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Sedimentary environments of the Neogene basins associated with the Cao Bang – Tien Yen Fault, NE Vietnam

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ABSTRACT:

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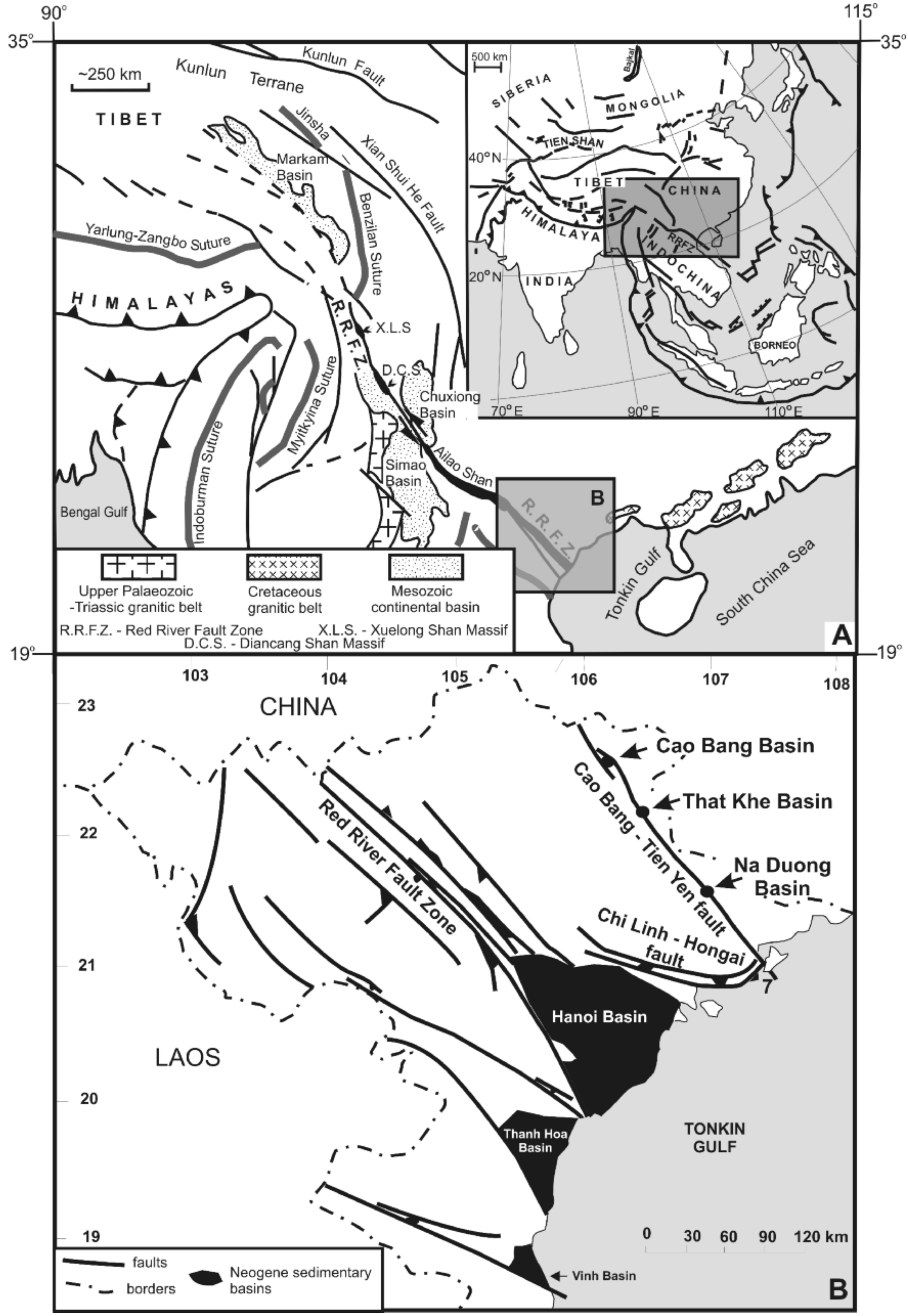
The Na Duong, That Khe and Cao Bang sedimentary basins associated with the Cao Bang – Tien Yen Fault (northern Vietnam) developed in the zone subparallel (distance ca. 150 km NW) to the major strike-slip Red River Fault Zone that separates the South China and the Indochina terranes. These fault-controlled basins are filled with thick series of Neogene terrestrial deposits. Thirteen sedimentary lithofacies were distinguished and grouped into facies associations to represent seven depositional environments, as follows: alluvial fans, gravel-dominated fluvial channels, sand-dominated fluvial channels, flood plains, lake margins and/or river mouths, lakes, and swamps. The facies association pattern, different in each of the investigated basins, is interpreted as a coal-bearing fluvial to lacustrine environment for the Na Duong Basin, and a fluvial environment for the That Khe Basin. The most complex pattern is displayed by the Cao Bang Basin and interpreted as an alluvial-fan to lacustrine environment. The origin of theses basins may be correlated with a sinistral transtensional regime which occurred in the Early to Middle Miocene. Besides tectonic activity, the evolution of particular basins was also controlled by the climate, which caused a change in the rate of sediment supply and weathering conditions. The present-day shape of these basins does not correspond to their original plan, having resulted from the post-sedimentary uplift and erosion.

Key words: Terrestrial sedimentary basins; Clastic deposits; Phytogenic deposits; Facies associations; Tectono-sedimentation; Cao Bang – Tien Yen Fault; Neogene; Vietnam.

INTRODUCTION

North-eastern Vietnam is a classic area of structural and geotectonic interest. One of the most important topics in this field is the Cenozoic movement along the Red River Fault Zone (RRFZ), the main strike-slip zone of SE Asia, which separates the South China and the Indochina terranes (Text-fig. 1A). The changes in the tectonic regime along this zone have created a series of sedimentary basins with various depositional patterns. The aim of the present paper is to describe the sedimentary facies of such basins associated with the Cao Bang – Tien Yen Fault (CB-TYF), subparallel to the major RRFZ, and to reconstruct their sedimentary environments and evolution. So far, only a few studies were devoted to this zone (Yem 1985; Petersen *et al*. 2001; Wysocka *et al*. 2002; Wysocka and Świerczewska 2003, 2005; Huyen *et al*. 2003; Wysocka *et al*. 2005, 2006; Gmur *et al*. 2006; Nguyen Quoc 2006) and the sedimentary history of this type of basin on the Vietnamese landward part of the RRFZ is poorly known.

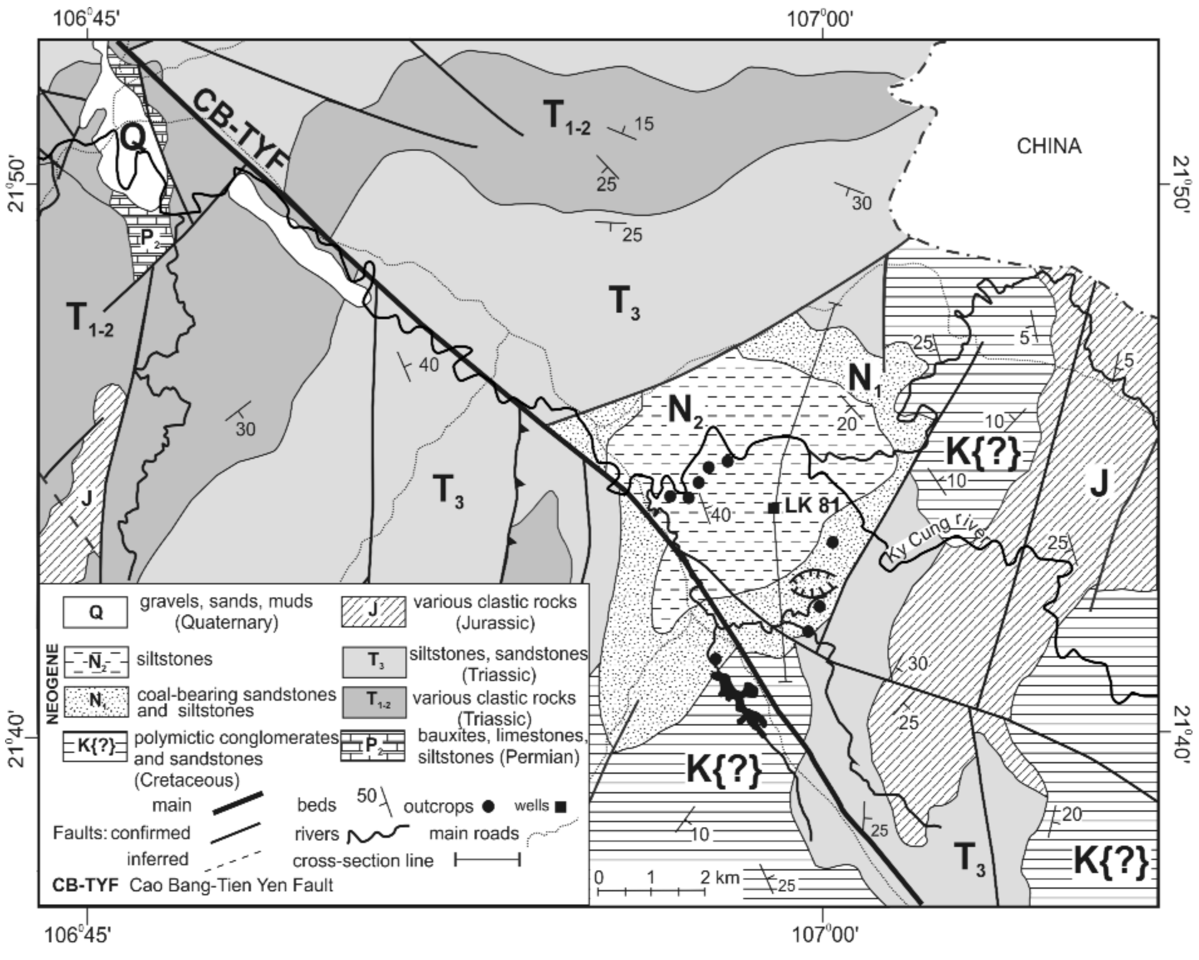


Text-fig. 1. (A) Tectonic sketch-map of SE Asia (based on Tapponnier *et al*. 1986). (B) Tectonic pattern of northern Vietnam (based on Viet 2003)

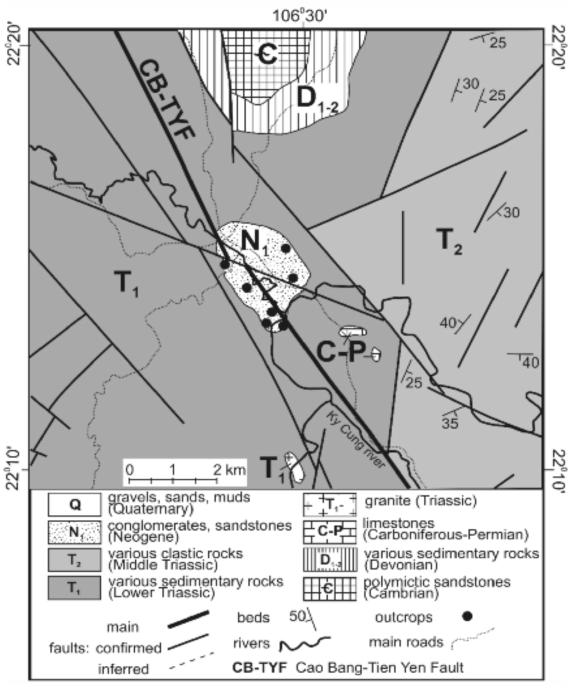
The present study deals with three basins: Na Duong, That Khe, and Cao Bang (Text-fig. 1B). Unfortunately, the structure and geology of the CB-TYF and the fault-related area is poorly recognized, with no relevant subsurface data available. The published materials are only geological maps: at a scale of 1: 50 000 for the Cao-Bang (Cuong 2000) and That Khe basins (Lap 1991), and at a scale of 1: 200 000 for the Na Duong Basin (Thuy 2000). Fortunately, a well studied reference area is the South China Sea, where intense petroleum investigations have been conducted. Well-documented geological data have been published, especially for the Yinggehai-Song Hong and Qiongdongnan basins (see e.g. Su *et al*. 1989, Rangin *et al*. 1995; Morley 2002; Ren *et al*. 2002; Clift *et al*. 2002; Clift and Sun 2006; Clift *et al*. 2006). Moreover, numerous studies were focused on the structural evolution of the RRFZ (see e.g. Leloup *et al*. 1995; Wang *et al*. 2000; Leloup *et al*. 2001; Gilley *et al*. 2003; Schoenbohm *et al*. 2004, 2005, 2006).

