Original article

Stratigraphy and sedimentary environment of late Middle—early Late Miocene Chiang Muan Formation, Phayao Province, Thailand.

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Abstract

The sedimentary facies analysis shows that the late Middle – early Late Miocene Chiang Muan Formation can be subdivided into five members: the Sa Nua Mudstone Member (Sa Nua Member), the Sa Tai Lignite Member (Sa Tai Member), the Sa Sandstone and Conglomerate Member (Sa Member), the Kon Lignite Member (Kon Member) and the Thung Nong Mudstone and Sandstone Member (Thung Nong Member) in ascending order. The mammalian fossil-bearing horizons are in the Sa Tai and Kon members. Each member is represented by unique sedimentary environments resulted from the changes of fluvial systems, which are expressed by braided-river and meandering-river facies associations. The braided-river facies association characterized by multiple synchronous channels, consisting of channel-fill and floodplain deposits, is recognized in the Sa Member. The meandering-river facies association is composed of the finer-grained sediments, including lignite. A channel, floodplain and fen/marsh environments can be recognized in this facies association. It is recognized in the Sa Nua, Sa Tai, Kon and Thung Nong members.

Key words: Miocene, stratigraphy, fluvial deposits, sedimentary facies, Thailand

Introduction

Neogene non-marine sediments in northern Thailand were briefly summarized and divided into two groups: the Mae Moh Group and the Li Group. The Mae Moh Group occupies almost all Neogene sedimentary basins in northern Thailand except Li Basin, which is occupied by the Li Group (Songtham, 2004). The deposits of those basins yield many vertebrate fossils. According to previous works (e.g., Ducrocq et al., 1994; Nakaya et al., 2002; Pickford et al., 2004), mammalian faunas from the Neogene Thailand can be correlated with those from the Middle Miocene of Siwaliks in Pakistan and the Late Miocene localities in China.

Suganuma et al. (2006) defined the Chiang Muan Formation, which is well exposed at the Chiang Muan Mine (N18°56 ′05–50 ″, E100°13 ′55 ″–14 ′30 ″), Chiang Muan District of Phayao Province in northern Thailand (Fig. 1). This open pit lignite mine is operated by the Chiang Muan Mining Company (CMMC). The earliest large-bodied Miocene hominoid in Southeast Asia was discovered from the mine (Kunimatsu et al. 2000, 2002, 2003, 2004, 2005a, 2005b; Chaimanee et al. 2003).

The Chiang Muan Formation yields vertebrate fossils, including fishes, amphibians, reptiles, birds and mammals (Nagaoka and Suganuma, 2002; Nakaya et al., 2002; Kunimatsu et al., 2003, 2004, 2005a, 2005b; Chaimanee et al., 2003; Pickford et al., 2004), but the fossil-bearing levels and the depositional environment of the horizons were less documented so far.

This article deals with the sedimentary facies analysis for reconstructing the sedimentary environment of the Chiang Muan Formation, and five members are proposed in order to clarify the fossil-bearing beds.

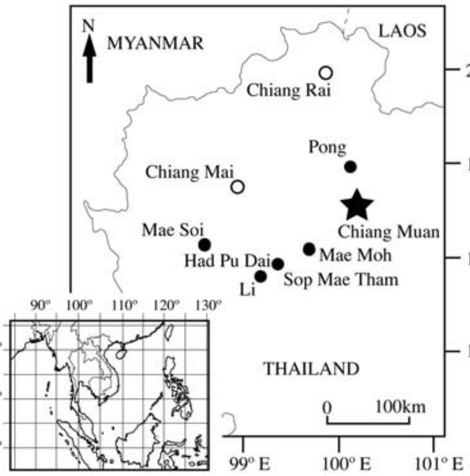

Figure 1. Location map of Chiang Muan in northern Thailand. Open circles are representative cities in northern Thailand. Filled circles represent Neogene mammalian fossil localities in northern Thailand.

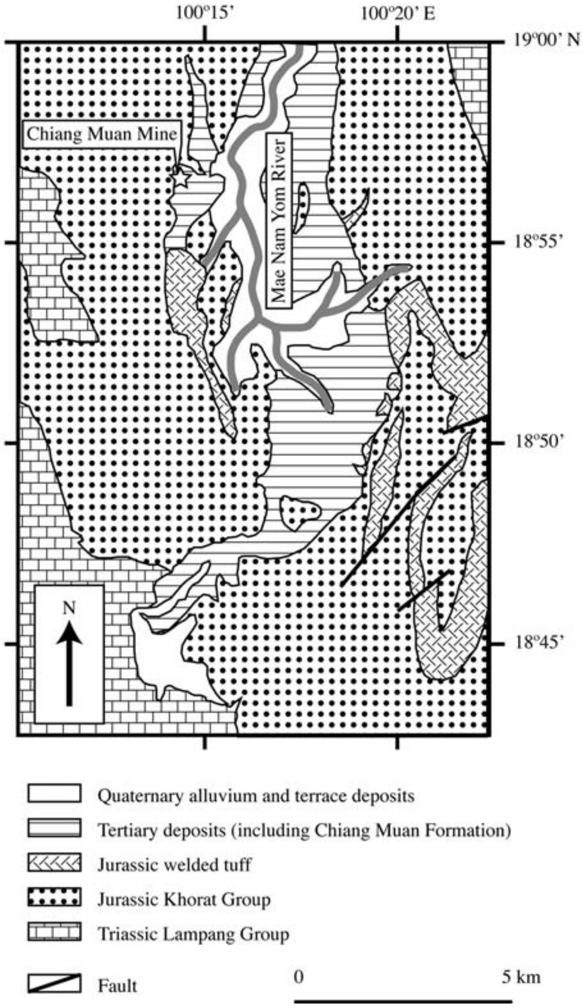

Figure 2. Geological map of the Chiang Muan Basin with position of the Chiang Muan Mine. Modified after Charoenprawat et al. (1994).

Geological setting

Tertiary sedimentary basins in northern Thailand involved in the escape tectonics caused by the India-Asia collision (e.g., Tapponnier et al., 1982). Morley (2001) proposed that the subduction rollback of the Indian plate to the west of Thailand might be related to the opening of rift basins in northern Thailand.

The Chiang Muan Basin, which is 14 km long and 6 km wide, is flanked on the west by a moderate slope and bordered on the east by a marked linear steep slope. The basement rock of the basin is chiefly composed of Jurassic Khorat Group, consisting of shale, sandstone and conglomerate, and of Jurassic welded tuff. Tertiary deposits including the Chiang Muan Formation are exposed at the foot of the mountains. The Chiang Muan Formation was inclined (approximately 20º toward the east) due to a tectonic movement. The flat lying Quaternary gravels and sands are distributed in the center of the basin and exposed along Mae Nam Yom River (Fig. 2).

Stratigraphy of the Chiang Muan Formation

The Chiang Muan Formation is characterized by two lignite layers. It is late Middle to early Late Miocene in age, based on the fossil mammalian fauna in the Chiang Muan Mine (Pickford et al., 2004) and on the paleomagnetic analysis (9.8 – 13 Ma) obtained by Suganuma et al. (2006). The formation is stratigraphically divided into several units that should be designated as members. We advocate five lithostratigraphic names on account of inappropriate procedure and naming of lithostratographic units proposed by previous works (Fig. 3). The new names for the members of the Chiang Muan Formation are as follows: the Sa Nua Mudstone Member, the Sa Tai Lignite Member, the Sa Sandstone and Conglomerate Member, the Kon

Songtham (2004)	Nagaoka and Suganuma (2002), Suganuma et al. (2006)		This paper
Overburden	Chiang Muan Formation	Overburden	Thung Nong Mudstone and Sandstone Member
Upper Coal Zone 1		Upper Lignite	Kon Lignite Member
Interburden 1			
Upper Coal Zone 2			
Interburden 2		Interburden	Sa Sandstone and Conglomerate Member
Lower Coal Zone		Lower Lignite	Sa Tai Lignite Member
Underburden		Underburden	Sa Nua Mudstone Member

Figure 3. Stratigraphy of the Chiang Muan Formation in the Chiang Muan Mine.

