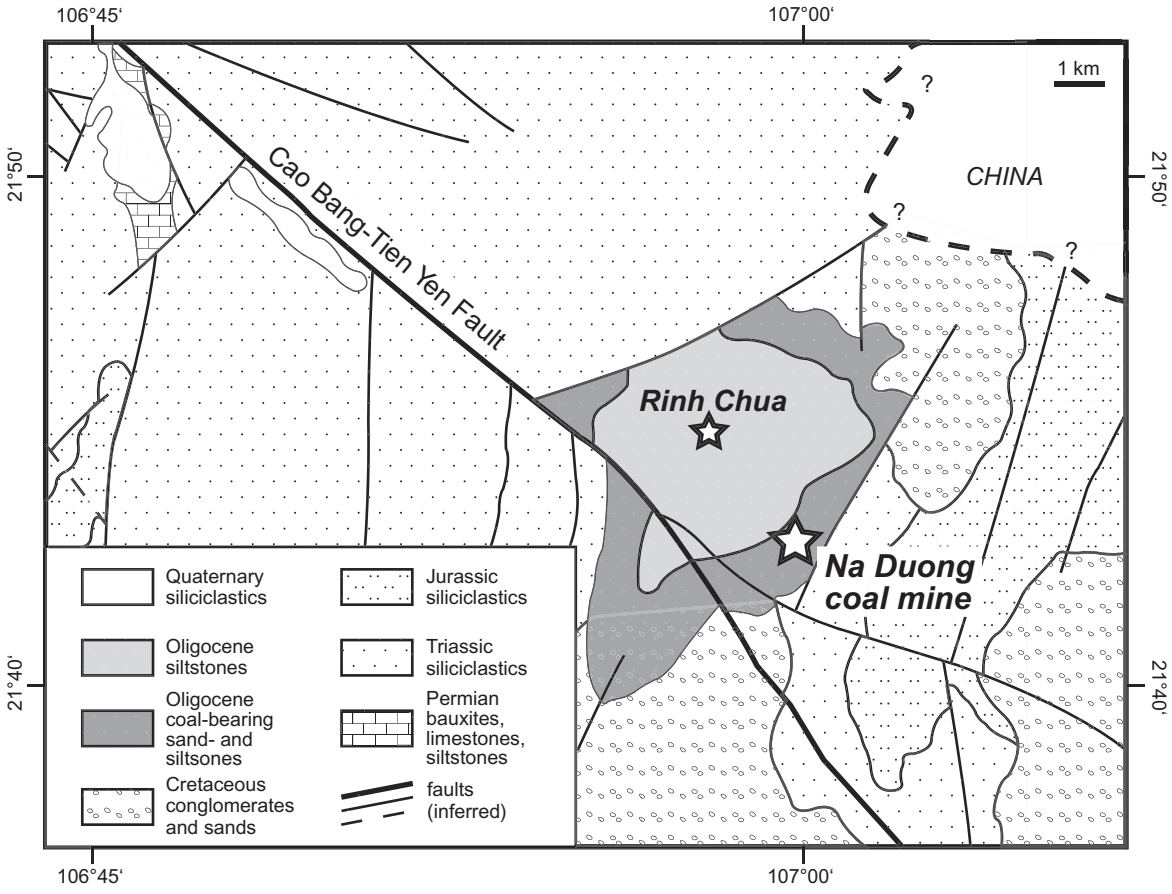

Fig. 2. Simplified geologic map of the Na Duong basin (redrawn after Wysocka, 2009).

Large tree trunk fragments appear sporadically in lignite seams (Figs. 4B and 5A) and in marls, but are most common in the upper third of the main lignite seam (Fig. 3, bed #80). Moreover, the base of the main seam and the underlying lignitic clays are extremely rich in vertebrate remains (see below).

The marls are typically beige, greyish, or brightly brownish in colour, occasionally bioturbated, and rich in plant debris. The sediment often contains fine-dispersed pyrite and, due to oxidation, may become reddish in colour after longer surface exposure. In several layers, molluscs occur in high abundance. Macrofloral remains (leaves and seeds) are usually well-preserved and the leaves still retain their cuticles. Fossil resin (pieces up to 2 cm in diameter) is found in several beds within brown to greyish-brown organic-rich marls, especially just above the top of lignite seams, but also within seams or within lignitic tree trunks.

The overlying, nearly 40 m thick Rinh Chua Formation lacks lignite seams and is dominated by brownish claystones (Fig. 3, bed #2, 9, 11, 13, 15, 16), which rhythmically alternate with marls containing fine-dispersed pyrite. The alternation is fairly regular and 0.45–0.8 m of claystone are usually followed by 0.15 m of marl. The thin-bedded marls appear brownish when fresh, but reddish to purple after subaerial alteration.

Cyclicity is also well developed within calcareous marls (Fig. 3, bed #10, 14) and silty marls (bed #4, 5, 7, 8) in the coal pit, as well as at the stratotype of the formation at the flank of the Ky Cung river at Rinh Chua village (Wysocka, 2009: Fig. 9). Minor components are massive fine- to middle-grained sandstones (bed #1, 3, 6, 12), which sometimes contain badly preserved plant debris. Claystones and marls yield abundant molluscs and fish remains. A silty to sandy marl bed near the top of the profile (bed #7) is densely stuck with gastropod shells and may be attributed as viviparid-?*Tarebia* coquina; a similar bed is also found in the stratotype section.

Both the Na Duong and the Rinh Chua formations are rich in mollusc (Fig. 6) and vertebrate fossils. Pelitic sediments frequently contain mussels and viviparid gastropods, whereas thiarids only occur in siliciclastically influenced beds of the Rinh Chua Formation. Vertebrate remains are present in all lithofacies types. Disarticulated fish bones and teeth (minnows, catfishes) are especially common in claystones, but also occur in lignites and sands. A few isolated crocodile teeth and a badly preserved isolated lower molar of a rhinocerotid have been found in the marl beds. However, the main vertebrate bearing horizons are located at the base of the main coal seam and in the underlying lignitic clays. During 10 days of excavation, more than 50 shells of freshwater turtles, as well as several crocodile and mammal remains have been found (Figs. 4D and 7).

3.2. The Cao Bang basin

The Cao Bang basin is a fault-bordered pull-apart structure situated along the Cao Bang – Tien Yen fault (Fig. 1). Cenozoic sediments are exposed in a small (10 × 7 km wide) NW–SE elongated area around the provincial capital Cao Bang (Fig. 8). Outcrops occur scattered and spatially restricted within the town, where they are found at roadside ditches, building pits, or in small, mostly abandoned lignite or clay mines.

The sediments dip with up to 40° either to the SW or NE and are heavily faulted, disabling a proper correlation of the outcrops. Long (2001) mentions a total thickness of the basin fill of