GEOLOGICAL SETTING

The Cenozoic history of northern Vietnam is closely connected with the evolution of the RRFZ (= Ailao Shan – Red River Shear Zone) (e.g. Leloup *et al*. 1995; Tapponnier *et al*. 1990), a structure that can be followed from Tibet to the South China Sea, for over 1000 km (Text-fig. 1A). The most intense sinistral shearing along the RRFZ is dated as Oligocene and Miocene, when it acted as a continental transform plate boundary (Leloup *et al*. 1995). Estimates of the associated sinistral offset range between 200 and 800 kilometres (e.g. Tapponnier *et al*. 1990; Sun *et al*. 2003). Curiously, the offset for the RRFZ in the area of the Tonkin Gulf probably does not exceed a few tens of kilometres (Rangin *et al*. 1995; see discussion in e.g. Morley 2002, 2007), suggesting that the difference in timing between onshore and offshore deformation along the RRFZ may reflect different stress regimes. Moreover, it is possible that the sinistral displacement along the RRFZ was dissipated as extension in the South China Sea (Morley 2002). Starting



Text-fig. 2. Geological sketch-map of the Na Duong Basin and adjacent areas (based on Thuy 2000 and Viet 2003)



Text-fig. 3. Geological sketch-map of the That Khe Basin and adjacent areas (based on Lap 1991 and Thuy 2000)

about 5.5 Ma ago, the movement along this zone changed to dextral (e.g. Allen *et al.* 1984; Leloup *et al.* 1995; Tapponnier *et. al.* 1990), with the estimated offset ranging between 5.5 and 30 kilometres (Allen *et al.* 1984).

The CB-TYF is located about 150 km northeast of the RRFZ (Text-fig. 1B). The two opposite motions are also suggested for this fault, which is considered as sinistral in the Miocene and dextral in the Quaternary (Chinh 2000). The studied basins were formed during the CB-TYF sinistral movement, with the opening of various pull-apart basins (Pubellier *et al.* 2003). The amplitude and rate of this movement is, however, only roughly known.

The sedimentary basins associated with the CB-TYF are filled with thick series of various Neogene siliciclastics, resting unconformably on various Mesozoic and Palaeozoic basements (Text-figs 2–4). There is a general gradual grain-size decrease towards the basin center. The successions are subdivided, in stratigraphical order, into the Cao Bang, Na Duong and Rinh Chua formations, dated as Miocene and Pliocene (Tran and Trinh 1975). Their stratigraphy (Tran and Trinh 1975; Thuan 2006) is based, however, on only a few palynological data and therefore the suggested ages should be treated with caution. The tectonic dip of strata is variable, with average being about 20°. All the basins are fault-bounded and cut by faults of the CB-TYF.

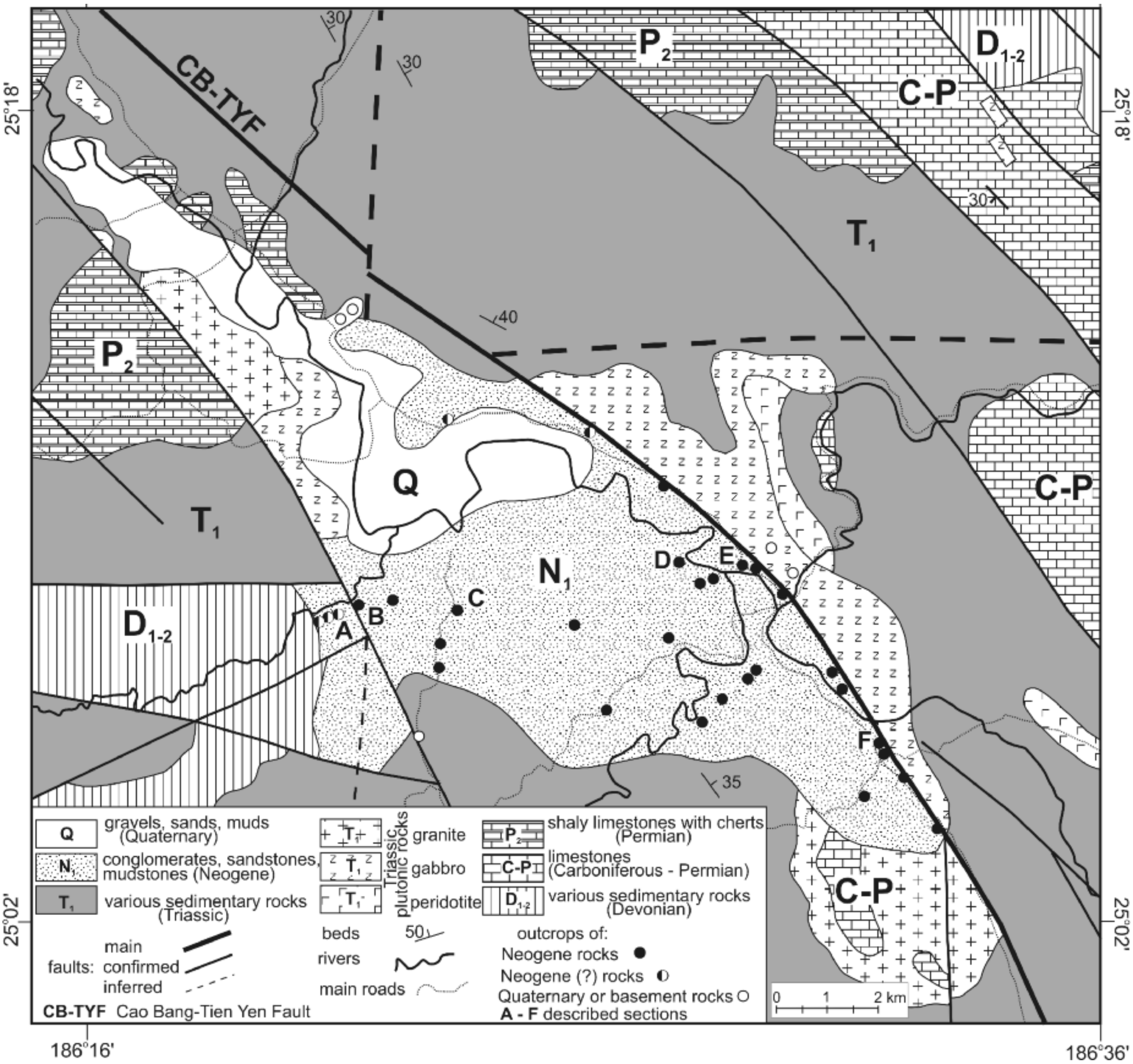
MATERIALS AND METHODS

The research was carried out between the towns of Lang Son and Cao Bang, over a distance of more than 150 km, in the area strictly connected with the CB-TYF (Text-fig. 1B). Fifty-eight geological sites were investigated, including Na Duong, the biggest Vietnamese brown coal pit. The standard sedimentary facies are described based on Miall's classification (Miall 1977, 1978, 1996). The sedimentary facies are grouped into facies associations representing distinct depositional environments. Samples of medium- and fine-grained sandstone and conglomerate were collected for standard petrographical analysis. Coal samples for petrological analysis were collected from seven major coal layers from Na Duong. All samples were made into polished particulate pellets according to the standard ICCP preparation methods. For maceral identification, the ICCP terminology was used. The tissue preservation index (TPI) and the gelification index (GI) by Diessel (1992), as well as the coal facies by Strehlau (1989) were used to determine the palaeopeatbogs conditions.

FACIES ASSOCIATIONS

Thirteen sedimentary lithofacies are recognized in the Na Duong, That Khe and Cao Bang basins (Table 1). Based on the dominant grain-size class, texture, stratification, degree of clast rounding and sorting, these are: sand- and mud-supported disorganised conglomerates (G); massive or amalgamated bodies of conglomerates (Gmm); sand- and mud-supported crudely stratified conglomerates (Gmg); planar and trough cross-stratified sand-supported conglomerates (Gp/Gt); massive or amalgamated beds of sandstones (Sm); planar and trough cross-stratified sandstones (Sp/St); ripple cross-laminated sandstones (Sr); horizontal-laminated sandstones (Sh); horizontal-laminated fine sandstones and siltstones, occasionally with normal grading (Sng); massive siltstones (Fsm); laminated siltstones (Fl); coaly claystones (FC); and coal (C).

The lithofacies were grouped into seven lithofacies associations [the concepts of lithofacies and lithofacies associations according to Reading (1996) and Miall (2000)] representing seven distinct depositional environments. These comprise (Table 2): alluvial fan (Facies Association I), gravel-dominated fluvial channel (Facies Association II), sand-dominated fluvial channel (Facies Association III), flood plain (Facies Association IV), lake margin and/or river mouth (Facies Association V), lacustrine (Facies Association VI), and swamp (Facies Association VIII). Based on field observations and



Text-fig. 4. Geological sketch-map of the Cao Bang Basin and adjacent areas (based on map Thuy 2000 and Cuong 2000)

the type of facies association facies maps were drawn (Text-fig. 5). They show strong correlation with the geometry of particular basins (Text-fig. 5), which suggests that the basins offset along the CB-TYF was relatively small.

Facies association I – Alluvial Fan

The alluvial fan association consists of coarse-grained deposits of the G, Gmm and Gmg lithofacies (Tables 1, 2). It is built of decimetre- to metre-thick, sand- and mud-supported disorganised pebble-to-cobble, and occasionally boulder-sized (Text-fig. 6A) conglomerates and subordinate breccia beds, occasionally with lenses of pebbly sandstones (Text-figs 6B, C). Generally, it contains two types of conglomerates. The conglomerate beds of type 1 are tabular, or broadly lenticular in shape (Text-fig. 6A), usually very poorly sorted, matrix- or clast-supported, with variable coarse sand or mud matrix content. Quite often they contain several large, outsized cobbles and boulders (Text-fig. 6A). The contact with the underlying or overlying facies associations is sometimes sharp and of erosional character. The conglomerate of type 2 is represented by several meters-thick, composite sequences of planar cross-bedded sand-supported conglomerates, occasionally with sandstone alternations (Text-fig. 6B). The beds are usually sheet-like, with limited or insignificant basal erosion. They are composed of sand- and clast-supported, poorly- to well-sorted, sub- to well-rounded pebble- to cobble-sized conglomerates. In some cases, the clasts are in parallel alignment (Text-fig. 6C).

Because of the massive structures within the beds, the lack of major erosional surfaces, the thick matrix-supported and disorganised conglomerate bodies of type 1 can be treated as deposited on the proximal and/or mid alluvial fan from high-concentration flows (e.g. Larsen and Steel 1985; Nemec and Steel 1984; Nemec and Postma 1993). Conglomerates of type 2, in contrast to conglomerates of type 1, are rather bi-modal, alternating occasionally with sandstone units, and their pebble-size beds are better sorted. This suggests that the assemblages of clasts were well sorted prior to their incorporation in this facies beds and that the large amount of sands were added either during or prior to the deposition. This suggests mixing with flood basin fines in the

Lithofacies	Description	Interpretation
Sand- and mud-supported disorganised conglomerates (G)	Decimetre thick; poorly defined, discontinuous beds; pebble-size and well-rounded clasts; sand to mud matrix.	Deposition from gravity and/or high-concentration flow.
Massive or amalgamated bodies of conglomerates (Gmm)	Up to several metres thick; highly amalgamated; cobble- to pebble-size and angular to sub-rounded clasts; clast- to sand-supported; undefined base and top.	Deposition from high-concentration flow.
Sand- and mud-supported crudely stratified conglomerates (Gmg)	Up to several metres thick; highly amalgamated; pebble- to cobble-size and angular to sub-rounded clasts; sand- to mud matrix; may be erosively based.	Deposition from high-concentration flow.
Planar and trough cross-stratified sand-supported conglomerates (Gp/Gt)	Up to 3 metres thick; highly amalgamated; planar or low angle trough cross-stratified; pebble-size and sub-rounded to well-rounded clasts; gravel patches with partly open-work fabric common; fining-up trend; very coarse to coarse sand matrix; erosively based.	Bedload transport; downstream migration of sinuous-crested barforms.
Massive or amalgamated beds of sandstones (Sm)	Up to several metres thick; poorly defined beds; poorly sorted; isolated pebbly sandstone lenticles and layers; occasionally normally graded; often developed above the Gt litofacies as part of a fining-up trend.	Upper plane bed flow.
Planar and trough cross-stratified sandstones (Sp/St)	Variable thickness of sets; poorly to well sorted; medium to coarse grained; low angle bounding surfaces; occasionally coalified flora fragments, and muddy intraclasts.	Downstream migration of ripple and dune scale sinuous- (St) or straight-crested (Sp) barforms, in some cases falling to low stage gravelly barform modifications.
Ripple cross-laminated sandstones (Sr)	Thin sets; well sorted; fine-grained; asymmetric straight or sinuous ripples.	Downstream migration of small-scale current ripples.
Horizontal-laminated sandstones (Sh)	Horizontally laminated fine sandstones; occasionally beds with coalified flora detritus, with rare molluscs.	Deposition from currents gradually decreasing in velocity.
Horizontal-laminated fine sandstones and siltstones with normal grading (Sng)	Horizontaly laminated fine sandstones and siltstones; erosively based, occasionally with normal grading.	Deposition from density currents.
Massive siltstones (Fsm)	Generally thick (a few metres); massive or poorly stratified; commonly alternated with sandy siltstones; occasionally pedogenic structures.	Deposition of fine grains from currents of low velocity and/or from suspension, occasionally subaerial conditions.
Laminated siltstones (Fl)	Thick series of stratified siltstones, occasionally with mollusc shells, bioturbated horizons and coalified flora detritus.	Deposition of suspended material.
Coaly claystones (FC)	Generally thick series (a few metres); poorly stratified; alternated with siltstone beds.	Phytogenic accumulation with a high supply of clastic material.
Coal beds (C)	Up to 3 metres thick; massive or stratified; occasionally with tree stumps and pyrite concretions.	Phytogenic accumulation.