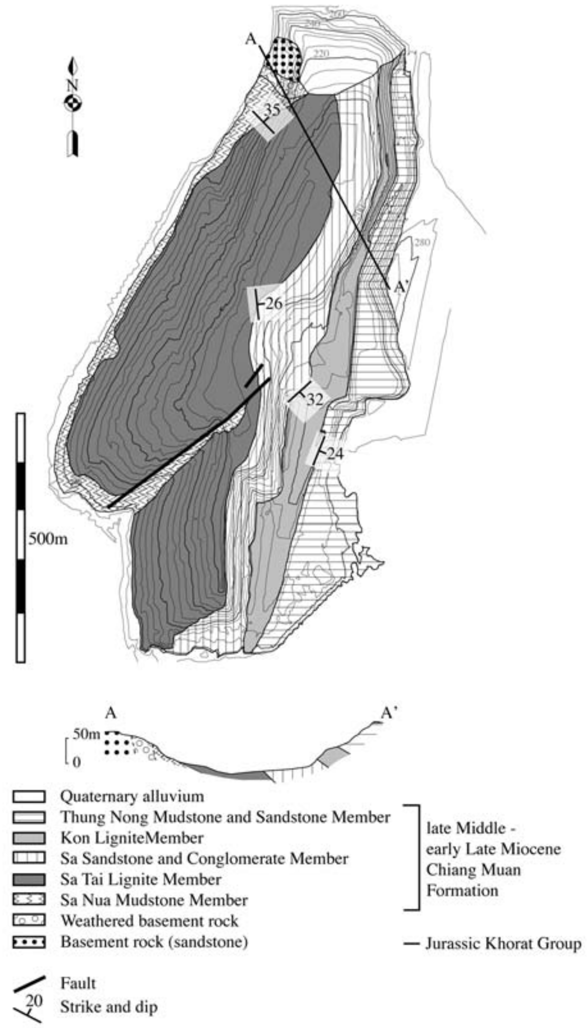

Figure 4. Geological map and cross section of the Chiang Muan Mine. Topographic map of the Chiang Muan Mine represented herein was made on July 8, 2005.

Lignite Member and the Thung Nong Mudstone and Sandstone Member in ascending order (Fig. 3). The names of the members are derived from villages around the Chiang Muan Mine. Figure 4 shows the geological map and the type section of the formation in the Chiang Muan Mine.

The Sa Nua Mudstone Member is correlated with the "Underburden" in previous works (Fig. 3). It unconformably overlies the Jurassic Khorat Group consisting of sandstone via saprolite. The contact between the basement rock and the Sa Nua Member is exposed in the northern part of the mine. The member is composed of red paleosols, consisting of mudstone with coarse-grained sands and granules of quartz, sandstone, chert and mudstone derived from the basement rock. The light gray paleosol beds were locally intercalated within the reddish paleosols. The top of this member is characterized by the massive carbonaceous mudstone. The thickness of the member is 50 m in the type section.

The Sa Tai Lignite Member corresponds to the previous "Lower Lignite" (Fig. 3). It is widely cropping out in the center of the mine (Fig. 4). It is mainly composed of lignite with laminations of carbonaceous mudstone (< 2 mm). The light gray colored massive mudstone (< 3 m) and the carbonaceous mudstone (< 5mm) were locally interbedded within the lignite. The depositional age of the member can be estimated to be latest Middle Miocene, based on the paleomagnetic analysis and the mammalian fossil assemblage including *Tetralophodon cf. xialongtanensis, Conohyus sindiensis and Pecarichoerus sminthos* (Pickford et al., 2004; Suganuma et al., 2006). Other vertebrate remains of hominoids, rhinocerotids, bovids, tragulids, birds, reptiles, amphibians and fishes were also reported (Nakaya et al., 2002). The burrows can be seen in the carbonaceous mudstone and lignite. The thickness of the Sa Tai Member is variable in places and ranges from 30 to 120m.

The Sa Sandstone and Conglomerate Member is renamed for the "Interburden 2" (Songtham, 2004) and the "Interburden" (Nagaoka and Suganuma, 2002; Suganuma et al., 2006). It is composed of two units: red sandy paleosols and channel-fill deposits (Fig. 5). The red sandy paleosols consist of poorly sorted very fine- to medium-grained sand. The granule- to pebble-size clasts of quartz, sandstone,

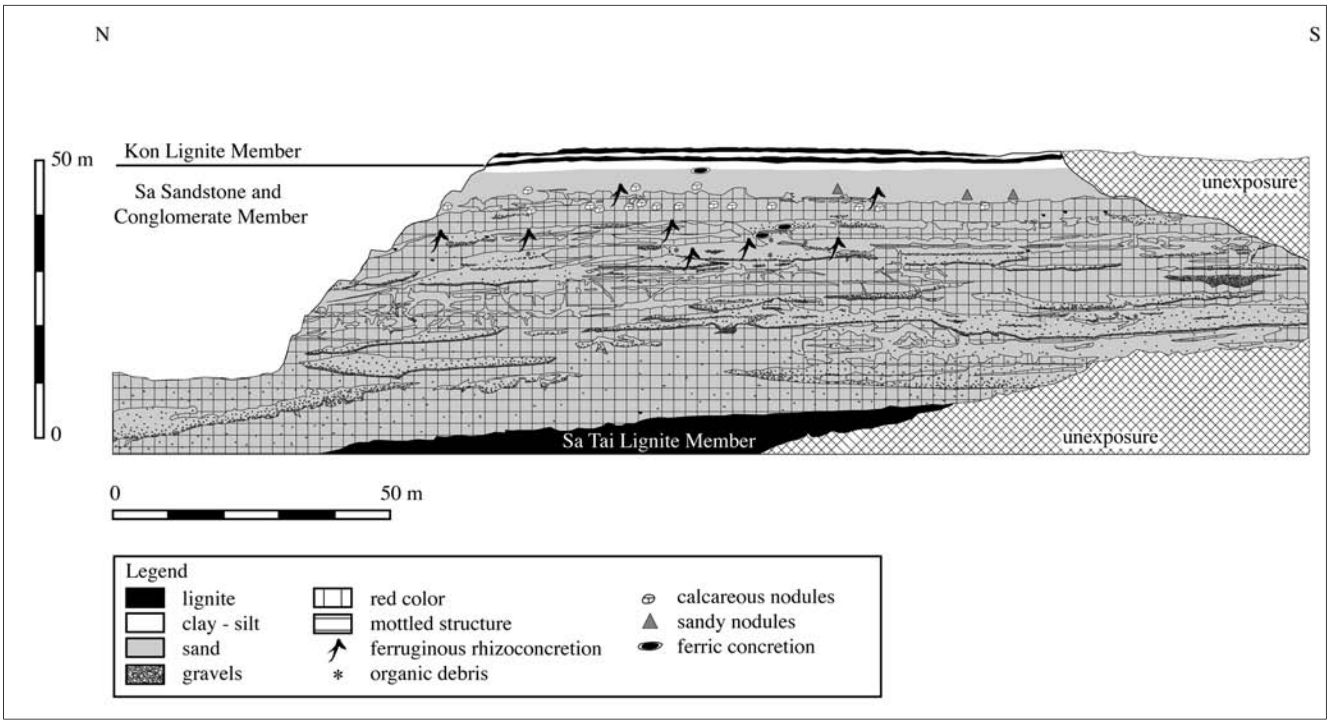

Figure 5. Field sketch of exposure showing the successions of the Sa Tai Lignite, the Sa Sandstone and Conglomerate and the Kon Lignite members.