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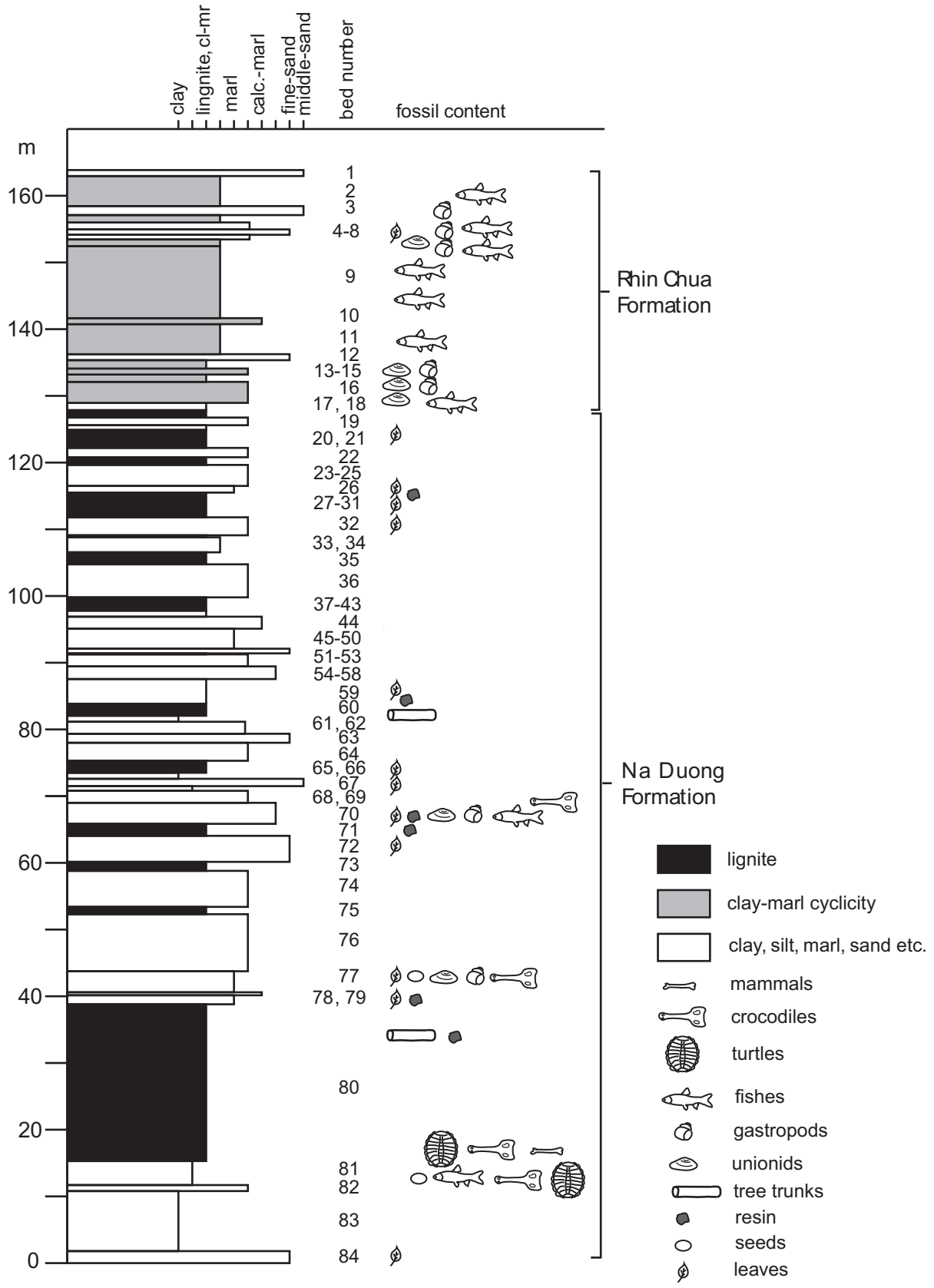

Fig. 3. Sedimentological profile and fossil content of the Na Duong coal mine (Loc Binh district, Lang Son province).

900–950 m referred to the Cao Bang (coarse grained lower part) and Na Duong Formations (fine grained upper part; Thanh and Khuc, 2006). This fluvial to lacustrine succession is subdivided by Long (2001) into eight members, the topmost of which contains up to 10 minor and horizontally limited lignite seams (up to 0.6 m thick).

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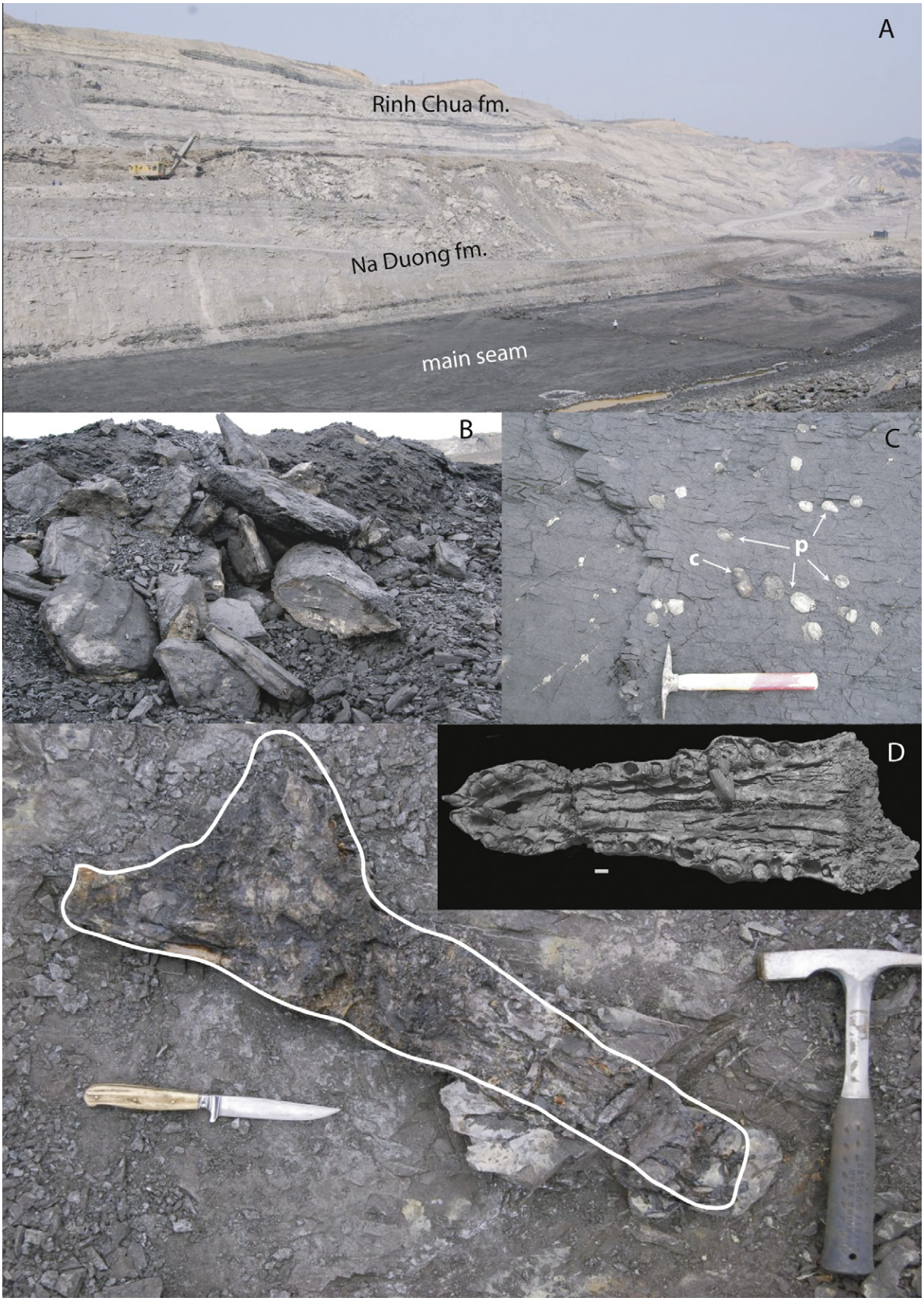

Fig. 4. (A) Overview of the Na Duong coal mine (viewing direction NE; coordinates: N21°42.2, E106°58.6), (B) carbonized tree trunks from the main seam, (C) lignitic clays (bed #81) with abundant markasite and pyrite concretions (p) and crocodilian coprolites (c), and (D) skull of a longirostrine crocodile during excavation and the anterior part of the snout after preparation (scale-size 1 cm).

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Fig. 5. (A) Stem of a large-sized arborescent Osmundaceae fern (Na Duong coal mine, bed #81; scale 1 cm). (B) Lower? first molar of a tragulid or lophomericid (Hang Mon coal mine), from left to right: labial, occlusal, lingual (scale 1 cm).

We have studied six outcrops in detail (see appendix for coordinates), where four main facies types can be distinguished: (1) lacustrine-deltaic, (2) lacustrine deep-water (both Na Duong Formation), (3) terrestrial overbank, and (4) fluvial facies (both Cao Bang Formation). The lacustrine-deltaic facies is characterized by brownish to greyish or bluish-grey clays and marls, which alternate with minor lignite beds or lignitic marls and thin, sometimes concretional carbonate marl beds. The marls contain fine-dispersed pyrite, which oxidized under longer surface exposure resulting in pink to red colours. Frequently, channel-like fine- to coarse-grained sand-stone beds showing cross- or flaser bedding are incised in the pelitic sequences. Fine-grained sediments are rich in molluscs, fish remains (see below), and leaves; the latter also occur in sandstones together with few fragments of turtle bones and crocodile coprolites.