Table 1. Lithofacies identified in the study; lithofacies code based on Miall (1977, 1978, 1996)

Association	Dominant lithofacies	Minor lithofacies	Depositional environment
I	G, Gmm, Gmg	Sm	Alluvial fan
II	Gp/Gt, Sp/St	Gmm, Sm, Fsm	Gravel-dominated fluvial channel
III	Sp/St, Sh, Sr	Gp/Gt, Sm	Sand-dominated fluvial channel
IV	Sh, Sr	Fsm	Flood plain
V	Fl, FC	G, Sp/St	Lake margin and/or river mouth
VI	Sh, Sr, Sng, Fl	Fsm	Lake
VII	C, FC	Fsm	Swamp

Table 2. Characteristic facies associations and their depositional environments

form of sheet flows, occasionally with shallow braided streams. It points to a sedimentary environment connected with a sheet flow-dominated alluvial fan setting.

Deposits of the Alluvial Fan facies association are confined to the marginal parts of the Cao Bang and That Khe basins. Moreover, the occurrence of these conglomerate bodies inside and/or overlapping with the coarse-sand deposits of facies association II and, in some cases, of facies association VI (Text-fig. 6D) suggesting deposition in an alluvial-fan setting in an area with a distinct relief that could be associated with active fault scarps.

Facies association II – Gravel-dominated Fluvial Channel

Facies association II is the most widely spread facies association in the That Khe and Cao Bang basins. It is composed predominantly of the Gp/Gt and Sp/St lithofacies, subordinately with the addition of the Gmm, Sm and Fsm lithofacies (Table 2). It is built of sand- and clast-supported, poor- to well-sorted, sub-rounded to well-rounded pebble-to-cobble conglomerates, and poorly sorted pebbly sandstones (Text-figs 7A–F). Sets of beds commonly have erosive bases (Text-figs 7A–D, F) and are sometimes amalgamated. As a rule, they show a fining-up trend in the topmost part of particular beds (Text-figs 7D, F). The set of beds is bound by distinct erosive surfaces and they build thick bodies, usually more than some metres thick (Text-figs 7A, B, D). In some cases, deposits of this facies association are observed as channelized forms cut in massive siltstones (Text-fig. 7C). Sometimes trough cross-stratification indicating downstream migration of barforms is observed (Text-fig. 7E). Massive or amalgamated beds of sandstones (Text-fig. 7D) may occur above facies Gp/Gt.

Facies association II is composed of repeated fining-upward cycles, usually more than 2 metres thick (Text-figs 7A, B). Such features indicate the deposition from bedload transport in the form of barforms with different fluid flow and sediment discharge that is characteristic of gravel-dominated fluvial channels. In some cases, sandstones indicating a decreasing sedimentation rate terminate the particular cycles (Text-fig. 7F). Moreover, the occurrence of these deposits inside and/or overlapping the gravely lithofacies of association I indicates to the deposition in shallow braided streams on the outer alluvial fan setting.

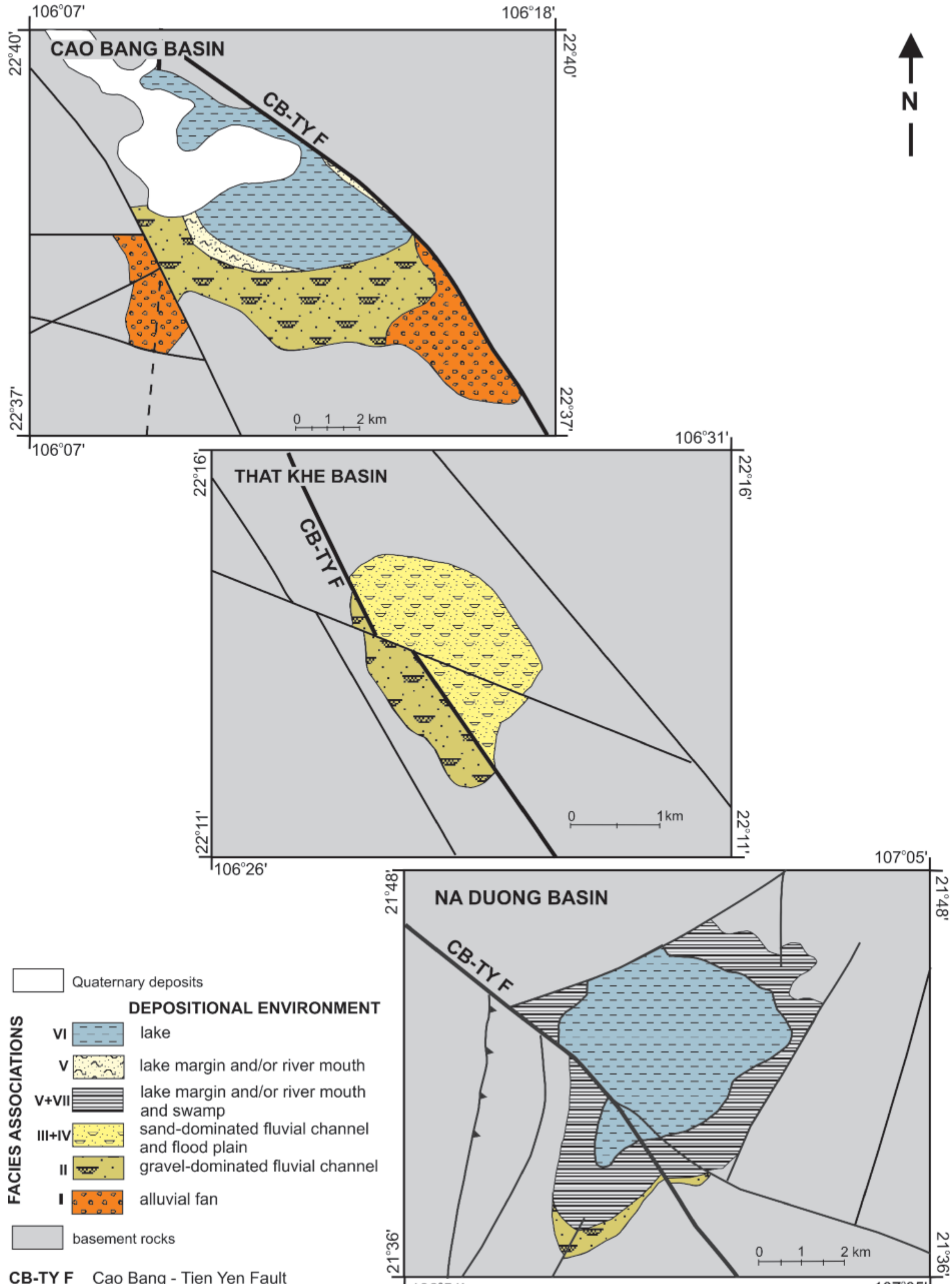
Facies association III – Sand-dominated Fluvial Channel

This association is composed of the lithofacies Sp/St, Sh, Sr and Gp/Gt, Sm (Table 2). It occurs rarely and only in the That Khe and Na Duong basins, and is characterized by poorly- to well-sorted, medium- to coarse-grained, occasionally fine-grained sandstones. Lithofacies Sp/St is represented by centimetre- to decimetre-thick sets building the metre-thick cosets (Text-figs 8A, B). They form channels cut in finer deposits of flood plain or lake margin facies associations (Text-figs 8A, B). Occasionally, lithofacies Sp/St contains coalified floral fragments and muddy intraclasts.

The alternation of the sandy lithofacies Sp, St and Sh with finer deposits indicates deposition from bedload transport in sand-dominated fluvial channels carrying dune-scale sinuous- and straight-crested barforms, in continuous, highly variable sediment discharge. They may be interpreted as a lithofacies deposited in a rather flat area covered by flood plains or in a lake margin and/or river mouth areas.

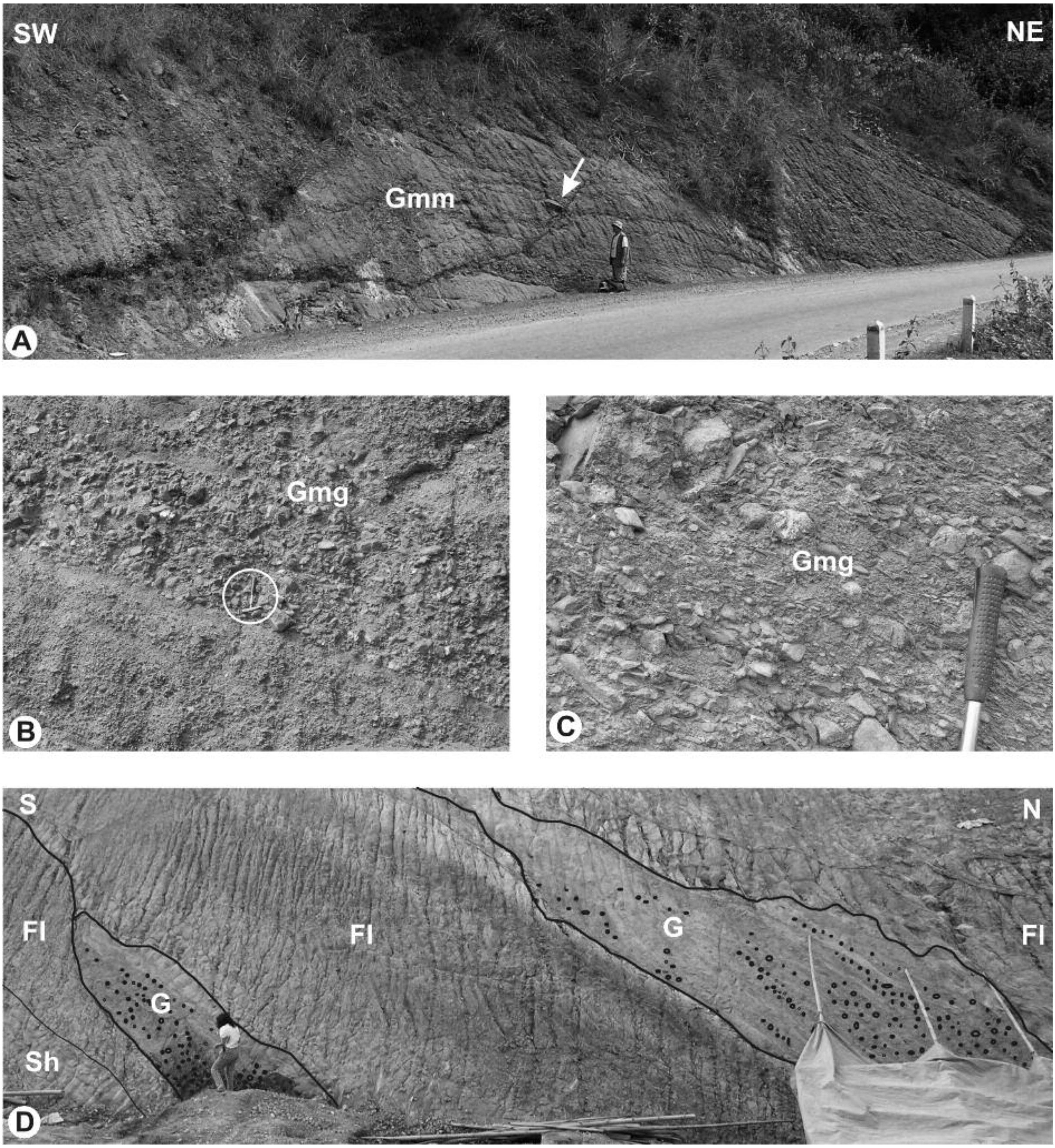
Facies association IV – Flood Plain

Facies association IV is dominated by the Sh, Sr and Fsm lithofacies (Table 2). It consists mainly of horizontally or ripple laminated fine sandstones (Text-fig. 8D) and massive or poorly stratified siltstones (Text-figs 7C, 8C). The reddish siltstones from the lower part of the Na Duong section commonly contain horizons of