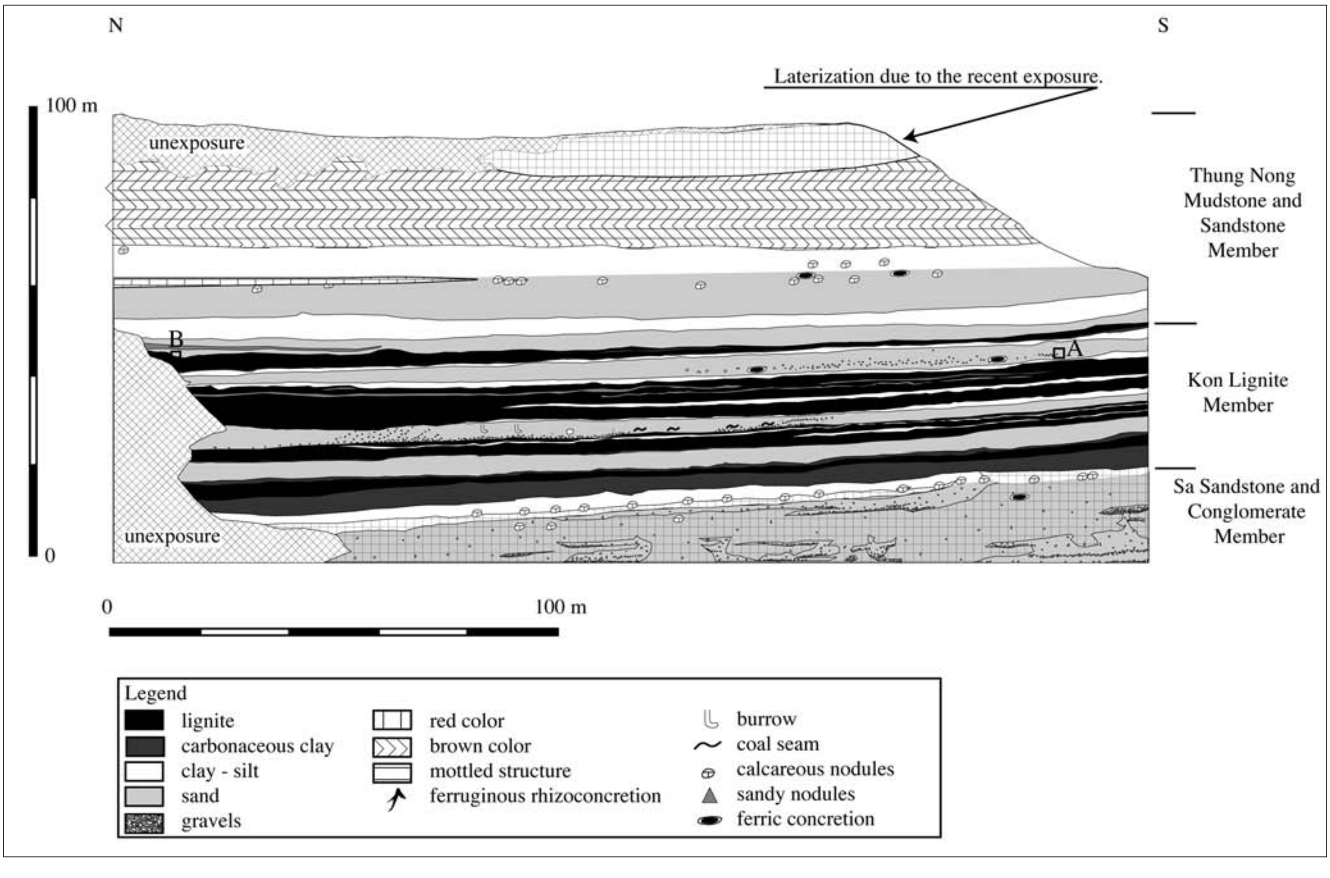

Figure 6. Field sketch of exposure showing the successions of the Sa Sandstone and Conglomerate, the Kon Lignite, the Thung Nong Mudstone and Sandstone members, Quaternary gravels and recent soils.

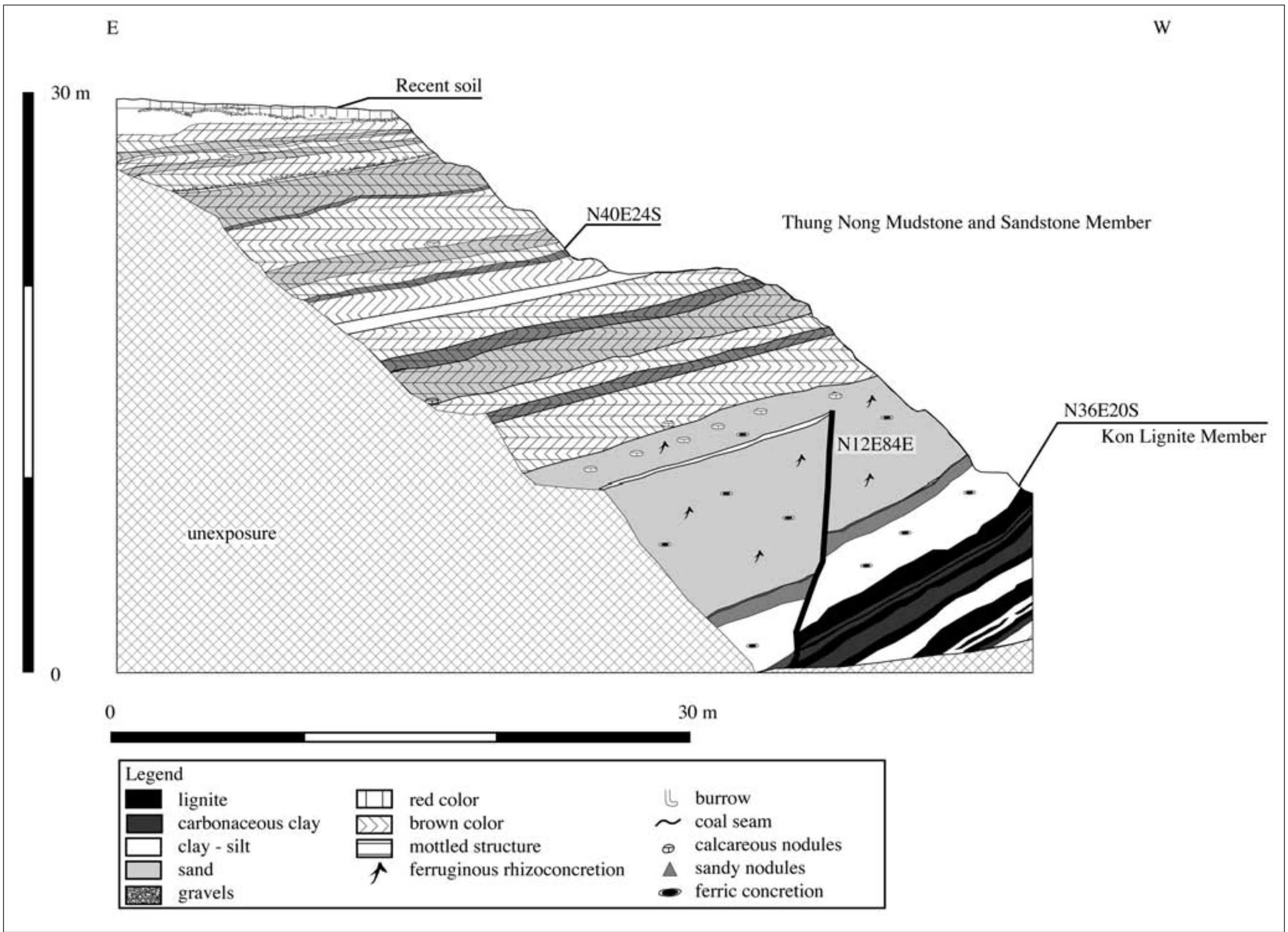

Figure 7. Field sketch of exposure showing the succession of Kon Lignite, Thung Nong Mudstone and Sandstone members, Quaternary gravels and recent soils.