The terrestrial overbank facies is represented by up to 20 m thick paleosoils composed of red- and yellow-mottled clays with frequent slickensides and root traces, but without pedogenic carbonate concretions, and can be addressed as planosol (a soil type typical for seasonally waterlogged areas of the subtropics; IUSS Working Group WRB, 2007). The outcrop situation indicates syndepositional pedogenesis. The paleosoils are interbedded with cross-stratified sandstones with minor fine-gravel content, which represent the fluvial facies type. The sandstones contain a badly preserved macroflora (leaf imprints without cuticles). Additionally, Wysocka (2009) describes conglomerate facies attributed to an alluvial fan.

The most important exposure with regard to paleontology is an active brickyard (coordinates: N22°40.72, E106°15.23) within the municipal area of Cao Bang (Fig. 9), where clays of the lacustrine-deltaic facies of the Na Duong Formation are mined. However, the present outcrop situation is too inadequate to provide an informative sedimentologic profile. The studied section is composed of an approximately 20 m thick succession of clays and marls with few intercalated silt and fine-sand bodies. These sediments are erosively overlain by middle to late Pleistocene gravels and palaeosoils (reddish–yellowish planosols), containing abundant indochinite tektites. The base of this terrace at 225 m a.s.l. is positioned 48 m above the level of the present-day Bang River.

Clays, marls, silts, and fine-sands all yield a rich unionid fauna (Fig. 10). Six species have been distinguished, representing forms of rather disparate shell shape. Additionally, a single species of hydrobiid gastropods has been found in certain clay levels in the lower part of the succession. Moreover, fish remains (teeth, bones, and fin spines) occur in high abundance and may be assigned to at least 12 species (Fig. 11).

3.3. The Hang Mon basin

The Hang Mon basin (Figs. 1 and 12; coordinates: N20°56.15, E104°22.22) has an extension of only a few square kilometres and is located at 920 m a.s.l. The Cenozoic sediments referred to as the Hang Mon Formation rest on Middle Triassic limestones (Bao, 2004), are 90–116 m thick (Thanh and Khuc, 2006), and are severely tectonically faulted. According to Thanh and Khuc (2006) the succession starts with clayey shales, thin travertine beds and siltstones, interbedded with lenses of conglomerates and coarse-grained sandstone, which are followed by 10 lignite seams that alternate with lignitic clays. The upper 60–70 m of the section are composed of clay- and siltstones with minor lignitic beds.

Today, the abandoned and groundwater-filled mine exposes only the upper ~10 m of this succession. Above the water-table, 3 m of marly siltstones with thin lignitic, gastropod-bearing beds are found (Fig. 13). All identified gastropods are land snails, which are moderately well-preserved and belong to three genera (Table 1). Most of the mammalian remains published by Covert et al. (2001) are derived from this horizon. Up-section, 2 m of grey,

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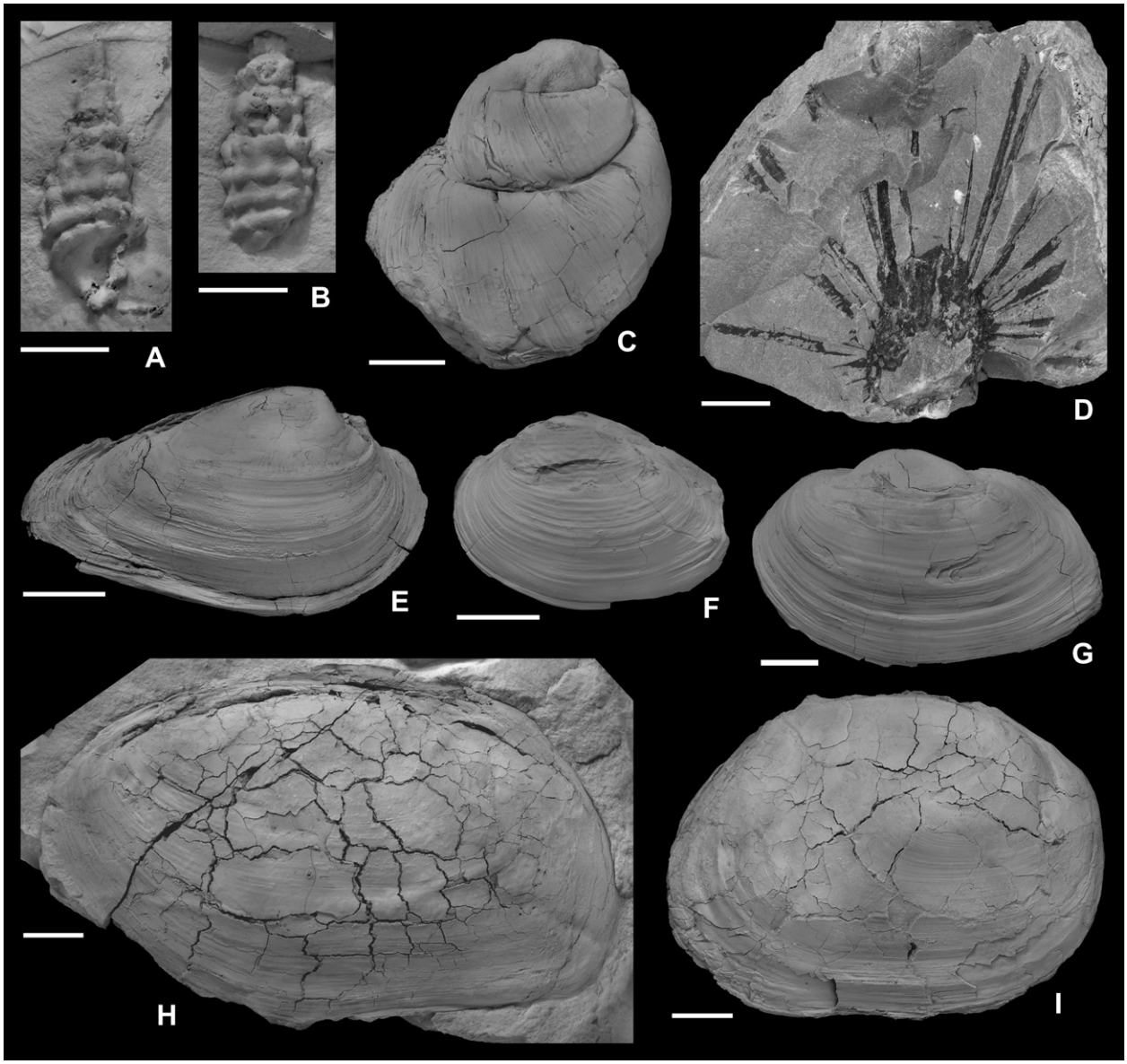

Fig. 6. Fossils from Na Duong coal mine. Scale bars = 1 cm. (A–C) Gastropods. (A and B) ?*Tarebia* sp.; latex casts from external moulds. (C) Viviparidae indet. (D) ?*Isoetes* sp.; corm with roots. (E–I) Unionidae. (E) ?*Cuneopsis* sp. 3; partial internal mould of articulated specimen. (F and G) Unionini indet.; articulated specimens with preserved shell. (H) *Anodontini* sp. 1; internal mould of articulated specimen. (I) *Anodontini* sp. 2; partial internal mould of articulated specimen. All specimens coated with NH_3Cl.

marly sandstones with thin irregular beds of fine-grained gravels containing abraded mammal bones follow. A similar bed, positioned ~6 m above the water-table has yielded a much worn mammal tooth (most likely a first lower molar, 1.05 × 0.60 cm, Fig. 5B). This specimen cannot be confidently determined and shows morphologic characters present in tragulids and lophomericids.

4. Discussion

4.1. Fossil content, paleoecology and paleoenvironment

4.1.1. Na Duong basin

The mollusc assemblage occurring in the marl beds of the Na Duong Formation is composed of numerous small unionines, two moderately large anodontin mussels, and frequent large viviparid gastropods (Table 1 and Fig. 6). Usually, the shells of the mussels are still articulated or preserved in butterfly-position and may therefore be considered as autochthonous. Fishes are less common in these beds. Several isolated pharyngeal teeth and one complete pharyngeal bone with attached teeth belong to a medium-sized new genus of barbel (?Barbinae nov. gen. 2) and show adaptations to malacophagy (feeding on molluscs). Altogether, the mollusc and fish assemblage of the marls indicates a shallow, well-oxygenated lacustrine environment. This observation is corroborated by the presence of ?*Isoetes* sp. (Fig. 6D), which is typically growing submersed in still waters. In several marl beds these plants occur in high frequency and have clearly been fossilized in live position. Likely, the filtering activity of a large mussel population was highly effective in clearing the water body, enabling ideal conditions for photosynthesis of ?*Isoetes*.