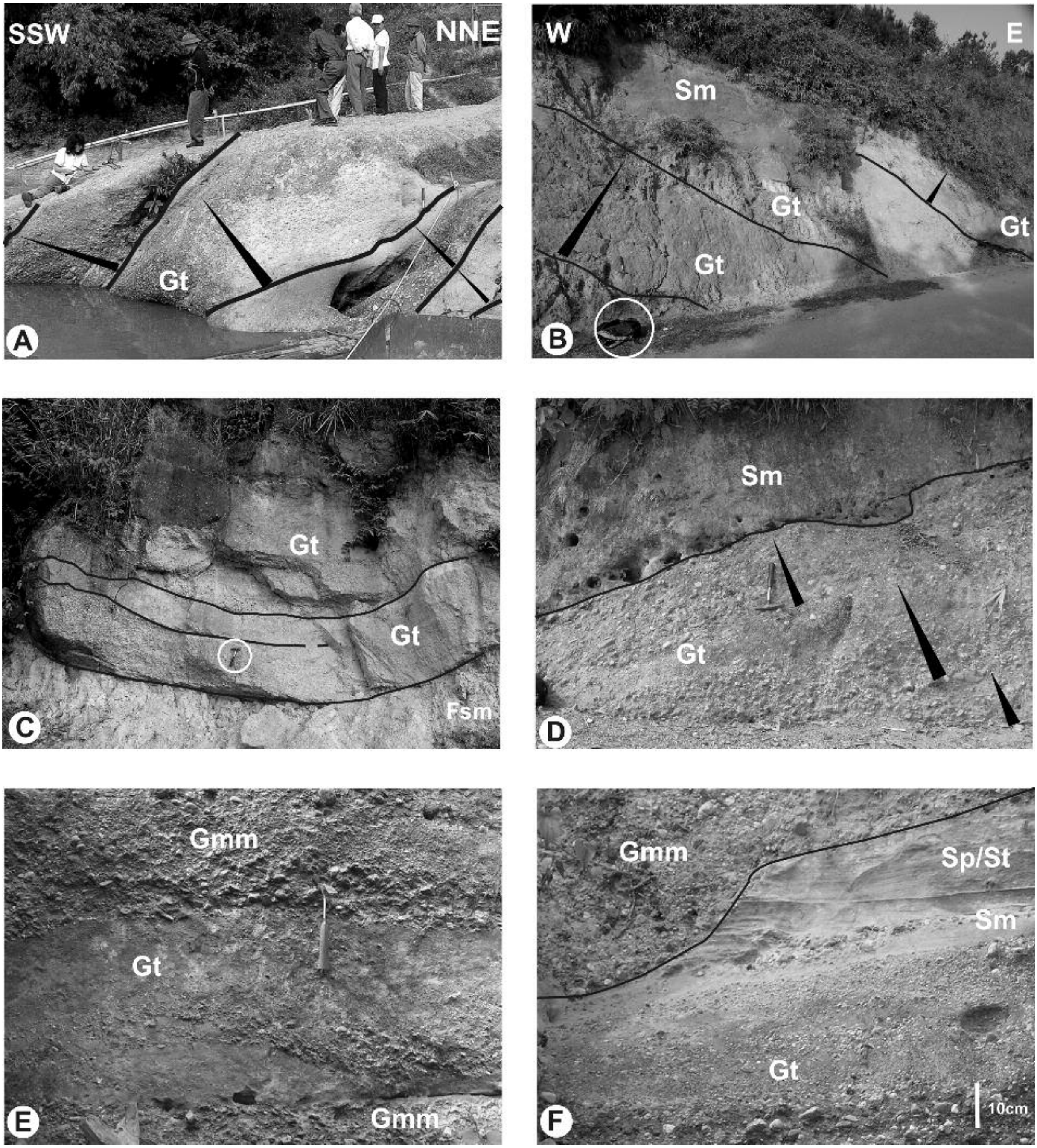
Text-fig. 5. Facies association patterns in the investigated basins (arranged from southeast to northwest) nodular textures interpreted as being of pedogenic origin (Text-fig. 8C). Moreover, the reddish siltstones terminate the fining-upward successions of facies association II from the Cao Bang Basin.

The thick reddish siltstones capping the fining-upward successions indicate deposition during the lowest velocity flow. The colour may suggest laterite conditions during or after deposition. The pedogenic structures are



Text-fig. 6. Aluvial fan facies lithofacies from the Cao Bang Basin. (A) Irregular and strongly amalgamated conglomerate bodies with rare outsized boulder (arrowed); lithofacies Gmm. (B) Crudely stratified conglomerates, poor sorted with angular clasts; lithofacies Gmg; note the strong amalgamation and variable grain-size; outcrop A – for location see Text-fig. 4, detailed section on Text-fig.13; hammer is 30 cm long. (C) Planar cross-bedded sand-supported conglomerates, elongated clasts are occasionally arranged linearly; lithofacies Gmg; outcrop A – for location see Text-fig. 4, detailed section on Text-fig. 13; hammer is 30 cm long. (D) Irregular gravel bodies of lithofacies G inside thick series of laminated siltstones of lithofacies Fl, interpreted as deposits of the distal inundated part of the steep alluvial fan reaching the lake; outcrop C – for location see Text-fig. 4, detailed section on Text-fig. 13

also indicative of subaerial exposure. Moreover, this facies association is closely related with a sand-dominated and gravel-dominated channel environment (facies association II and III), especially in the Cao Bang and That Khe basins. In Na Duong Basin it is connected with the lake margin and/or river mouth facies.



Text-fig. 7. Gravel-dominated fluvial channel lithofacies from the That Khe Basin. (A) Repeated fining-up fine-conglomerate sets started with concave erosional surfaces; lithofacies Gt. (B) Repeated fining-up fine-conglomerate to massive sandstone sets beginning with concave erosional surfaces; lithofacies Gt and Sm; bag is ca. 60 cm long. (C) Channel built of fine-conglomerates cut in massive siltstones; lithofacies Gt and Fsm; hammer is 30 cm long. (D) Amalgamated cosets of fining-up conglomerate beds overlying with sharp erosional surface the massive sandstones; lithofacies Gt and Sm; hammer is 30 cm long. (E) Alternating conglomerate beds of lithofacies Gmm and Gt; hammer is 30 cm long. (F) Fining-up succession of gravel- and sandy lithofacies (Gt→Sm→Sp/St), beginning with low-angle trough cross-stratified conglomerates and ending with planar cross-stratified sandstones cut by massive gravelly deposits of lithofacies Gmm

Facies association V – Lake Margin and/or River Mouth

Facies association V is composed of the Fl, FC and G, Sp/St lithofacies (Table 2). This facies association was only found in the Cao Bang Basin. It is characterized by thick series of stratified grey siltstones beds occasionally alternating with coaly claystones. Unfortunately, in all exposures they are strongly weathered. The most spectacular features of this facies is the occurrence of irregular gravel bodies of slump-shape (Text-fig. 6D). The gravel bodies are built of disorganised or massive fine conglomerates. They are sharply delimited and, in some cases, slightly deformed by folding.

The occurrence of synsedimentary deformed gravelbodies within the siltstone layers can be interpreted as the effect of the liding of a coarse sediment into the deeper part of a lake bounded by a steeper slope. The coarser deposits were supplied to the lake by the gravel-dominated fluvial channels as well as by the distal inundated part of alluvial fans.

Facies association VI – Lacustrine

This facies association is dominated by horizontally stratified fine- to very fine-grained, occasionally normal-graded, sandstones with siltstone interlayers (Text-fig. 8F), and thick series of massive or laminated siltstones (Text-fig. 6D). It consists of the Sh, Sr, Sng, Fl and Fsm lithofacies (Table 2). The terrestrial and freshwater mollusc assemblages are rather poor and dominated by bivalves (families Unionidae, Corbiculidae) and gastropods (families Bradybaenidae, Viviparidae, Lymnaeidae, Pleuroceridae) (Wysocka *et al*. 2007). These fossils are extremely numerous in some parts of the siltstones from the Na Duong basin (Text-fig. 10; lithofacies Fl) and form coquina beds. Gastropods are the most frequent components of the coquinas, being represented mainly by the genus *Viviparus* and subordinately by the genus *Lymnaea* and the family Pleuroceridae (Wysocka *et al*. 2007). Strongly bioturbated horizons (Text-fig. 8E) are typical of the deposits occurring between the coquina beds. Some of these beds are rich in coalified flora remains.

The lithology, sedimentary structures and fauna of these deposits point to deposition in a lake environment. Centimetre-thick, normally-graded fine sandstone and siltstones layers may be interpreted as formed by low-density turbidity currents. On the other hand, thick series of stratified siltstones indicate the deposition of suspended fine material. The coquina beds can be interpreted either as lag deposits, or as resulting from the supply of flood- and/or storm-derived shell material.

Facies association VII – Swamp

Facies association VII is composed of the FC, C and Fsm lithofacies (Table 2). This facies association is characterized by the occurrence of thick coaly series alternating with siltstone layers (Text-figs 8G, H and Text-figs 9, 10). The coaly series are built of coaly claystones and coal beds. The coaly claystones are generally thick, stratified with thin siltstone interlayers (Text-fig. 8G). In siltstones interlayers rather rare bivalve shells (subfamilies Anodontinae and Unionidae) (Wysocka *et al*. 2007) were found. The coal beds, up to 3 m thick, are massive or stratified; they occasionally contain tree stumps, as well as pyrite and carbonate concretions.

The deposits of facies association VII indicate a high-rate of phytogenic accumulation with a variable supply of clastic material. The lithology, sedimentary structures and fauna of these deposits point to the deposition in a swamp environment near a lake margin and/or river mouth. Typical deposits of the swamp facies association are found only in the south-west margin of the Na Duong basin.