chert, mudstone and rarely feldspar originated from the basement rock were occasionally interbedded within paleosols. The channel-fill deposits show the fining-upward patterns from conglomerate to sandstone with erosional bases. The transition to the Kon Member is expressed in floodplain deposits. The Sa Member is about 70 – 90 m in thickness.

The Kon Lignite Member is corresponding to the previously proposed the "Upper Coal Zone 1", the "Interburden 1" and the "Upper Coal Zone 2" by Songtham (2004) and the "Upper Lignite" by Nagaoka and Suganuma (2002) and Suganuma et al., (2006). The upper and lower lignite layers are characteristic in the Kon Lignite Member (Fig. 6). Those lignite layers were segregated by a thick (< 10 m) sandstone unit. The base of the Kon Member is late Middle Miocene in age, and the top is dated to be early Late Miocene time (Suganuma et al., 2006). The mammalian fossils such as *Chilotherium intermedium, Hippopotamodon* cf. *hyotherioides* and hominoid were reported (Kunimatsu et al., 2003, 2005a; Pickford et al., 2004). The thickness of this member is approximately 40 m.

The Thung Nong Mudstone and Sandstone Member is correlated with the "Overburden" in previous works (Fig. 3). Locally, channeled and cross-bedded coarse-grained sandstones were recognized in its basal part. This member is characterized by alternating beds of clayey paleosol and fine- to very coarse-grained sandstone (Fig. 7). This member is more than 60 m in thickness and unconformably underlies the Quaternary gravels.

Facies description

The composite log of the Chiang Muan Formation in the Chiang Muan Mine (Fig. 8) shows that the formation comprises the alternating beds of lignites and fluvial deposits that are interpreted to represent a flood basin to a floodplain with a

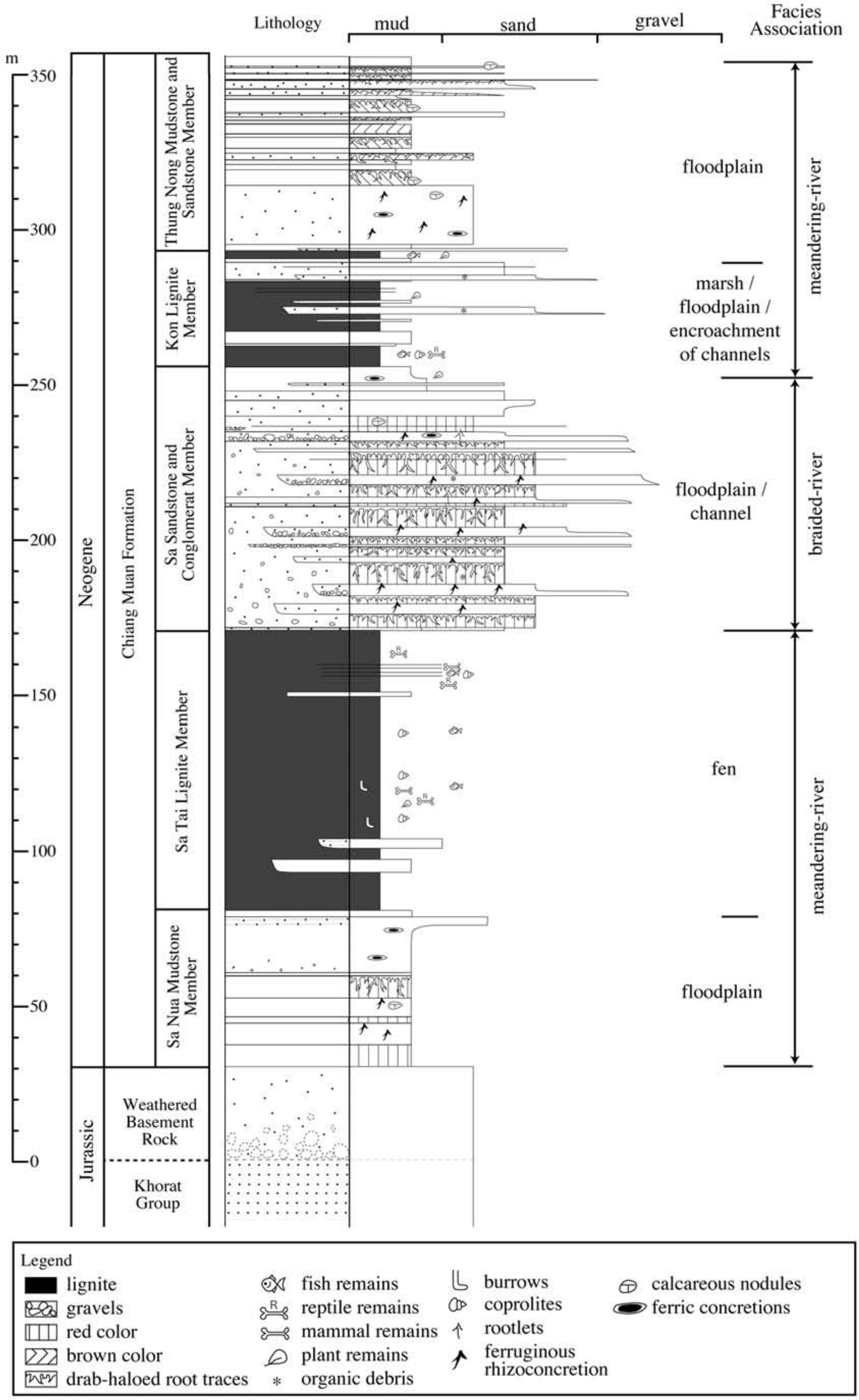

Figure 8. Composite log of the sequence exposed in the Chiang Muan Mine.

channel environment. These deposits can be divided into the following eight facies.

The facies 1 is characterized by a fining-upward sequence from conglomerate to sandstone. The conglomerate comprises granule and pebble. The sandstone is coarse- to very coarse-grained. The basal contact is sharp and has erosional planar nature. The conglomerate shows a clast-supported framework. The thickness of this facies is highly variable, ranging from 10 cm to 5 m.

The facies 2 of about 2.5 m thick clearly shows an inverse grading sequence of the fine- to medium-grained sandstone.

The facies 3 of 0.3 to 8 m thick is characterized by very fine- to coarse-grained sandstone. The fossil root traces and the mottled structures are abundant. The fossil rootlets are occasionally found. The soil structures of cutan can be observed.

The facies 4 consists of structureless very fine- to medium-grained sandstones. The thickness of this facies is 1 to 3 m.

The facies 5 is characterized by sandy mudstone and sandstone. It shows an upward increase in grain-size from clay to fine-grained sand. The thickness of this facies ranges from 10 to 30 cm.