In the main vertebrate bearing horizons at and just below the base of the main lignite seam, the malacophagous barbels are accompanied by remains of a catfish (Siluriformes indet.) and a yet unidentified teleost (Teleostei indet.). However, the most common vertebrates from these horizons are turtles. Frequently, their

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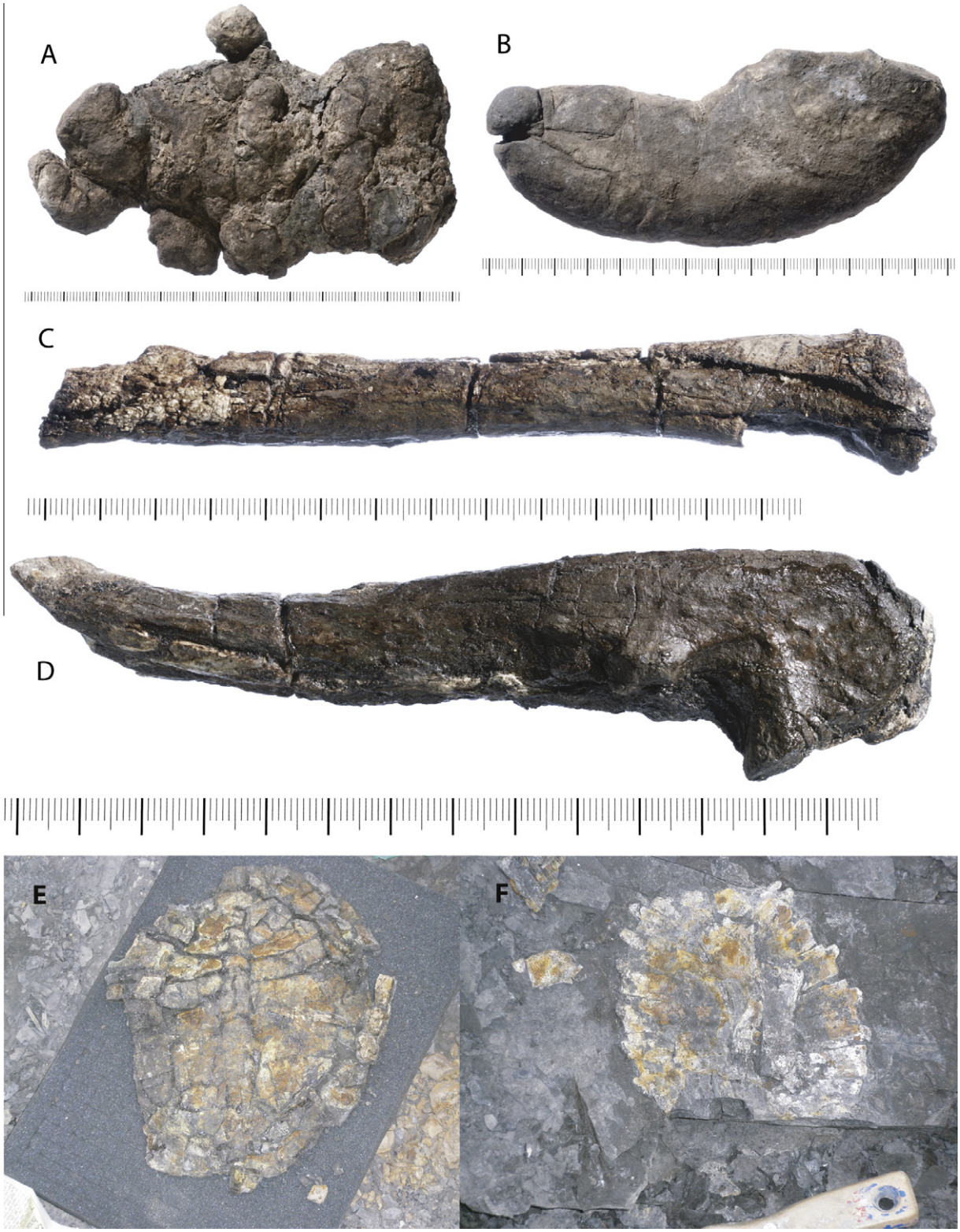

Fig. 7. Fossils from Na Duong coal mine, bed #81. (A and B) Different-shaped phosphatic coprolites referred to crocodiles. (C and D) Tibia (C) and ulna (D) of a tragulid or lophomericid. (E) Shell of geoemydid turtle (carapax length 35 cm). (F) Shell of a trionychid turtle (carapax length 15 cm) (scale in mm).

shells are still articulated, but lack the cranial and appendicular skeleton. Based on preliminary identification, the diversity of turtles is remarkably high, comprising six taxa that belong to the Geoemydidae, Trionychidae, and possibly Ptychogastridae (Table 1 and Fig. 7E and F), all of which exhibit an aquatic lifestyle. Crocodile remains have been found either as disarticulated bones or as partially articulated skeletons. A single almost complete skull (Fig. 4D) clearly belongs to a longirostrine taxon. Exceptionally common are phosphatic coprolithes that may also be referred to crocodiles (Fig. 7A and B). The few mammalian remains from this horizon, a tibia and an ulna, belong to a large-sized tragulid or lophiomericid (Fig. 7C and D). Both bones are distally broken and

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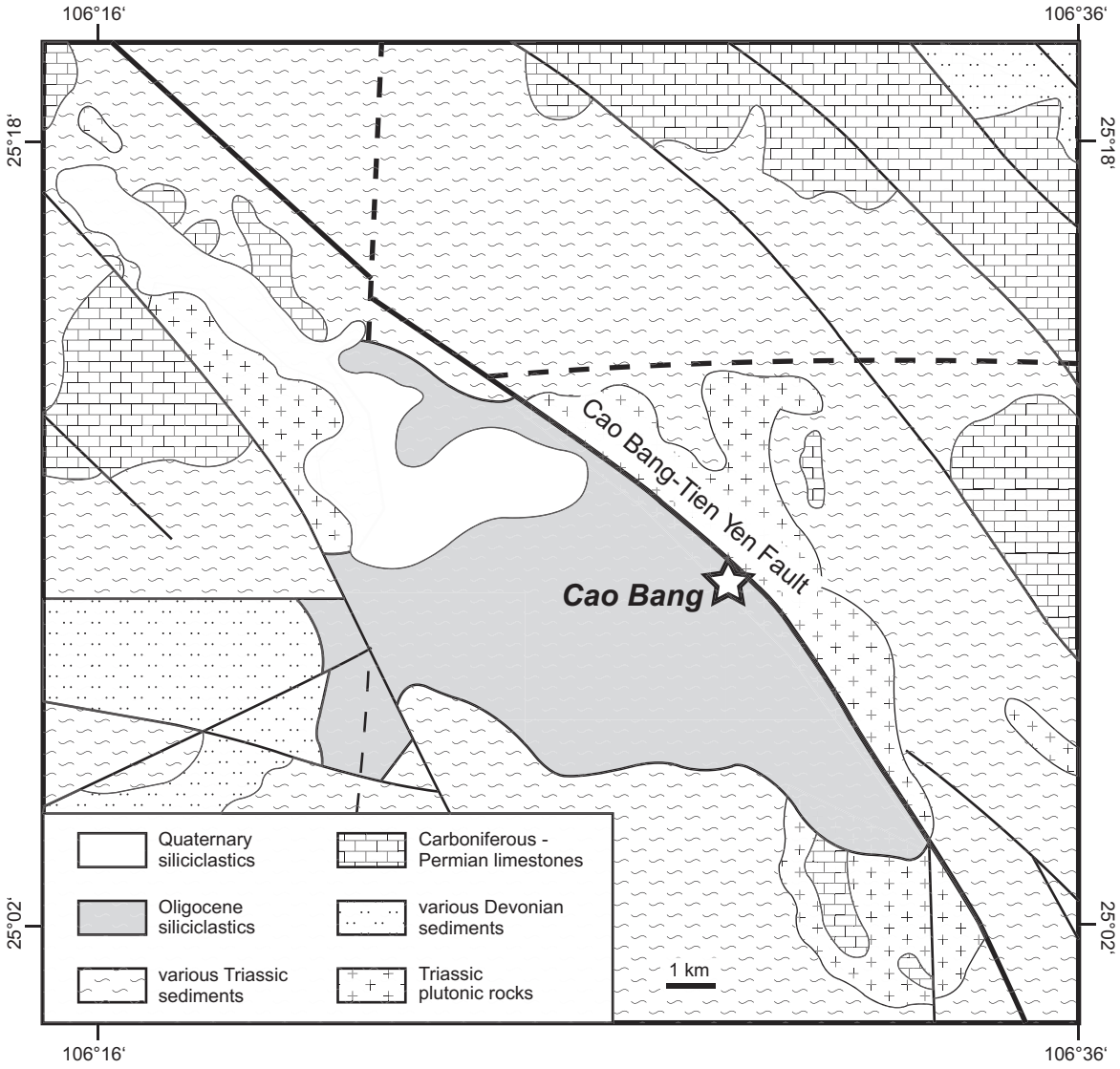