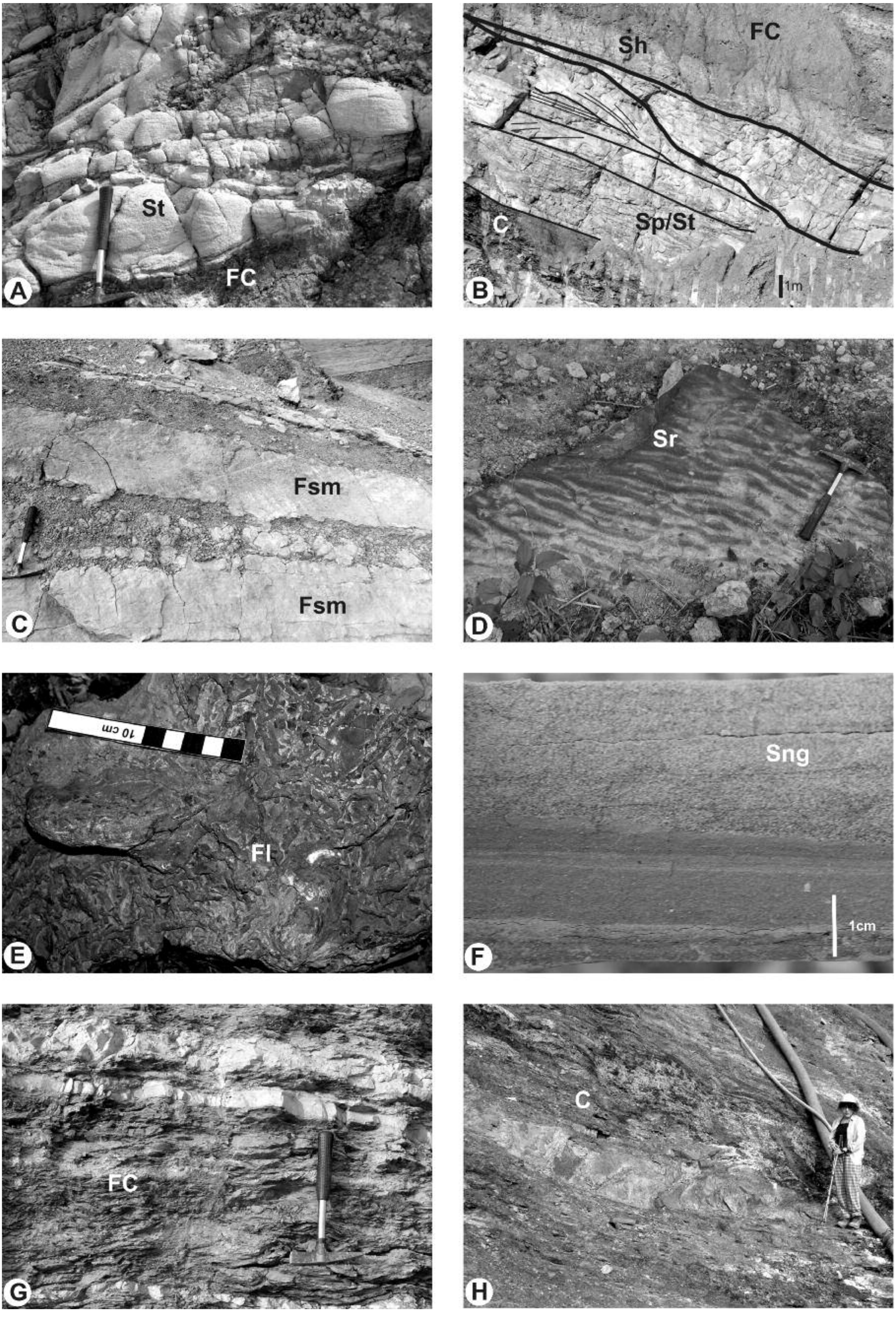
THE BASIN ANATOMY

Na Duong Coal-bearing Fluvial to Lacustrine Basin

The Na Duong Basin is the southernmost of the basins studied (Text-fig. 1B). In comparison to the other two, it is quite well known thanks to data from the Na Duong coal pit (Text-fig. 10), other natural exposures, and numerous boreholes. The age of the basin infill is referred either to the Miocene-Pliocene or to the Oligocene (Tran and Trinh 1975; Trinh 1979; Trung *et al*. 2000; Thuan 2006; Wysocka *et al*. 2007). The basin is elongated slightly NNE-SSW. The tectonic dip of the strata is variable and in some cases exceeds 30°. Based on unpublished data from the Na Duong coal pit, the sedimentary infill is slightly folded, forming a gentle syncline (Text-fig. 10).

The basement of the Na Duong Basin consists of Triassic and Cretaceous terrigenous siliciclastics (Text-fig. 2) with a maximum thickness of over 500 m (Text-figs 9, 10). The succession is subdivided into the lower, Na Duong Formation, comprising coal-bearing facies over 200 m thick, and the upper, Rinh Chua Formation.

The sedimentological logging of the Duong Formation was carried out in the Na Duong coal pit (Text-figs 9, 10). Generally, the succession is characterized by a fining-up trend. The lower part of the exposed suc-


St
FC
A
Sh
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C
H

cession is built of alternating siltstone and claystone layers (lithofacies Fsm and Fl) with coal seams (lithofacies FC and C) (Text-fig. 9B; section I), and characteristic, up to 2-m thick, sandstone layers (lithofacies Sp/St). The latter are complex planar- and trough-cross stratified (Text-figs 8A), occasionally with distinct erosional surfaces (Text-fig. 8B), interpreted as small-scale channels cut in the phytogenic deposits. The lower part is also characterized by several metres-thick massive reddish siltstones (lithofacies Fsm) with numerous horizons with nodular texture (Text-fig. 8C). The middle part of the exposed succession is built of alternating layers of grey, massive or laminated siltstones and coal seams (lithofacies Fl, FC and C) (Text-fig. 9B; section II). Also characteristic are siltstone layers with abundant shelly bivalves (subfamilies Anodontinae and Unionidae) (Wysocka *et al.* 2007). The coal beds, up to 3 m thick, contain tree stumps and pyrite and carbonate concretions. The upper, coal-bearing part of the formation consists of successive couplets of fine-grained clastic and phytogenic deposits (see Text-fig. 9B, section II). The cyclothems are composed principally of Fl→FC or Fl→FC→C, representing an alternation of energy levels on the flood plain. Based on well data (unpublished materials) the thickness of the coal seams in the uppermost part of formation decreases to almost nil, and they are gradually replaced by siltstones (Text-fig. 9A). The coal-bearing strata seem to be limited to the south and southeastern part of the Na Duong Basin.

The majority of the Na Duong Formation coals belong to coaly shales and bright-banded coal. The bright coal intervals are dominated by the vitrinite macerals group, mainly telinite and collotelinite; inertinite and liptinite are very rare. The random reflectance of the collotelinite (R_o) is 0.46, what allows the coals to be classified as subbituminous B rank, according to the ASTM classification. The coaly shales are composed of alternating thin laminae of clay minerals and thin layers of collotelinite and detrovitrinite with high values of the TPI and GI indexes (Gmur *et al.* 2006; Wysocka *et al.* 2007).

The coal seams from the Na Duong coal pit represent mainly the telocollinite subfacies and originated mostly under conditions of a wet forest swamp with a high water level (Text-fig. 11; see also Diessel 1992; Strehlau 1989). Peat accumulation took place under neutral to weakly alkaline conditions, in calcium-rich water (Hung *et al.* 2005).

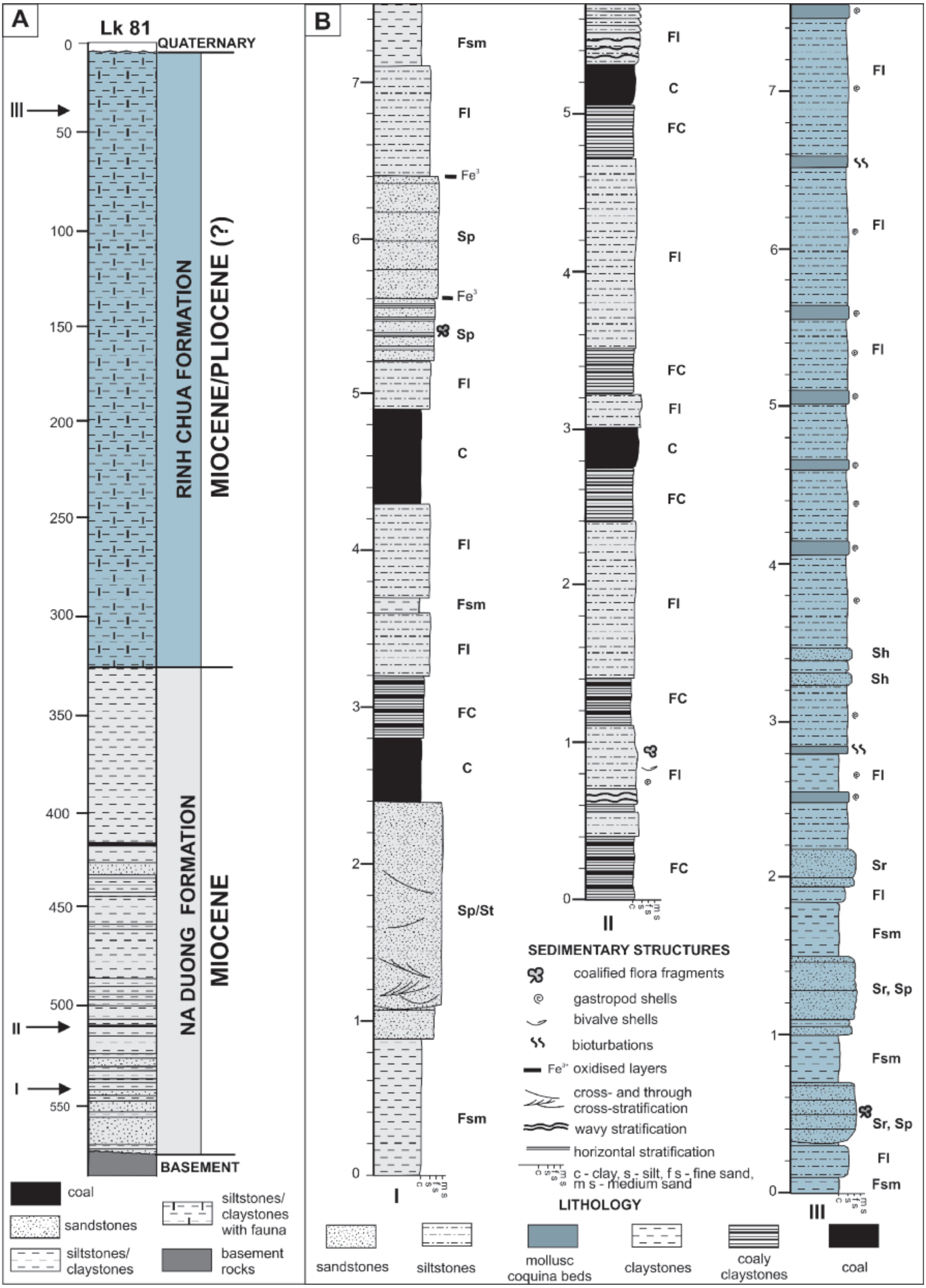
Summing up, the phytogenic deposits from the Na Duong Basin were laid down mostly in a wet forest swamp, and represent the swamp, lake-margin and lacustrine facies associations. The wide lateral extent of both the coal seams and clastic layers indicates the wide geographical extent of the basin. A relatively high supply of clastic material could probably have been provided by fluvial distributaries passing through a swamp into a lake. In such an environment, due to frequent flooding, there was a high terrigenous clastic input (Jerzykiewicz and McLean 1980; Sachsenhofer *et al.* 2003). The swamps were limited to the south and south-eastern part of the basin, as indicated by the absence of coal seams in its northern margin (Text-fig. 12). The Okefenokee Swamp, shallow peat-filled wetland at the Georgia/Florida border in the USA (Cohen 1974; Fair-Page and Cohen 1990) is a good modern analogue of the Na Duong coals.

With erosional contact and small angular unconformity, the Na Duong Formation is overlain by the 300 m-thick Rinh Chua Formation (Text-figs 9, 10). Again, only part of this formation is exposed (Ky Cung River bank; Text-figs 9A, 9B, section III; 10).

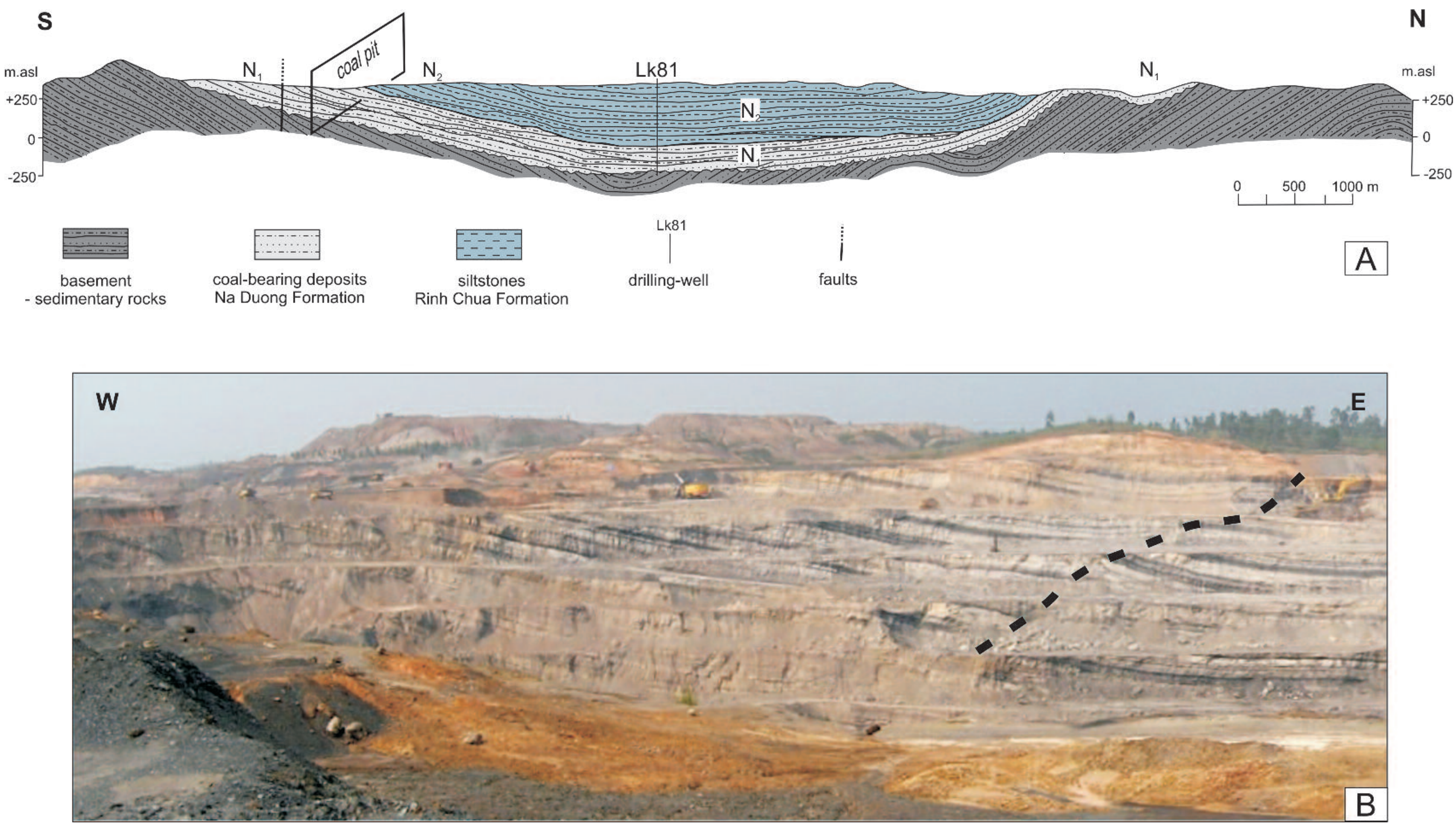
The formation is built of fine sandy and muddy facies with abundant terrestrial and freshwater molluscs, forming coquina beds dominated by gastropods of the genera *Viviparus* and *Lymnaea* and of the family Pleuroceridae (Wysocka *et al.* 2007). The inter-coquina beds are strongly bioturbated (Text-fig. 8E). Some of them are rich in coalified flora remains and/or their impressions.