The facies 6 is characterized by mudstone with individual bed ranging from 1 to 10 m in thickness. Its color is red in the Sa Nua Member, and brown in the Thung Nong Member. Fossil root traces and mottled structures are common. There are many cracks showing the subangular blocky shape (peds) in this facies. The soil structures of cutan can be recognized in the subangular blocky peds.

The facies 7 definitely shows the structureless feature of mudstone, consisting mainly of clay. The thickness ranges from a few centimeters to 10 m.

The facies 8 is characterized by lignite. Thin (< 2 mm) carbonaceous mudstone was occasionally interbedded within the lignite layer. This facies contains the plant remains, vertebrate fossils and coprorites.

Depositional environment of facies association

Two fluvial systems, the braided-river and the meandering-river, are recognized by summing up the facies transitions (Fig. 9).

The braided-river facies association is characterized by the coarser-grained sediments, and definitely shows multiple synchronous channels. It can be subdivided into the channel and the floodplain sub-associations (Fig. 9).

The channel sub-association is characterized by the facies 1 and 4. Coarse sandy to conglomeratic channel fill lenses are both laterally and vertically amalgamated, commonly 15 to 40 m wide. The facies 1 of the channel-fill sub-association varies in grain size composition. The scour-and-fill structures, medium- to small-trough cross-stratification and fining-upward patterns are common. The rip-up

facies	lithofacies	sedimentary structures
1	medium- to very coarse-grained sandstone, conglomerate	fining-upward, erosional base
2	fine- to medium-grained sandstone	coarsening-upward
3	very fine- to coarse-grained sandstone	fossil root, fossil root trace, cutan, mottled structure
4	very fine- to medium-grained sandsone	structureless
5	mudstone, fine-grained sandstone	coarsening-upward
6	mudstone	fossil root, fossil root trace, cutan, mottled structure
7	mudstone	structureless
8	lignite	vertebrate fossil, plant fossil, coprolite, burrow

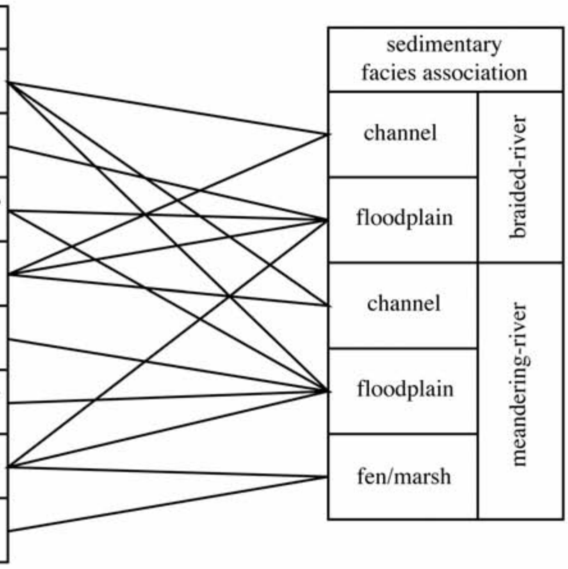

Figure 9. Sedimentary facies recognized in the Chiang Muan Formation exposed in the Chiang Muan Mine, and facies association obtained by summation of facies transition.

clasts are commonly found in the facies 1. This facies sub-association is recognized in the Sa Member.

The floodplain sub-association is characterized by the facies 2, 3, 4 and 7. The facies 3 is a diagnostic feature of this sub-association. Fossil rootlets and organic matters were occasionally preserved. The cutans (faint clay films) were locally formed. The soil structures of sepic plasmic fabrics (highly birefringent clay fabrics) are common in thin sections. The skelsepic plasmic fabric (highly birefringent clays around clastic grains) is well expressed. Inverse graded structures in levee and floodplain sediments have been studied and documented in recent river sediments (e.g., Masuda and Iseya, 1985; Suzuki, 1995). Previous works suggested that inverse-grading sediments reflect the nature of over flooding into the floodplain environments and the maximum concentration of suspended load precedes the peak discharge. The amount of fine-grained sediment load is extremely high at the beginning stage of over flooding, and these sediments are deposited by increasing flood-flow velocity. Suzuki (2000) examined the grain-size analysis for the recent flood deposits and reported that the fining-upward sequence often overlay the inverse-grading sediments. Following those features of the recent floodplain deposits, the succession of the facies 2 and 4 from the bottom to the top can be regarded as flood deposits due to an over flooding into floodplain or levee. It is recognized in the Sa Member.

The meandering-river facies association is distinguished from the braided-river association by the finer-grained sediments that are typically composed of mudstone. They can be subdivided into three facies sub-associations: the channel, the floodplain and the fen/marsh.

The channel sub-association consists of the facies 1 and 4. It can be distinguished from the channel sub-association of the braided-river facies association mainly by its composition of the fine-grained sandstone. Internal stratification types include a trough cross bedding and current ripple. Organic matter is occasionally found. This sub-association is recognized in the Kon Member.

The floodplain sub-association consists of the facies 1, 3, 5, 6 and 7 (Fig. 9). This facies sub-association is characterized by the facies 6. Fossil root traces and the mottled structures are characteristic in the facies 3 and 6. The clayey cutan (argillan) is often found in the facies 6. The micromorphological soil structures are well recorded in the facies 3 and 6. The clinobimasepic plasmic fabric is well developed. The calcareous nodules and ferruginous rhizoconcretion can be found in the facies 6. The over flooding deposits, represented by the facies 5 and 7, overlie the paleosol beds like those of the braided-river association. The facies 1 of this sub-association can be regarded as a crevasse channel-fill based on the width ranging from 2 to 16 m, which is narrower in contrast to the braided-river channel (Galloway, 1981). The floodplain sub-association of the meandering-river association is recognized in the Sa Nua and the Thung Nong members.

The fen/marsh sub-association is definitely characterized by facies 8. The facies 7 is locally recognized in this facies sub-association (Fig. 9). The lignite chiefly consists of leaves of plants like grasses, rushes and sedges. Twigs, peels and small pieces of wood are also found in lignites, whereas the large pieces of wood and tree stumps are absent. Nichols and Uttamo (2005) suggested a swamp for depositional environment of lignites in the Ban Pa Kha Formation (Li Formation in that paper) in the Li Basin, whereas the lignite in the Chiang Muan Formation was possibly deposited in a fen or marsh environment rather than in a swamp based on the classification of a wetland proposed by Martini and Glooschenko (1984). The dominant grassy vegetation in lignites, the absence of the large tree root traces in the soils under lignite beds and near neutral to alkaline conditions suggested by mineral assemblages of anhydrite, calcite and hematite in lignites (Silaratana, 2005) support that the deposition under a fen or marsh environment is more probable than under a swamp for the lignite beds in the Chiang Muan Formation (Krassilov, 1981; Philips and DiMichele, 1998; Retallack, 2001). The Sa Tai and the Kon members are composed of this facies sub-association.

Vertebrate fossil occurrences and their implication for the depositional environment

Vertebrate fossils are contained in organic-rich deposits such as lignite and carbonaceous mudstone in the Sa Tai and the Kon members. We examined those fossils discovered *in situ* to consider the burial processes and the depositional environment.