Fig. 8. Simplified geologic map of the Cao Bang basin (redrawn after Wysocka, 2009).

Fig. 9. Sampled outcrop (marls with minor silt- and sand-stone beds) in the brickyard of Cao Bang (coordinates: N22°40.721, E106°15.231; the Pleistocene terrace can be seen in the background, to the left; profile height ~5 m).

may have been crushed by the crocodiles. Potentially, turtles have also been an important food source for the crocodiles. This is suggested by bite-marks in several isolated shell plates. A turtle shell accumulation of 2.5 sq. m size (Fig. 14), that is composed of at least six individuals belonging to different species, may provide further evidence for this hypothesis, as the up to 30 cm long turtles are associated with few fish bones and a single crocodile tooth.

In the upper third of the main lignite seam fossilized tree trunks occur. The up to 5 m long stems are early-diagenetically carbonized and synsedimentary compressed (Fig. 4B), and wood-anatomical structures are badly preserved. Commonly, the trunks were abraded before fossilization and lack the stump, indicating transport and allochthonous deposition. Additionally, up to 1 m long stems of arborescent Osmundaceae ferns occur relatively frequent (Fig. 5A). The fossil assemblage together with the geologic observations (see above) indicate that the lignitic marls and lignite seams were deposited in a shallow aquatic environment, virtually a swamp, that was prone to extremely low oxygenation.

In the sediments of the Rinh Chua Formation, no significant change in mollusc faunal composition occurred. However, two additional taxa appear in the upper part of the succession, i.e. the gastropod ?*Tarebia* (Fig. 6A and B; bed #7 in Fig. 3) and a

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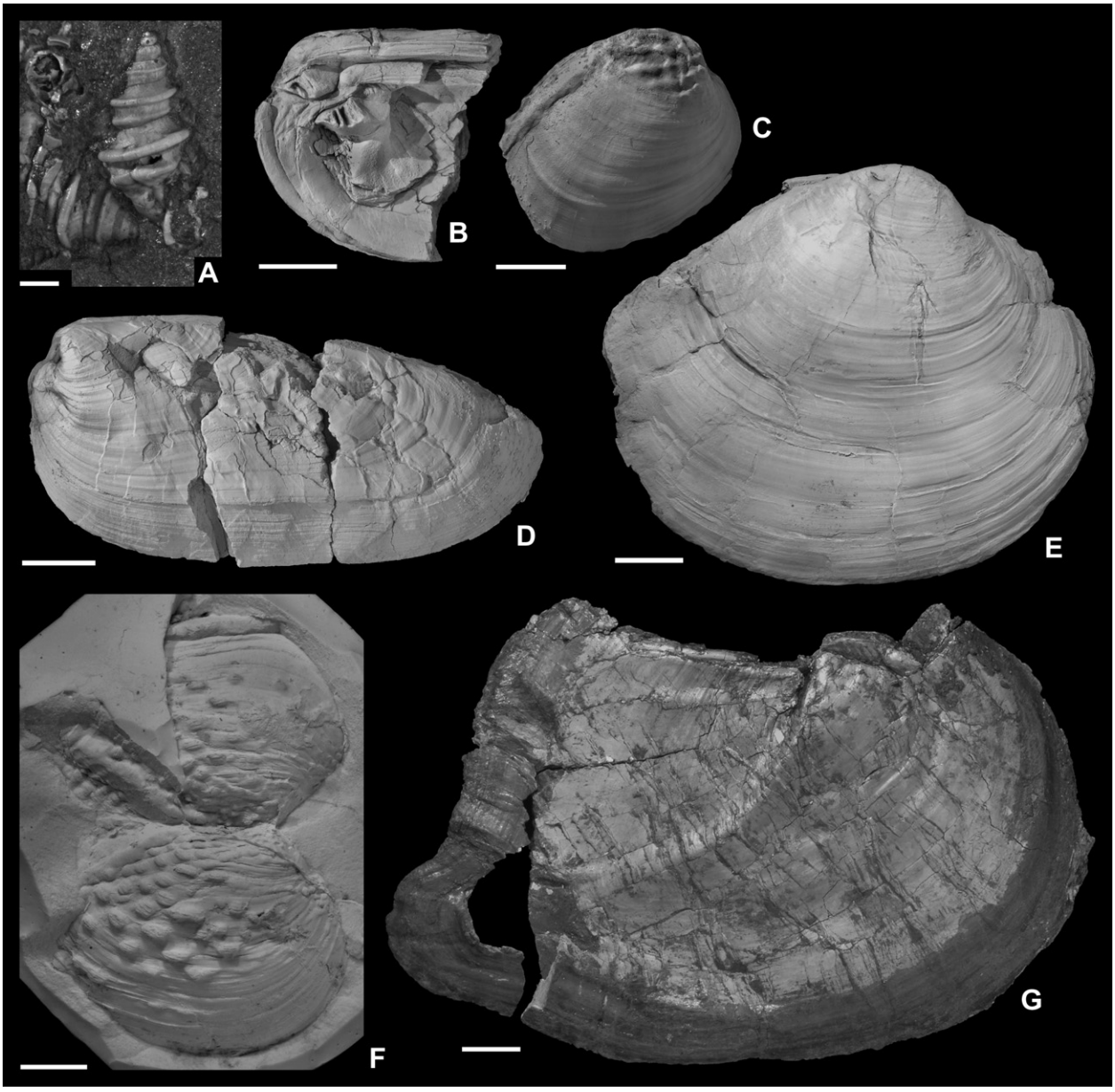

Fig. 10. Molluscs from Cao Bang brickyard. (A) Hydrobiidae indet. Scale bar = 1 mm. (B–G) Unionidae. Scale bars = 1 cm. (B) *Cuneopsis* sp. 1; hinge fragments of two right valves. (C) Juvenile *Lamprotula* sp.; right valve showing typical W-shaped wrinkles. (D) *Cuneopsis* sp. 1; articulated specimen. (E) *Lamprotula* sp.; articulated specimen. (F) ?*Lamprotula* sp.; specimen in butterfly-position; latex cast of external mould. (G) ?*Hyropsis*/*Cristaria* sp.; articulated specimen. Specimens B, D–F coated with NH_3Cl.

moderately slender representative of ?*Cuneopsis* (Fig. 6E). Although modern representatives of *Tarebia* are rather opportunistic in habitat selection (Brandt, 1974), they seem to be restricted to sandy sediment in the Rinh Chua Formation, occurring only in viviparid/?*Tarebia* coquinas, which may have accumulated during phases of low sedimentation. In contrast to the molluscs, the fish fauna of the Rinh Chua Formation has changed significantly in comparison to the Na Duong Formation. Ten species have been identified, i.e. one catfish and nine cyprinid fishes (Table 1). The cyprinid fauna is dominated by two small-sized omnivorous barbels (Barbinae sp. 1, 2). In addition, the malacophagous ?Barbinae nov. gen. 2, two phytoplanktophagous cyprinids (Hypophthalmichthyinae nov. gen., Xenocyprininae indet.), three species of zooplanktophagous cultrins and/or acheilognathins, and a further, yet unidentified cyprinid taxon occur.