The Rinh Chua Formation is built of predominantly fine-grained light-coloured, grey or reddish series of massive or stratified sandstones and silt-

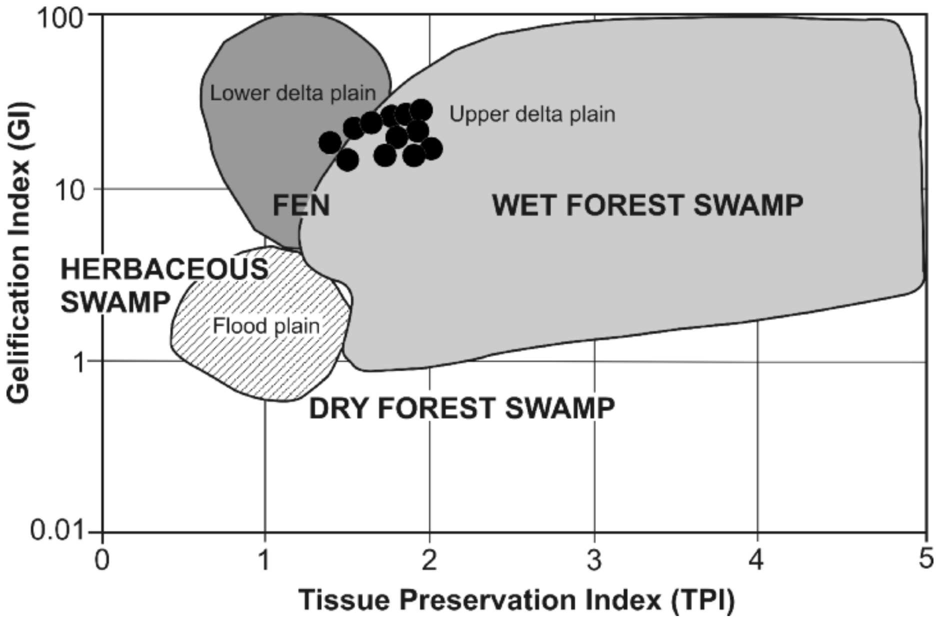
Text-fig. 8. Sand-dominated fluvial channel, flood plain, lacustrine and swamp lithofacies. (A) small-scale channel built of trough cross-stratified sandstones cut in a coal seam; lithofacies St and FC, Na Duong Basin, Na Duong Fm; hammer is 30 cm long. (B) A coal seam cut by complex channel sandstones, note different type of stratification in the sandy cosets and distinct erosional surfaces; lithofacies Sp/St, Sh, FC and C, Na Duong Basin, Na Duong Fm. (C) Horizons of nodular texture inside massive reddish siltstone series; lithofacies Fsm, Na Duong Basin, Na Duong Fm; hammer is 30 cm long. (D) Surface of fine-grained sandstones covered by sinuous-crested current ripples, Na Duong Basin, Rinh Chua Fm; section III (Text-fig. 9B); hammer is 30 cm long. (E) Strongly bioturbated siltstones; lithofacies Fl, Na Duong basin, Rinh Chua formation; section III (Text-fig. 9B); scale bar is 10 cm long. (F) Horizontal laminated siltstones (lower part) and erosively based fine sandstones with fining-up trends (upper part); lithofacies Sng, Cao Bang Basin; outcrop D – for location see Text-fig. 4, detailed section on Text-fig.13. (G) Stratified coal seams alternating with siltstones beds; lithofacies FC, Na Duong Basin, Na Duong Fm; section I (Text-fig. 9B); hammer is 30 cm long. (H) Massive or poorly-stratified coal seams with lenticular carbonate concretion; lithofacies C, Na Duong Basin, Na Duong Fm



Text-fig. 9. (A) Log of the Lk81 Borehole succession (based on unpublished material from the Na Duong mine); arrows point to the parts of the Na Duong and Rinh Chua formations with detailed sections. (B) Measured sections; I, II – from the brown-coal pit, Na Duong Fm, III – from the natural exposure on the Ky Cung river bank, Rinh Chua Formation (lithofacies codes as in Table 1)



(A) Cross-section of the Na Duong Basin; note the brown-coal pit and the location of the Lk81 Borehole (based on unpublished materials from the Na Duong mine). (B) General view of the Na Duong brown-coal pit. The main fault in the pit is emphasized by a dashed grey line



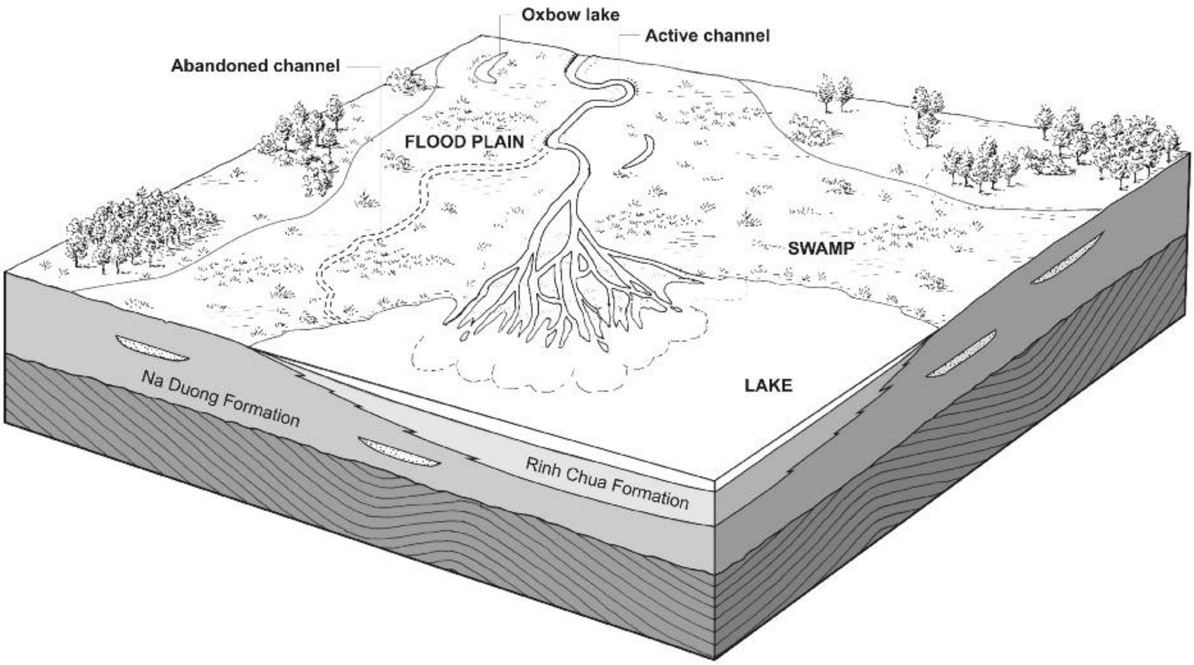
Text-fig. 11. Diessel's facies diagram of the coal seams studied (after Gmur *et al*. 2006)

stones, occasionally with ripple cross-stratification (lithofacies Sh, Sr, Fl and Fsm). Such lithofacies are generally characteristic of the lacustrine facies association. However, this is a very general statement because there are no universal facies models for the lacustrine environment. The Rinh Chua Formation displays evidence of wave or current processes, along with pervasive bioturbation and organodetritus accumulation. These features point to an oxygenated, shallow-lake environment. The gastropod coquinas can be interpreted as lag deposits or flood- and/or storm-derived detritus.

Sedimentation in the Na Duong Basin was initially dominated by fluvial and peat-forming processes (Na Duong Formation), followed by the lake deposition (Rinh Chua Formation). Generally, the basin is filled with a fining-up succession composed of fine-grained, mature clastic material (Wysocka *et al*. 2007). There is no evidence of raised relief in the surrounding areas.

The critical point in the interpretation of the evolution of the Na Duong Basin is chronostratigraphic interpretation of its sedimentary record. Until recently, the age of the Na Duong Formation was broadly ascribed to the Oligocene-Late Miocene, while the age of the Rinh Chua Formation ranges, in offered interpretations, between the Oligocene and Pliocene (Tran and Trinh 1975; Trinh 1979; Trung *et al*. 2000; Thuan 2006; Wysocka *et al*. 2007).

Because of these basic uncertainties, two possible scenarios of its evolution may be suggested. The first possibility is based on the assumption that the Na Duong and Rinh Chua formations differ in age. The Na Duong Formation, the older, was deposited in a swamp-dominated environment with minor influence of fluvial and lacustrine conditions. The Rinh Chua lacustrine Formation, the younger, was formed after a period of slight folding and erosion suggesting tectonic activity after deposition of the Na Duong Formation. In the second possibility, time-equivalence of the Na Duong and Rinh Chua Formations is assumed (Text-fig. 12). In this scenario, the basin was first filled with mostly fluvial and phytogenic deposits, with only minor influence of lacustrine sediments. The cyclicity of the coal-bearing Na Duong Formation indicates a variable energy level on the flood plain. The higher energy and coarser sediments point to flood peaks, whereas the lower energy and finer phytogenic deposits are indicative of periods of waning floods and/or intermittent floods. Subsequently the lake area expanded progressively, replacing the swamps. Lacustrine deposits terminate the fining-up sequence that fills the Na Duong Basin. The demise of the basin could have resulted both from climatic and tectonic processes that caused a change of the rate of sediment supply to the basin and/or the rate of subsidence. It is noteworthy that discussion of the regional uplift, changes in drainage systems, and the monsoon circulation in southeastern Asia is still in progress (see e.g. An 2000; Clift *et al*. 2002; Clark 2004; Clift and Sun 2006; Clift *et al*. 2006; Wan *et al*. 2007).