The commonest deposits containing bone

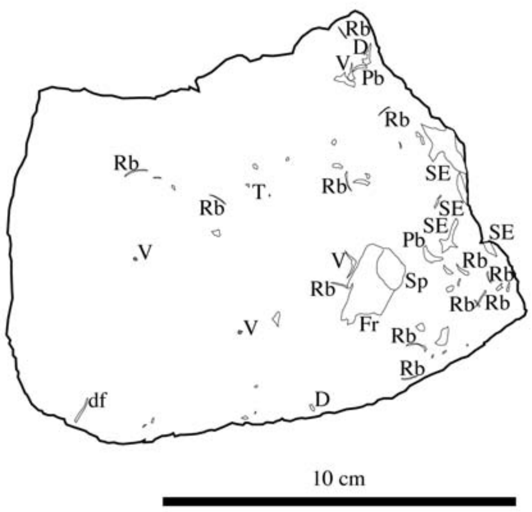

Figure 10. Scattered fish skeletons of catfish (Claridae sp.) and cyprinids preserved in a carbonaceous mudstone in the Sa Tai Lignite Member. Scale bar is 10 cm. Abbreviations: D, dentary; df, dorsal fin; Fr, frontal; Pb, pharyngeal bone; Rb, rib; SE, indeterminate skull element; Sp, sphenotic; T, isolated tooth; V, vertebra.

concentrations are the carbonaceous mudstone. The carbonaceous mudstones are mixtures of clay- and silt-clasts plus organic debris.

Fish fossils preserved in the carbonaceous mudstone show the multidirectionally scattered disarticulated skeletons (Fig. 10). Elder and Smith (1988) examined that a dispersal of fish skeletons due to scavenging caused a multidirectional scattering, and a dispersal of fish skeletons due to a current resulted in a unimodal distribution pattern of bones. Therefore, the multidirectionally scattered fish fossils in the carbonaceous mudstone suggest that a scavenging process might be rather dominant than a current-related process in the burial history of the fossils. It implies that fossils were buried in a shallow zone so as to provide enough oxygen for a scavenger.

Mammalian fossils were also preserved in the carbonaceous mudstone with fish fossils. One individual fossil of suid was discovered from the Sa Tai Member. Although its mandible was destroyed and dispersed, the fracture surface was not abraded, and the fractured bones are well mechanically refitted. Therefore, it is appropriate to suppose that the dispersal and the destruction were not caused by the current-related processes. A treadage involved with trampling and kicking might cause the destruction and the dispersal of bones (Gifford-Gonzalez et al., 1985; Haynes, 1991; Yellen, 1991). The fracture and the dispersal of the bones of this specimen could be caused by a treadage.

Both features suggest that the carbonaceous mudstone containing vertebrate fossils were deposited in a shallow zone of wetland.

Fish fossils in lignites show a completely articulated skeleton (Fig. 11). The absence of dispersal suggests that the skeleton was buried in a deeper zone where the oxygen level is too low for scavengers to be active. The massive lignite supports the idea that they were buried in static water. Those features indicate that it was buried in a deep zone of wetland.

Depositional history

The depositional history of the Chiang Muan Formation was reconstructed based on the sedimentological studies and taphonomic analyses (Fig. 12).

The flood deposit was the primary depositional unit of the Sa Nua Member. After flooding, deposits were exposed and undergone soil-forming process, producing the reddish clayey paleosols. The accumulation of clay minerals and sesquioxides indicates that the reddish paleosol in the Sa Nua Member can be correlated with the well-drained soils in the subhumid – semiarid climatic belt. Consequently, it is reasonable to suppose that the Sa Nua Member was deposited in the well-drained floodplain.

The transition from the Sa Nua to the Sa Tai members is represented by the transition from a sub-aerial to sub-aqueous environment. An increasing upward supply of organic matter caused the gradational change in lithology from mudstone to lignite. The lignite of the Sa Tai Member is composed of the shaly coal and the massive coal. The shaly coal caused by flood water (Diessel, 1992) and the massive lignite, consisting mainly of grassy vegetation and poorly of charcoals of wood pieces, could be deposited in a fen environment (Retallack, 2001). The occurrences of vertebrate fossils suggest variable depth of a fen.

The primary sedimentary units of the Sa Member were channel-fills and bar deposits of the braided-river. Reddish sandy paleosols were formed in

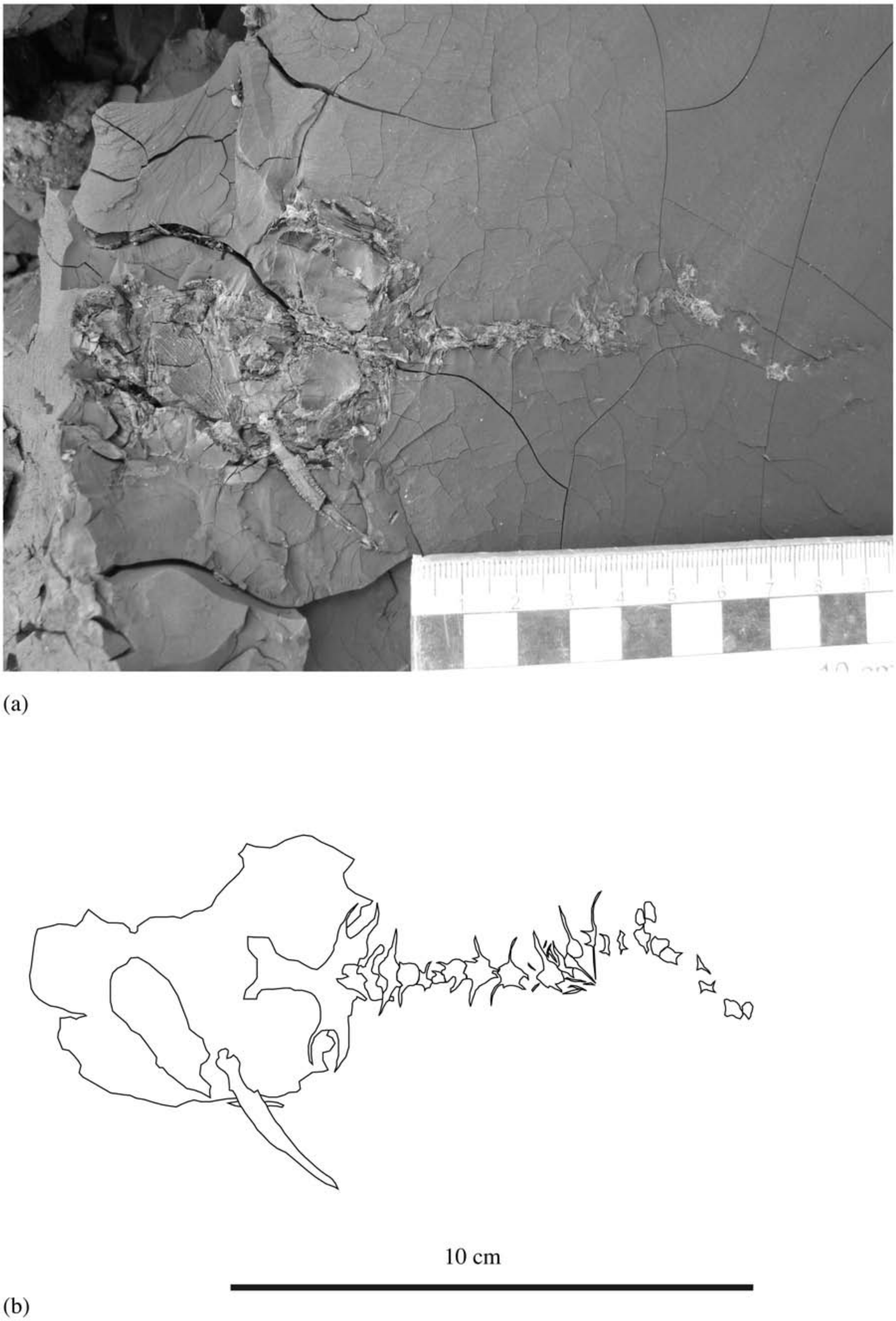

Figure 11. Completely articulated skeleton of catfish (Claridae sp.). (a) photograph showing the catfish skeleton in lignite of the Sa Tai Lignite Member. (b) the skeleton of catfish from the Sa Tai Lignite Member. Scale bar is 10 cm.