The mollusc and fish assemblage indicates a lacustrine environment of somewhat greater water depth than represented by the marl sediments of the Na Duong Formation, as may already be suspected from the cyclic alternation of claystones with pyrite-bearing marls. This cyclicity may display changes in productivity and/or sediment oxygenation. The sand-stone beds, which feature ripple marks in the stratotype section (see Wysocka, 2009: Fig. 8D), may have formed during periods of lower water level.

4.1.2. Cao Bang basin

Although attributed to the Na Duong Formation, the mollusc fauna of the sediments exposed in the Cao Bang brickyard section does not share any species with the Na Duong and Rinh Chua Formations of the type localities in the Na Duong basin (Table 1). This is particularly remarkable, because part of these mollusc bearing strata may be assigned to similar environments. The unionid fauna of Cao Bang is more diverse than at Na Duong. It is dominated by two species of *Cuneopsis* (Fig. 10B and D) and large, wing-shelled ?*Hyropsis*/*Cristaria* (Fig. 10G). Relatively frequent is a large

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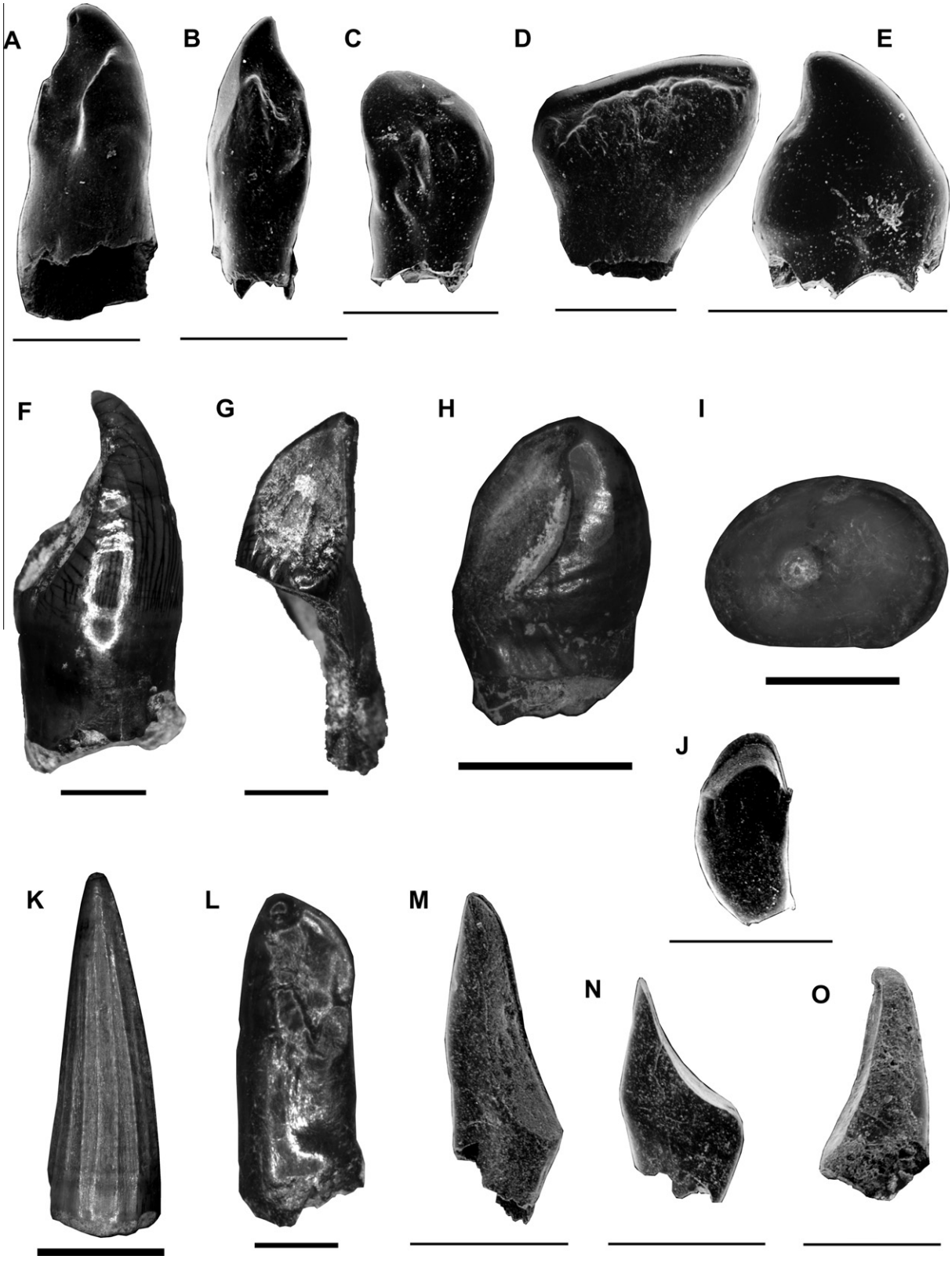

Fig. 11. Fishes and crocodiles from Cao Bang brickyard. (A and B) Barbinae sp. 1. Scale bar = 1 mm. (C–E) Barbinae sp. 2. Scale bar = 1 mm. (F and G) Barbinae sp. 3. Scale bar = 2 mm. (H and I) Barbinae nov. gen. Scale bar = 5 mm. (J) Labeoninae indet. Scale bar = 1 mm. (K) ?Tomistominae indet. Scale bar = 5 mm. (L) Gobioninae indet. Scale bar = 2 mm. (M) Xenocyprininae sp. 1. Scale bar = 1 mm. (N) Xenocyprininae sp. 2. Scale bar = 1 mm. (O) Cultrinae sp. 1. Scale bar = 1 mm.

globular-shaped species of *Lamprotula* (Fig. 10C and E). In addition, ?*Lanceolaria* and probably a second *Lamprotula* species occur (Fig. 10F). The shells of all mussel taxa are frequently preserved articulated or in butterfly-position, but single valves may also occur. Nonetheless, they may clearly be considered as autochthonous. Interestingly, viviparid gastropods, although being among

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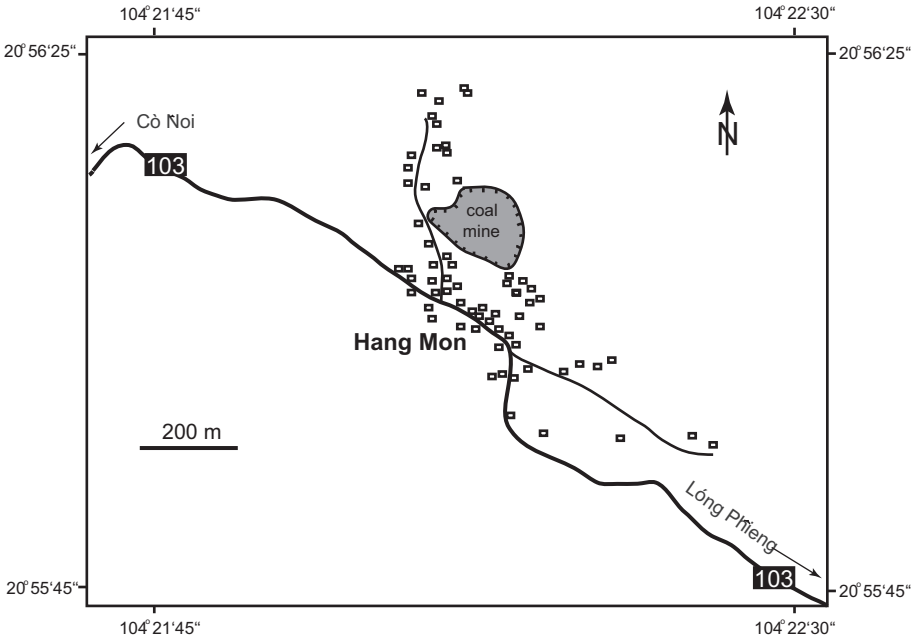

Fig. 12. Map showing the position of the Hang Mon coal mine (Yen Chau district, Son La province).

the most frequent fossils in the Na Duong and Rinh Chua formations of the type area, are totally absent. The only gastropod recorded from Cao Bang is a small strongly carinate hydrobiid (Fig. 10A), which occurs in high abundance in thin levels of clayey sediment.