Text-fig. 12. Sedimentary environment model for the Na Duong Basin

That Khe Fluvial Basin

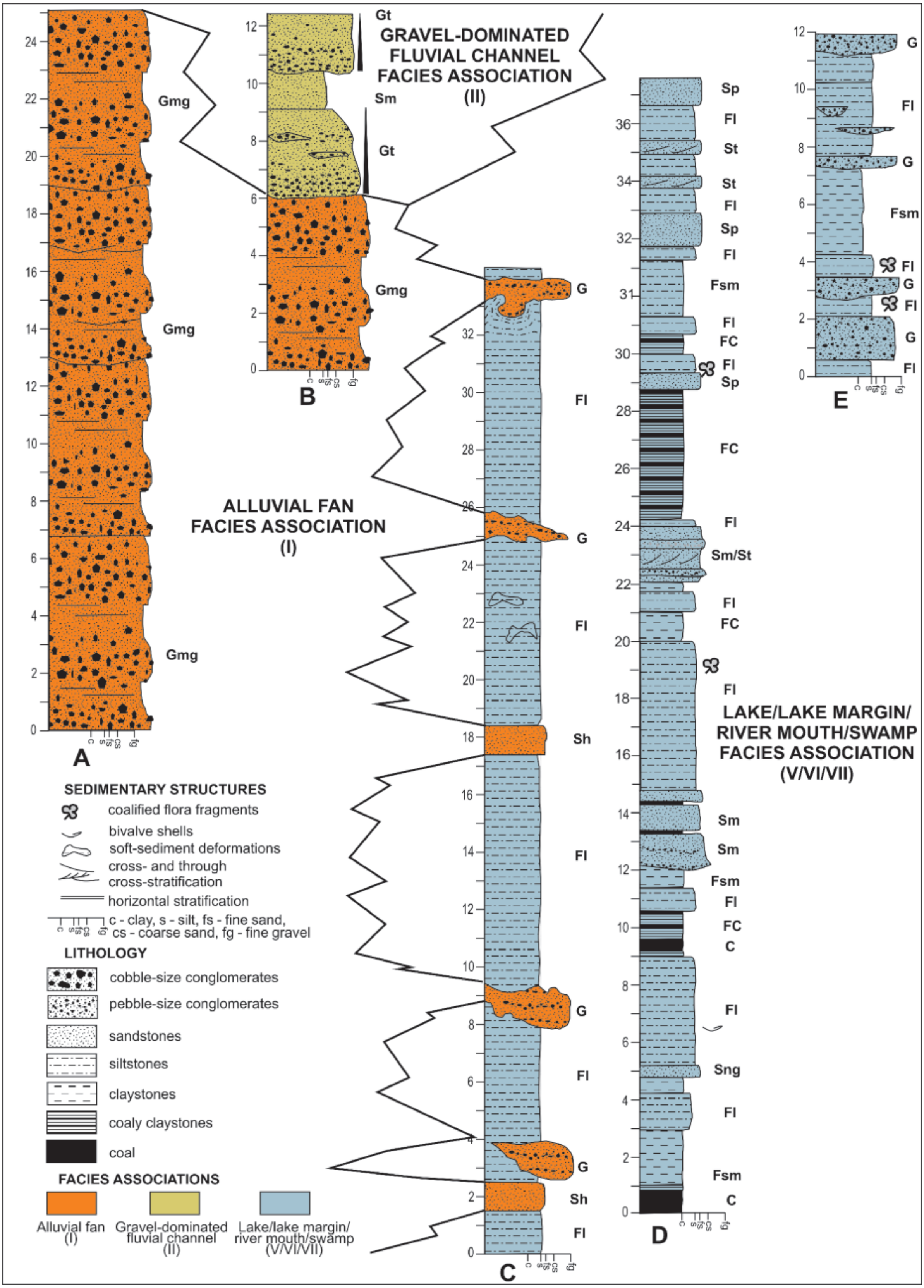
The That Khe Basin is located in the central part of the CB-TYF zone (Text-fig. 1B). This is the smallest of the three basins investigated. Its basement is built of Triassic sedimentary rocks (Text-fig. 3). It is oval in outline, elongated slightly NNE-SSW, and dissected by the CB-TYF from the SSW. The basin is filled with Miocene strata dipping slightly to the SW and SE. It is noteworthy that it is still active; its central part is occupied by a subsequent sedimentary basin, where Quaternary deposits cover most of the Miocene strata with the exception of its southwestern, uplifted margin, built of Neogene sediments. The published geological data are very scarce and, therefore, this interpretation is based entirely on field data.

The That Khe Basin is filled mainly with conglomerates, coarse-grained in the southern and fine-grained in the northern part. The coarse-grained conglomerate is represented by decimetre- to metre-thick, sand- and mud-supported disorganised pebble-size conglomerate beds of lithofacies Gmm and Gt (Text-figs 7A–F). The bed sets commonly have erosional bases, and are sometimes amalgamated. The topmost parts of particular beds show a fining-up trend. This conglomerate often occurs in the form of channel fills cut in massive siltstones, which are interpreted as gravel-dominated fluvial channel deposits of facies association II. Fine-grained conglomerates from the northern side of the basin are well exposed only in small tributaries of the Ky Cung River (Text-fig. 3). They are built of planar and trough cross-stratified fine conglomerates and sandstones of the mixed, gravel- and sand-dominated fluvial channel of facies association III.

Cao Bang Alluvial-fan to Lacustrine Basin

The Cao Bang Basin is the northernmost of the basins investigated (Text-fig. 1B). Its basement is built of various Mesozoic and Palaeozoic sedimentary (e.g. conglomerates, sandstones, siltstones and limestones) and magmatic rocks (e.g. Triassic granites, peridotites and gabbros, as well as Permian basalts and tuffs; Text-fig. 4). The basin is elongated NW-SE and filled with Miocene strata dipping slightly, mostly to the NE and SW. At present, it is directly bordered by two fault lines. Similarly as in the That Khe Basin, the Cao Bang Basin is partly occupied by a subsequent Quaternary sedimentary basin.

The precise stratigraphical position of the Neogene deposits of the Cao Bang Basin is unknown. Based on the general geological map (Thuy 2000), the basin is filled with Late Miocene deposits of the Na Duong Formation. However, the detailed geological map suggests their Middle Miocene age, and refers them to the

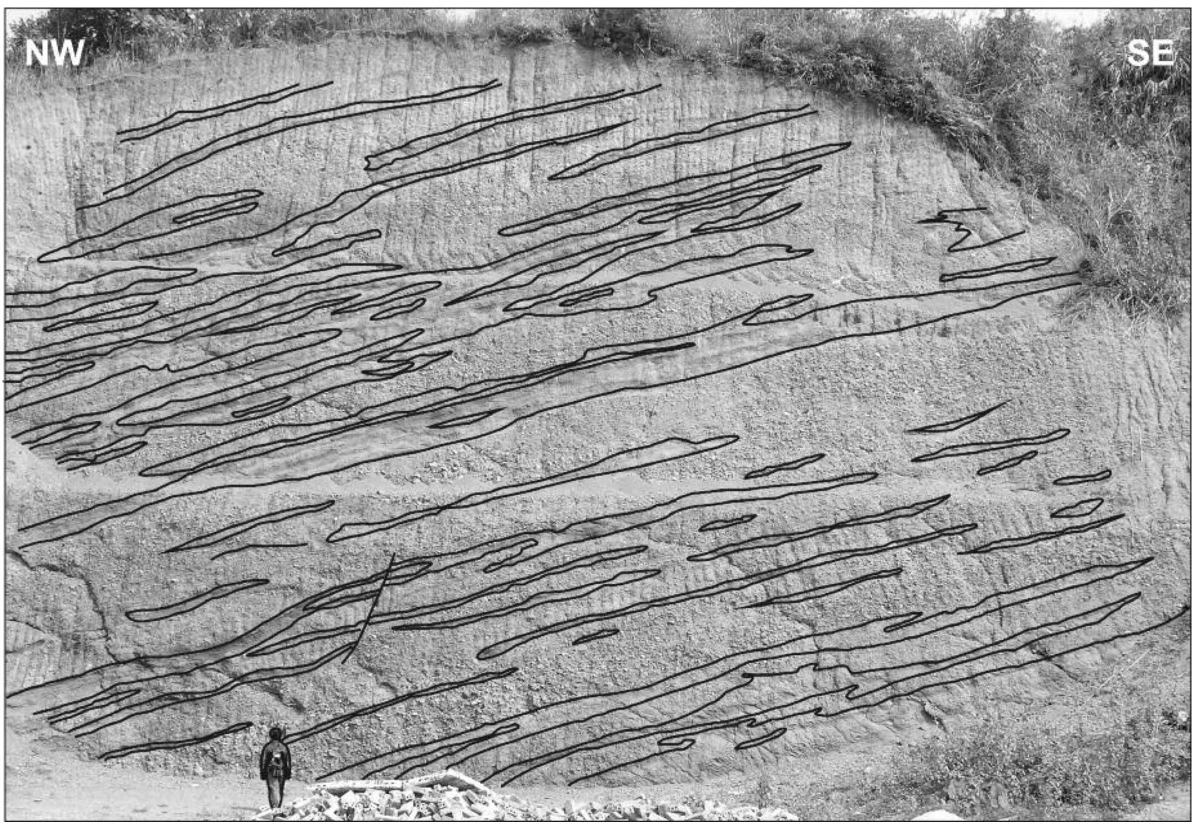


Text-fig. 13. Spatial relationships of the facies associations from the Cao Bang Basin; for section locations see Text-fig. 4

Cao Bang Formation (Cuong 2000). They are sometimes referred broadly to the Oligocene-Miocene (e.g. Viet 2003).

The Cao Bang Basin is filled with a broad variety of clastic deposits of the following lithofacies: sand- and mud-supported disorganised conglomerates (G), massive or amalgamated bodies of conglomerates (Gmm), sand- and mud-supported crudely stratified conglomerates (Gmg), planar and trough cross-stratified sand-supported conglomerates (Gp/Gt), massive or amalgamated beds of sandstones (Sm), planar and trough cross-stratified sandstones (Sp/St), ripple cross-laminated sandstones (Sr), horizontal-laminated sandstones (Sh), horizontal-laminated fine sandstones and siltstones, occasionally with normal grading (Sng), massive siltstones (Fsm), laminated siltstones (Fl), and coaly claystones (FC). Based on the lithofacies assemblages (Table 2), they represent an alluvial fan, gravel-dominated fluvial channel, flood plain, lake margin and/or river mouth, and lacustrine depositional environments.

The coarse-grained deposits were found in the western and southeastern margins of the basin (Text-fig. 5). The conglomerates of the western margin represent type 1, characterized by a tabular or broadly lenticular shape (Text-fig. 6A, and sections A and B on Text-fig.13), very poor sorting, variable coarse sand or mud matrix content, and the presence of outsized cobbles and boulders (Text-fig. 6A). Such conglomerate bodies can be interpreted as proximal and/or mid debris-flow dominated alluvial fans deposited from high-concentration flows (e.g. Larsen and Steel 1985; Nemec and Steel 1984; Nemec and Postma 1993). Towards the basin centre, the exposed deposits are finer, and composed of siltstones with gravel pathes, with slump and load structures (section C on Text-fig. 13). The transitional facies zone is rather narrow, and is followed by lacustrine facies. Such a pattern suggest that the alluvial fan slopes were steep and that the distal fan segments were inundated in a lake. The conglomerates of the south-eastern basin margin are of type 2. They form several metres-thick, composite sequences of planar cross-bedded sand-supported conglomerates, occasionally alternating with sandstones (Text-fig. 14). The sedimentary features of these conglomerates suggest a

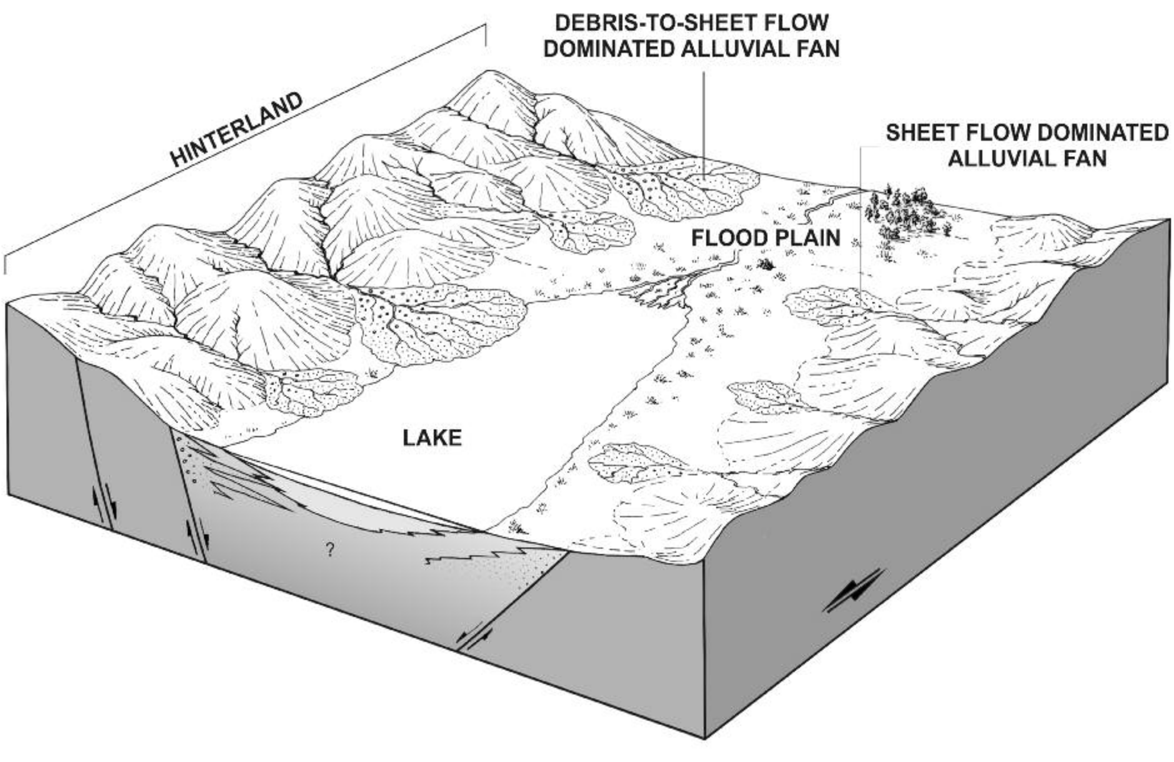


Text-fig. 14. Internal structure of the 2nd type alluvial fan conglomerates; composite sequences of planar cross-bedded sand-supported conglomerates, occasionally alternating with sandstones (outlined); Cao Bang Basin, outcrop F, along the road-cutting – for location see Text-fig. 4; man is about 170 cm tall mixing with flood-basin fine-clastics in the form of sheet-flows, occasionally with shallow braided streams, and are interpreted as deposited in sheet-flow-dominated alluvial fan setting.