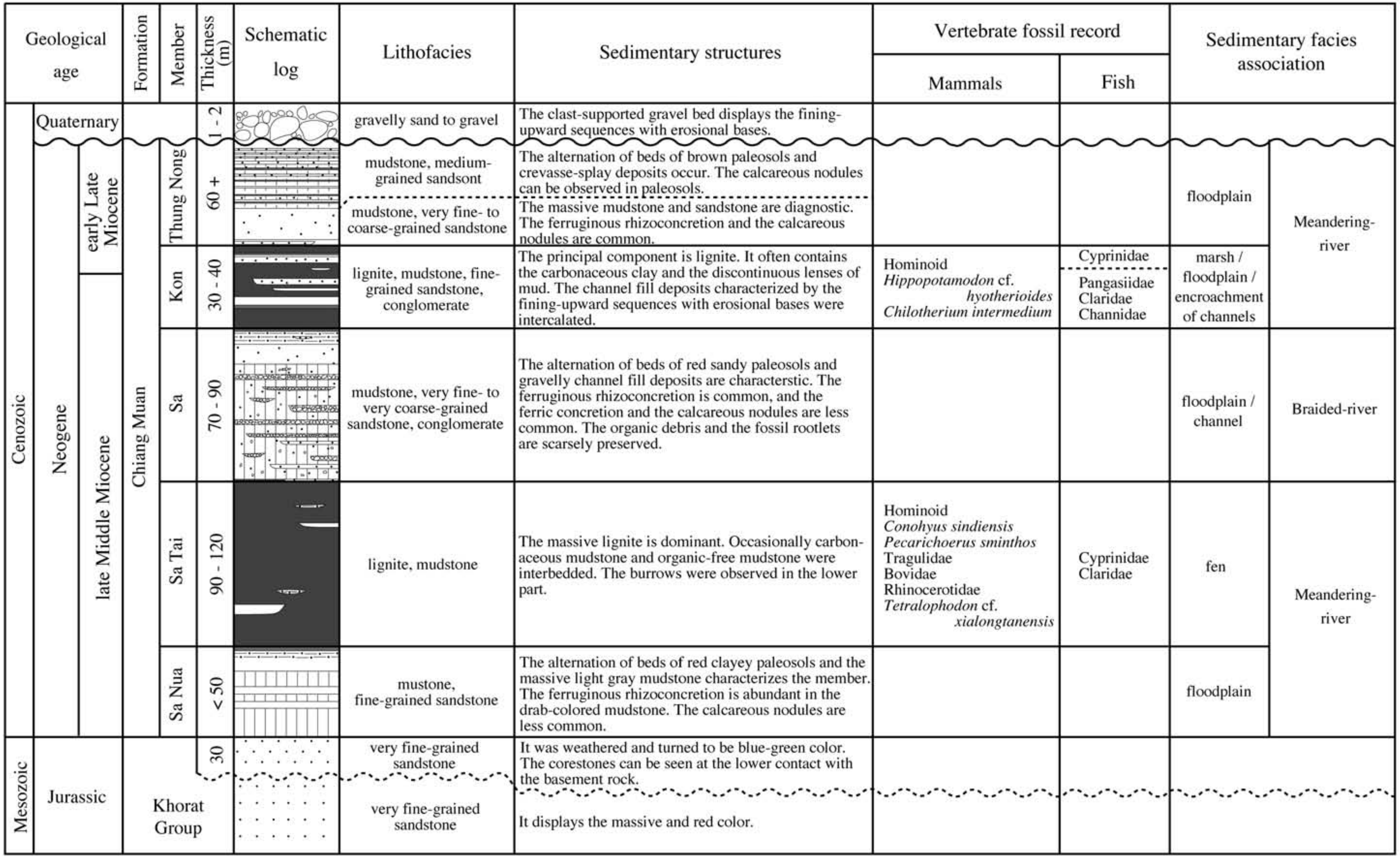

Figure 12. Generalized stratigraphic section of the Chiang Muan Formation in the Chiang Muan Mine.

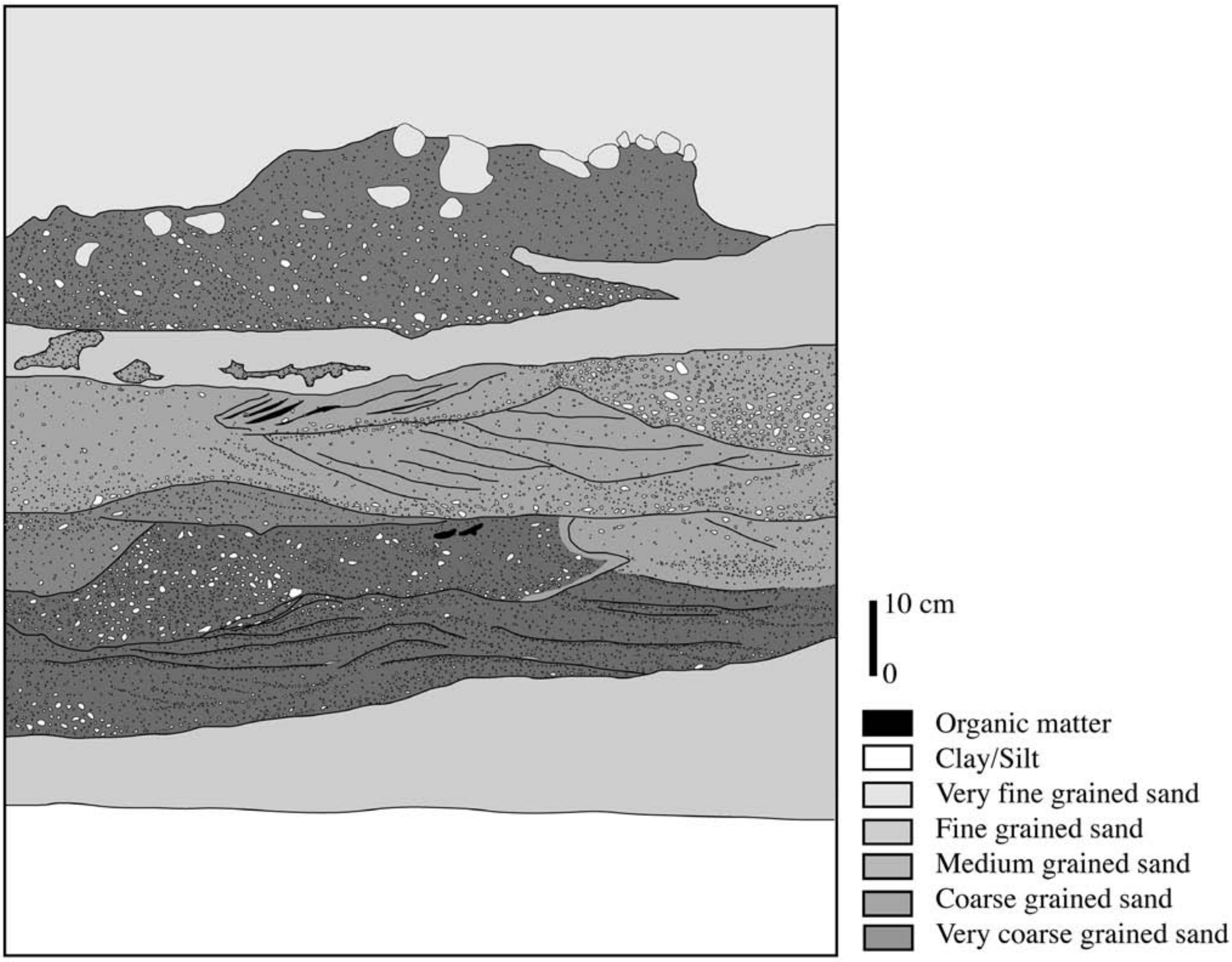

Figure 13. Field sketch of exposure at Point A on Figure 6 showing fluvial deposits in the Kon Lignite Member. Channel-fill deposits consisting of gravelly sandstone represent cross-bedding and erosional bases.

abandoned channels and bars. The lithology changes from lignite to sandstone at the base of the member without the erosional contact. The tectonic movement might result in the drastic lithologic change.