Similar to the molluscs, the fish fauna is taxonomically largely different from, and, with 12 species recorded, somewhat more diverse than in the Na Duong basin. In addition, the fossil content of the sediment is much higher, with up to 100 determinable fish fragments (teeth, bones) found in 100 g of sediment. The most common fish taxon is the phytoplanktophagous Xenocyprininae sp. 1 (Fig. 11M), followed by the two omnivorous barbels Barbinae sp. 1 and 2 (Fig. 11A–E). The latter two taxa, together with Cultrinae sp. 1, (Fig. 11O) may represent the only fish species that are shared with the Rinh Chua Formation; however, species level taxonomy of these fishes is not completely disentangled to date. Large piscivorous barbels (Barbinae sp. 3, Fig. 11F and G), the phytoplanktophagous Labeoninae indet. (Fig. 11J), and Xenocyprininae sp. 3 (Fig. 11N), the omnivorous Gobioninae indet. (Fig. 11L), as well as two medium-sized catfishes (*Mystus* sp., Bagridae indet.) and a yet unidentified teleost species all represent relatively rare elements of the Cao Bang fossil fauna. The by far largest fish at Cao Bang was an impressive representative of the Barbinae (Barbinae nov. gen. 1, Fig. 11H and I) that is relatively frequently recorded by isolated teeth, tooth-bearing pharyngeal bones, cranial bones and vertebras. It clearly belongs to a new genus and species and shows pronounced morphological adaptations for malacophagy. Estimated from the collected fossils, these fishes may have reached a maximum size of more than 2 m, which would be roughly the size class of the largest living cyprinids. Both the remarkable size and the specialized tooth morphology may suggest that these barbines preyed even on adult, heavy-shelled unionids, which would be an adaptation that is unique among cyprinids and, moreover, among freshwater fishes at all.

The only tetrapod remain found at Cao Bang is a slender crocodile tooth (Fig. 11K), which may belong to a piscivorous tomistomin.

Based on a first comparison with modern representatives, all mollusc taxa are moderately indicative of environment, as they may occur in calm habitats within rivers (unionids rarely occur in turbulent environments) as well as in well-oxygenated ponds or lakes (Brandt, 1974; Savazzi and Peiyi, 1992; observation S. Schneider). However, the extended, thin-shelled, peculiar wings of ?*Hyropsis*/*Cristaria* may rather point to fluviatile conditions. This agrees with the fish fauna, which indicates an eutrophic lake bearing an extraordinarily complex trophic structure. From sedimentology, a moderately deep and near-deltaic paleoenvironment may be concluded.

4.1.3. Hang Mon basin

The land snails found at Hang Mon may tentatively be assigned to three different genera, i.e. *Lagochilus*, *Ptychopoma* and ?*Tortaxis*. However, preservation is too limited to enable specific determination. As data on ecology of these snails are extremely scarce, any paleoecological conclusions may not be drawn to date. However, the absence of fishes and aquatic molluscs, and the presence of a relatively diverse mammal fauna in the exposed portion of the section (Fig. 5B; Ginsburg et al., 1992; Covert et al., 2001) may point to a largely terrestrial riverine environment with back-swamp habitats. The absence of well-developed paleosoils may indicate rapid sedimentation.

5. Biostratigraphy

Recent palynological studies in the Na Duong and Hang Mon basins revealed several spore and pollen taxa of biostratigraphical importance, i.e. *Cicatricosisporites dorogensis*, *Verrutricolporites pachydermus*, and *Gothanipollis bassensis* (see Trung et al., 2000: Na Duong Formation, Na Duong coal mine; Dy et al., 1996: Rinh Chua Formation, stratotype section; Thanh and Khuc, 2006: Hang Mon Formation). These palynomorphs typically co-occur in the late Paleogene, especially in the Oligocene (Krutzsch, 1967; Germeraad et al., 1968; Trung et al., 1999; Jianguo et al., 2008). Highly similar palynologic assemblages are also reported from the Dinh Cao Formation of the Hanoi basin (Thanh and Khuc, 2006) for which an Oligocene age is broadly accepted (Clift et al., 2006). Germeraad et al. (1968) established the *C. dorogensis* palyno-zone and pointed

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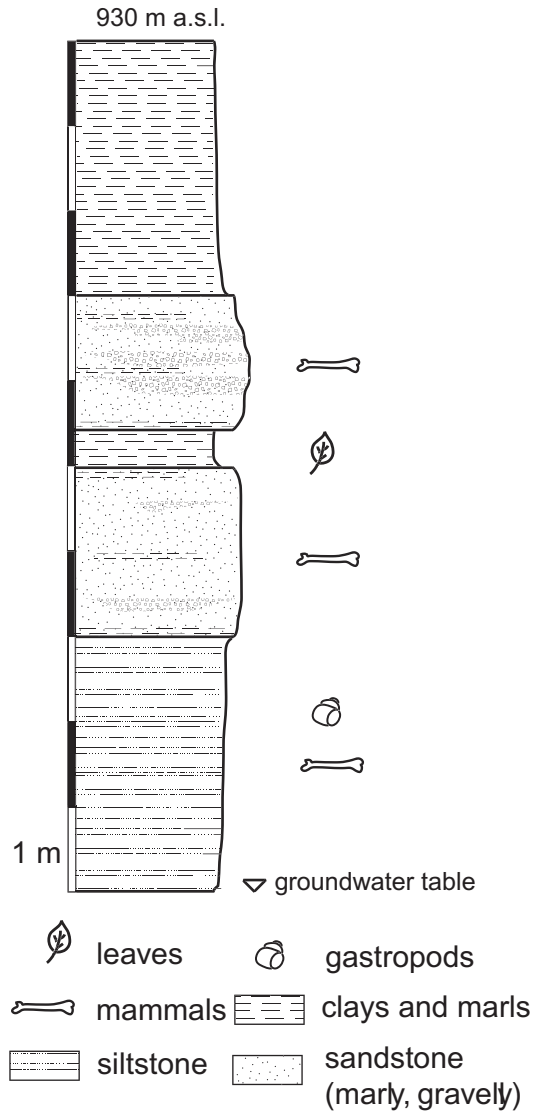

Fig. 13. Sedimentological profile of the exposed section at the Hang Mon coal mine (Yen Chau district, Son La province; coordinates: N20°56.15, E104°22.22).

out that this species has its globally last occurrence in the planktonic foraminifer *Paragloborotalia kugleri* zone (top at 21.12 Ma; Lourens et al., 2004), which corresponds roughly to the Aquitanian (23.03–20.43 Ma). In Europe, *C. dorogensis* has its last appearance in the Rupelian (33.90–28.45 Ma) (Krutzsch, 1967; Krutzsch et al., 1992). Our new macrofossil data from the Na Duong and Hang Mon basins are in good accordance with an Oligocene age of these deposits; final conclusions, however, require a more detailed study of the fossils. Hoang et al. (2009) dated single detritical zircons from the sandstones of the Na Duong Formation (Na Duong mine) using the U–Pb method. All 98 analysed grains are older than 185 Ma (Hoang et al., 2009: Table 1 and Fig. 5D) and thus do not contribute to the age discussion.

According to Wysocka (2009), it may be assumed that the opening of the basins along the Cao Bang – Tien Yen fault occurred diachronous from NW to SE, starting with the Cao Bang basin and followed by the That Khe and Na Duong basins (Fig. 1). To date, no palynomorphs have been recorded from the Cao Bang basin. Based on the conformity with the overlying Na Duong Formation, however, a late Eocene age is proposed for the Cao Bang Formation (Khuc et al., 2005; Thanh and Khuc, 2006). This supposition is based on the assumption that the Na Duong Formation is similar in age both in the Cao Bang and Na Duong basins. Interestingly, the mollusc faunas of this formation at Na Duong are completely different from those recorded from Cao Bang (see below). However, freshwater bivalves and gastropods usually are of minor biostratigraphic value, but may rather be diagnostic with regard to facies and habitat. Anyway, if the mostly tentative generic assignment to extant genera turns out to be right during further taxonomic study, most of the taxa from both basins could be regarded the oldest representatives of these genera recorded to date.