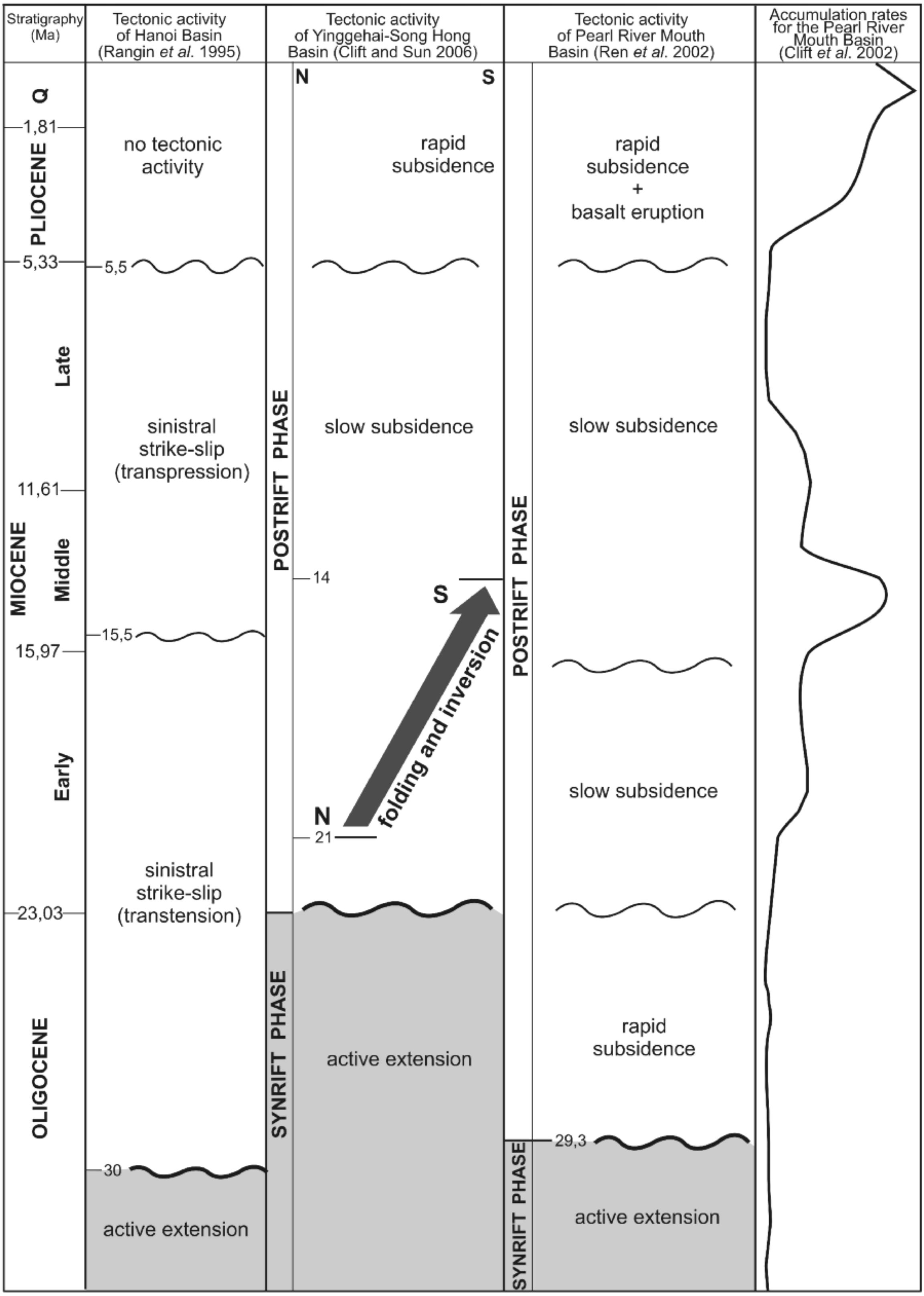
Towards the basin centre (Text-fig. 5), the alluvial fan conglomerates are replaced with a succession of usually more than 3 m-thick fining-up cycles, composed predominantly of sand- and clast-supported pebble-size conglomerates (section B on Text-fig. 13). In all cases, siltstones indicating a relatively low sedimentation rate terminate the individual cycles. Such features indicate the deposition from bedload transport in the form of barforms with different fluid flow and sediment discharge, characteristic of gravel-dominated fluvial channels.

In the central part of the basin (Text-fig. 5), the sandstones, siltstones, and siltstones with freshwater fauna and coaly claystones predominate (section D on Text-fig. 13). Coaly claystones within this clastic succession point to a high organic influx and to deposition in standing bodies of water. Such facies indicate the deposition on a flood plain, occasionally occupied by lakes.

In the Cao Bang Basin, the facies association pattern shows strong correlation with basin geometry (Text-fig. 5). The alluvial fan facies association of the western and southeastern margins of the basin build two separate zones, interpreted as alluvial fans developed on steep slopes between high-relief areas and the basin floor. This suggests the occurrence of source areas west and southeast of the present-day basin, connected with the fault-flank areas. Moreover, a narrow transitional facies zone between alluvial fan and fluvial associations (Text-figs 5 and 13) suggests that the alluvial fan slopes were steep and connected with a steeper basin margin. Therefore, the distal fan segments could be inundated in a lake. Beside a lake environment, the central part of the basin was occupied by a rather flat area covered by river channels and flood plains. Such a depositional pattern suggests that the Cao Bang Basin was a small elongated depression surrounded by high-relief catchment areas connected with the footwall of the fault zones characterized by high sediment supply (Text-fig. 15). Such a palaeogeomorphological pattern has caused distinct directions of the sediment supply, along both fault margins and the axial region of the basin. This situation is typical of an extensional basins connected with a strike-slip setting (e.g. Crowell and Link 1982; McLaughlin and Nilsen 1982; Blair and Bilodeau 1988; Nilsen and Sylvester 1995; Porębski 1997; Ryang and Chough 1999; Gawthorpe and Leeder 2000; Kim *et al.* 2003). Moreover, as was lately suggested by Pubellier *et al.* (2003), the Cao Bang Basin had a polyphase evolution with a high component of extention and evolved as a sigmoid pull-apart.



Text-fig. 15. Sedimentary environment model for the Cao Bang Basin



Text-fig. 16. Compilation of tectonic evolution for the Tonkin Gulf area, Yinggehai-Song Hong and Pearl River Mouth basins (based on Rangin *et al*. 1995; Ren *et al*. 2002 and Clift and Sun 2006) and the accumulation rate curve for the Pearl River Mouth Basin (based on Clift *et al*. 2002)

DISCUSSION

The variable basin-fill patterns of the basins studied suggest their complex evolution which resulted from the tectonic and climate history of southeastern Asia. The crucial tectonic factor was the CB-TYF (Text-fig. 1B), one of the main strike-slip faults in the region, which acted as sinistral in the Miocene and dextral in the Quaternary (Chinh 2000). No direct studies on the amplitude and the rate of movement along this fault have been undertaken (Chinh 2000; Pubellier 2003). However, indirect inferences from the fault itself and the accompanying basins come from other well-documented sedimentary basins in the region: the Hanoi (Text-fig. 1B) and Yinhhegai – Song Hong basins southward of the studied area, and the Pearl River Mouth Basin to the north (for location of these basins see Clift and Sun 2006, fig. 1).

Four main stages of structural evolution were suggested for the Hanoi Basin (Rangin *et al*. 1995): (I) before 30 Ma, an active extension stage during the rift opening; (II) 30–15.5 Ma, a sinistral transtensional regime; (III) 15.5–5.5 Ma, a sinistral transpressional regime after cessation of the sea-floor spreading within the South China Sea; and (IV) after 5.5 Ma, the recent stage of dextral movement (Text-fig. 16). By inference, the basins studied probably originated during the sinistral transtensional regime of the second stage, sometime between 30 and 15.5 Ma years ago. Accordingly, it is also assumed that the opening-vanishing cycles in the CB-TYF basins were diachronous, with the Cao Bang Basin formed first, followed by the That Khe and Na Duong basins. Finally, the post-depositional uplift, tectonic deformations and pre-Quaternary erosion in the basins should be correlated with the sinistral transpressional regime of the third stage.

Without detailed tectonic, stratigraphic and petrographic studies, this interpretation should be treated with great caution. There are several possible modifying factors, such as the lateral offset of the basins fill from its source area, diachroneity of processes or different structural styles along particular segments of a fault, creating different basin types (fault-bend, pull-apart, transrotational, or transpressional basins) (Nilsen and Sylvester 1995). The time-shift of processes along the strike-slip fault is well illustrated by the Yinggehai-Song Hong Basin, at the southern termination of the Red River Fault Zone. In the course of basin evolution the depocentres have migrated southward in time since the Oligocene. The basin was then folded and inverted 21 Ma years ago in the north and 14 Ma years ago in the south, before a rapid subsidence after ~5 Ma (Clift and Sun 2006).

Inevitably, the proper interpretation of sedimentary patterns of particular basins should also consider the evolution of the regional climate. The coal-bearing fluvial-to-lake succession from the Na Duong Basin points to the rather warm and wet conditions characteristic of the present monsoonal climate. The best on-land record of the climate evolution in South-East Asia is in the Chinese Loess Plateau, which suggests the initiation of the monsoonal climate in the area around 8.0-8.5 Ma (An 2000). A much earlier start of the East Asian monsoon is suggested, however, by the ODP Site 1146, in the northern South China Sea (e.g. Clift and Sun 2006; Clift *et al*. 2006; Wan *et al*. 2007), with the beginning of monsoon evolution dated as ca. 20 Ma ago. Clift and Sun (2006) confined the fast Early to Middle Miocene sedimentation to a wetter climate at that time and its slower rate to drier conditions during subsequent Late Miocene time. As one of the factors influencing the climate evolution they point to the regional uplift of the Tibetan Plateau.

The next problem in this region is the evolution of the drainage pattern, especially because both climate and tectonics have a strong impact on it. The present-day, non-dendritic drainage pattern of the rivers in SE Asia reflects the progressive capture of headwaters from the Red River as a result of the uplift of Eastern Asia (Clift *et al*. 2006). Moreover, modern river systems represent remnants of an ancestral Red River system that dominated southwest China and Indochina prior to the regional Tibetan uplift (Clark *et al*. 2004). The CB-TYF is subparallel to the Red River Fault Zone, where the modern Red River, Lo River, and Chay River follow the course of the strike-slip faults. The basins studied are directly bounded by the CB-TYF but they belong to different modern river systems. The Na Duong and That Khe basins are connected with the Ky Cung River running to the northwest, whereas the Cao Bang Basin area is connected with the Bang River running to the southeast. It is noteworthy that all the basins investigated are partly occupied by subsequent Quaternary basins and belong to the modern Pearl River catchment. Such a structure of the studied basins is believed to reflect a post-depositional reorganization of the region.

CONCLUSIONS

The sedimentary sequences of the three studied Vietnamese basins, developed along the CB-TYF, potentially hold the key to understand how sedimentation, erosion, climate, and tectonics interact in this region and could be linked to the geotectonic evolution of the South China Sea region. On the basis of this study, the lacustrine (Na Duong), fluvial (That Khe), and alluvial-fan to lacustrine (Cao Bang) basins were distinguished. The most complex, tectonically-controlled pattern is displayed by the Cao Bang Basin, which was bounded by a high-relief catchment area connected with the footwall of the CB-TYF. In contrast, the sedimentation pattern in the Na Duong Basin was controlled less by tectonic and more by climatic factors, which is reflected by an alternation of clastic sediment supply and phytogenic accumulation probably resulting from the climate humidity and/or monsoon intensification.

The origin of the accommodation space in the basins studied can be linked with the Early to Middle Miocene sinistral transtensional regime then prevailing in SE Asia. Such a tectonic setting is thought to have caused complex changes in both lateral and vertical displacement through time. Displacement through time, resulting in the appearance of releasing and restraining bends located alternately on either side of the CB-TYF. In effect, various forms of basins developed along particular segments of this fault. Consequently, the basins studied were possibly diachronous and could reflect complex unconformities. The post-depositional uplift, the tectonic deformations, and the pre-Quaternary erosion in the basins studied may also be correlated with the above-discussed sinistral transpressional regime.

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