The transition from the Sa to the Kon members is similar to that from the Sa Nua to the Sa Tai members. The grassy vegetation of the Kon Member is more prominent than that of the Sa Tai Member. Together with the absence of shaly coal in the Kon Member, it is reasonable to suppose a marsh environment for the depositional environment of the member (Retallack, 2001). The occurrence of a gigantic catfish (Pangasiidae gen. and sp. indet.) that is similar in size to the extant *Pangasius gigas* from the lower lignite layer of the Kon Member suggests that the Chiang Muan Basin might be joined to a drainage basin of the Mekong River before the deposition of the member. Minor erosion (< 1 m) in the lower lignite layer of the member was possibly associated with crevasse splay. On the other hand, the major erosion (thickness is ca. 8 m) represented by the fine-grained sandstone with gravelly cross- and trough cross bedding and current ripple (Fig. 13) can be interpreted as the encroachment of a river channel. The upper lignite layer above the major erosion also represents a marsh environment. The upper lignite layer contains only pharyngeal teeth of cyprinids, whereas the lower one with reptiles and four families of fish fossils (Channidae, Claridae, Pangasiidae and Cyprinidae). The differences in fossil assemblages between two layers indicate that their paleoenvironments were not the same. Chaimanee et al. (2003) reported that the hominoid fossils were collected from the middle and upper lignite seams of the Chiang Muan Mine that

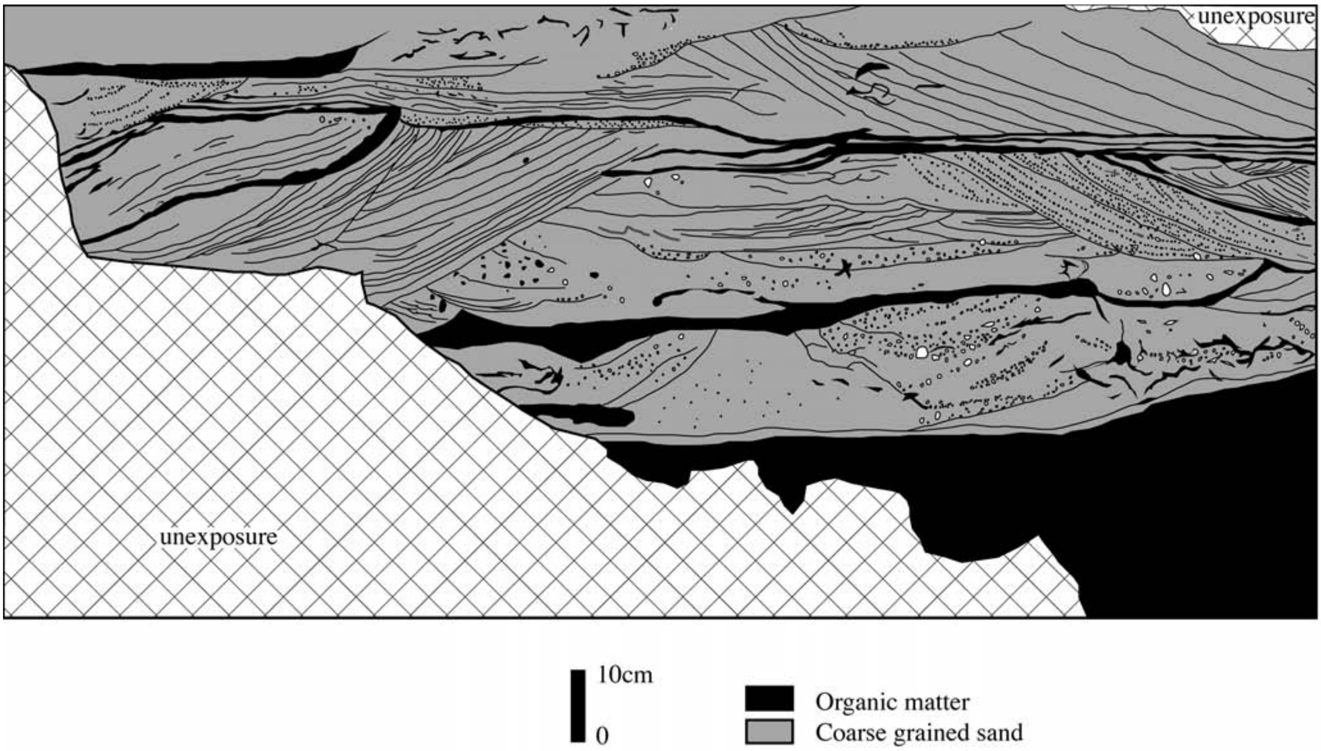

Figure 14. Field sketch of exposure at Point B on Figure 6 showing the contact between Kon Lignite and Thung Nong Mudstone and Sandstone Members. Cross-bedded sandstone with erosive bases of channel-fills are represented. Rip-up clasts are composed of lignite.

have not been correlated with previous lithostratigraphic units. Based on the geologic and paleontologic data collected from the mine, they can be correlated with the lower lignite layer of the Kon Member.

The basal part of the Thung Nong Member is represented by fluvial deposits, consisting of gravelly sandstones with erosive bases in places (Fig. 14). The paleosols were well developed above the light gray colored fluvial deposits. Together with the crevasse splay deposits intercalated in paleosol beds, we infer that the depositional area shifted from a marsh to a floodplain environment via a channel environment.

Conclusions

The following conclusions were obtained by the sedimentological studies on the Chiang Muan Formation.

1. Five members of the Chiang Muan Formation were defined as follows: the Sa Nua Mudstone Member, the Sa Tai Lignite Member, the Sa Sandstone and Conglomerate Member, the Kon Lignite Member and the Thung Nong Mudstone and Sandstone Member in ascending order. The mammalian fossil-bearing horizon is in the Sa Tai Lignite Member and the lower lignite layer of the Kon Lignite Member.

2. The Sa Nua Member characterized by reddish clayey paleosols might be formed in a floodplain environment.

3. The Sa Tai Member is characterized by lignite, containing the grassy vegetation with the shaly coal. It might be deposited in a fen environment.

4. The Sa Member, consisting of channel-fill deposits and reddish sandy paleosols, could be deposited in a braided-river system.

5. The Kon Member is composed of sandstone and lignite. Thick sandstone showing the trough cross bedding and current ripples could result from an encroachment of a river channel. The lignites, which are mainly composed of the grassy vegetation without the shaly coal, suggest a marsh environment for the depositional area.

6. The Thung Nong Member, which typically shows brownish clayey paleosols and crevasse splay

deposits, might be deposited in a floodplain environment.

7. Sedimentary facies analysis revealed that the Chiang Muan Formation consists of fluvial and alluvial sediments deposited in a channel, a floodplain and fen/marsh environments associated with the braided-river and the meandering-river systems.

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