This present chronostratigraphic concept contrasts with previous age estimations based on macroflora, molluscs, and mammals. According to Dzanh (1995, 1996), the leaf flora and bivalve fauna indicate a Late Miocene age for the Na Duong and Hang Mon formations and an Early Pliocene age for the Rinh Chua Formation. However, the macroflora is only of limited value for biostratigraphy, while an evolutionary concept for the Cenozoic Unionidae of Southeast Asia, which would be a prerequisite for any dating, does not exist to date.

From the Hang Mon locality, Ginsburg et al. (1992) and Covert et al. (2001) described nine mammalian taxa, based on relatively sparse material. Whereas Ginsburg et al. (1992) inferred an Early Miocene age mainly from the presence of *Amphicyon* cf. *giganteus*, *Protaceratherium* cf. *minutum* and *Hyotherium* cf. *soemmeringi*, Covert et al. (2001) concluded on a Late Miocene age from the occurrence of *Dorcatherium minus*, *Chleuastochoerus stehlini* and cf. *Chilotherium anderssoni*. However, more and better preserved material is needed to resolve these significant discrepancies.

6. Paleobiogeography

During the Paleogene and probably also the early Neogene, the Paleo-Red River was the major drainage system in Southeast Asia, as it was supplied by waters from part of southeast Tibet and almost the entire Yangtze Craton in southern China (Clift et al., 2008a: Fig. 16). Consequently, the catchment of the Paleo-Red River represents a key area for tracing the origins and understanding the biogeography of Cenozoic and Recent freshwater organisms in East Asia.

Whereas the Hang Mon basin was likely part of the Paleo-Red River drainage system, the ancient position of the Cao Bang and Na Duong basins is not yet finally resolved. Today, the basins along the Cao Bang – Tien Yen fault are drained by the Bang and Ky Cung rivers, which direct into the northwestern Guanxi Province in southern China and are part of the Pearl River drainage system (contrary to Fig. 1 of Hoang et al., 2009). Possibly, this independent flow system already existed in the late Paleogene, which is corroborated by sediment provenance studies of Clift et al. (2008a). These data suggest that the area northeast of the Red River (Lo River catchment) was disconnected from the Paleo-Red River prior to the Late Miocene and must therefore have drained via a Paleo-Pearl River or else. Another scenario is proposed by Hoang et al. (2009) based on provenance analyses performed on detritic zircons from sandstones of the Na Duong Formation. These zircons show similarities to the Songpan Garze block (eastern Tibet) and to modern sediments deposited at the "first bend" of the Yangtze River. Therefore, another major N–S flowing river may have existed during the Cenozoic, which drained part of the Yangtze Craton, supplied the sediments at Na Duong while running sub-parallel to the Paleo-Red-River for several 100 km, and finally emptied into the latter (Hoang et al., 2009: Fig. 8).

The fossil cyprinid fishes from the Na Duong and Rinh Chua formations show certain similarities to those of the modern rivers of northern Southeast Asia (Yangtze, Pearl and Red River), as xenocyprinins, cultrins, acheilognathins, gobionins and hypothalmichthyins are dominant or genuine elements of these waters. In

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Table 1
Fossil plants, bivalves, gastropods, fishes, turtles and mammals recovered from the Hang Mon, Cao Bang and the Na Duong basins during excavations of 2008 and 2009.

	Hang Mon fm. at Hang Mon	Na Duong fm. at Cao Bang	Na Duong fm. at Na Duong	Rinh Chua fm. at Na Duong, Rinh Chua
Plantae				
?*Isoetes* sp.			x	
Osmundaceae			x	
Bivalvia				
Unionini indet. sp. 1			x	x
Anodontini indet. sp. 1			x	x
Anodontini indet. sp. 2			x	x
Cuneopsis sp. 1		x		
Cuneopsis sp. 2		x		
?*Cuneopsis* sp. 3				x
?*Lanceolaria* sp.		x		
?*Hyriopsis*/*Cristaria* sp.		x		
Lamprotula sp.		x		
?*Lamprotula* sp.		x		
Gastropoda				
Viviparidae indet.			x	x
Hydrobiidae indet.		x		
?*Tarebia* sp.				x
Brotia sp.			x	x
Lagochilus sp.	x			
Ptychopoma sp.	x			
?*Tortaxis* sp.	x			
Pisces				
Teleostei indet.		x	x	
Barbinae sp. 1		x		x
Barbinae sp. 2		x		x
Barbinae sp. 3		x		
Barbinae nov. gen. 1		x		
?Barbinae nov. gen. 2			x	x
Labeoninae indet.		x		
Gobioninae indet.		x		
Xenocyprininae sp. 1		x		
Xenocyprininae sp. 2		x		
Xenocyprininae indet.				x
Cultrinae sp. 1		x		x
Cultrinae sp. 2				x
Cultrinae vel Acheilognathinae				x
Hypophthalmichthyinae nov. gen.				x
Cyprinidae indet.				x
Siluriformes indet.			x	?
Mystus sp.		x		
Bagridae indet.		x		
Testudines				
Geoemydidae indet. sp. 1			x	
Geoemydidae indet. sp. 2			x	
Geoemydidae indet. sp. 3			x	
Geoemydidae indet. sp. 4			x	
?Ptychogastridae indet.			x	
Trionychidae indet.			x	
Crocodylia				
?Tomistominae indet.		x	x	
Mammalia				
Rhinocerotidae indet.			x	
Tragulidae vel. Lophomerycidae	x		x	

contrast, the high diversity of barbins (five taxa) and the occurrence of a labeonin rather indicate affinities to the Mekong (and Salween) system. These records, however, may feature an ancient distribution pattern, which may be substantiated by the presence of at least two barbel genera that are obviously new to science. Probably, the Barbinae have been replaced by members of the above mentioned subfamilies in the rivers of northern Southeast Asia during the Neogene. A dominance of northern Southeast Asiatic elements is suggested by the mollusc fauna of Cao Bang, which clearly indicates disconnection from the Mekong drainage system or other rivers in the southern part of Southeast Asia, as several of the unionid genera (e.g., *Cuneopsis*, *Lamprotula*) are today restricted to the Yangtze, Pearl, and Red River drainage systems and have undergone prominent radiations in these areas. However, the modern faunas of these rivers are obviously very closely related, and it is impossible to state on ancient connectivity from the present state of knowledge.

7. Paleoclimate

The planosol paleosoils of the Cao Bang Formation appear remarkably similar to recent (or Pleistocene) soils in Northern Vietnam, indicating a similar paratropical and humid climate.

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Fig. 14. Part of an accumulation of turtle shells (Na Duong coal mine, bed #81) composed by at least six individuals (scale 1 m).

Several indicators of elevated temperature and/or humidity can further be found in the Na Duong Formation, i.e. (1) the presence of arborescent Osmundaceae ferns (Fig. 5A) and (2) diverse spores of pteridophyts (Trung et al., 2000), (3) the high diversity of aquatic turtles (Table 1), (4) the occurrence of a large-sized longirostrine crocodile (Fig. 4D), and (5) the absence of pedogenic carbonate concretions or evaporates in all studied basins. In contrast, pollen of dry-adapted plants (*Ephedripites*) are described from the Na Duong (Trung et al., 2000), Rinh Chua (Dy et al., 1996), and Hang Mon formations (Thanh and Khuc, 2006); however, detailed quantitative palynological studies are still lacking. Among the molluscs, unionids, viviparids, and hydrobiids may thrive under a variety of climatic conditions reaching from subarctic to tropic regimes. However, the composition especially of the Cao Bang fauna mirrors associations from similar habitats in present day Southeast Asia and may therefore indicate similar (sub-)tropical climate. This is corroborated by the presence of ?*Tarebia* and *Brotia*, because both fossil and modern representatives of these genera are restricted to (sub-)tropical waters (Glaubrecht, 2006).

More detailed studies on several subjects of palynology and palaeontology are needed in order to generally qualify and quantify climatic parameters and to evaluate the potential influence of monsoonal climate, which is assumed to develop around the Paleogene–Neogene transition in Southeast Asia (Sun and Wang, 2005; Clift et al., 2008b).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jseaes.2010.11.002.

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