Journal of Paleolimnology **22:** 81–95, 1999.

Diatomaceous sedimentation in the Tertiary Lampang Basin, Northern Thailand

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Received 19 February 1998; accepted 3 August 1998

Key words: *Aulacoseira*, diatomite, Tertiary, Thailand, palaeogeography, lakes

Abstract

The Lampang Basin is the second largest Tertiary graben in northern Thailand and was formed in response to the Himalayan orogeny. Deposition started with Miocene sandstone, lignite, mudstone, shale and oil shale of the Mae Sot Formation, which gave way to Pliocene diatomite, diatomaceous clay and silty clay of the Ko Kha Formation, with coarse clastics being restricted to the basin margins. Secondary iron-staining and iron-rich nodules are also common in the latter formation.

Diatoms only occur in the Ko Kha Formation, where they are abundant and well-preserved. Five assemblages, indicative of fresh to moderately alkaline water, are present. These floras are variously dominated by *Aulacoseira granulata*, *A. granulata* var. *valida*, *A. agassizi*, *A goetzeana*, *A. ambigua*, *A. italica* var. *bacilligera* and *A. italica* var. *tenuissima.* Pennate species are present, but infrequent.

During the Pliocene, in the Ban Pa Muang area, non-diatomaceous lacustrine sediments were initially laid down. These gave way to the deposition of diatomaceous clays and diatomites dominated by *A. granulata* and *A. agassizi*, which flourished in the deeper and shallower sectors (respectively) of a fresh water body. The palaeolake then became mildly alkaline, with a flora dominated by *A. granulata* var. *valida.* Shallow, fresh conditions followed, characterised by varied *Aulacoseira* diatoms, before the lake again became deeper. This latter phase may be related to increased river recharge.

Introduction

The Lampang Basin (about 1000 km^2) is the second largest of its type in northern Thailand. It lies approximately 250 m above sea level, about 70 km directly to the south east of Chiang Mai, and is located 500 km north of Bangkok (see inset B, Figure 1). The basin is an intracontinental graben bounded by a series of en echelon, north-south trending, normal faults. These faults are thought to have resulted from strike-slip tectonics induced by the collision and progressive subduction of the Indian Plate beneath the Eurasian Plate, which began in the Oligocene (Polachan & Sattayarak, 1989). Based on gravity data, Piyasin (1978) and Sripongpan (1985) have suggested that there may be three distinct sub-basins: the Lampang, Hang Chat and Mae Tha sub-basins.

In the Lampang Basin, Tertiary strata rest on an erosion surface that cuts across folded Triassic limestone, shale, sandstone and conglomerate, and Permo-Triassic volcanic rocks, of the Lampang Group (see inset A, Figure 1). The Tertiary sediments consist of fluvial, lacustrine and non-marine deltaic deposits. Volcanism occurred intermittently. Evidence from radiometric dating indicates that eruptions took place in the Middle Miocene (22.4–18.5 Ma), and at 5.64 ± 0.28 Ma and 0.8 ± 0.3 Ma (Ratanasthien, 1992).

The Tertiary rocks comprise the Mae Mo Group (see inset A, Figure 1), which is locally >1000 m thick and ranges up to 600 m in the Mae Tha area of the Lampang

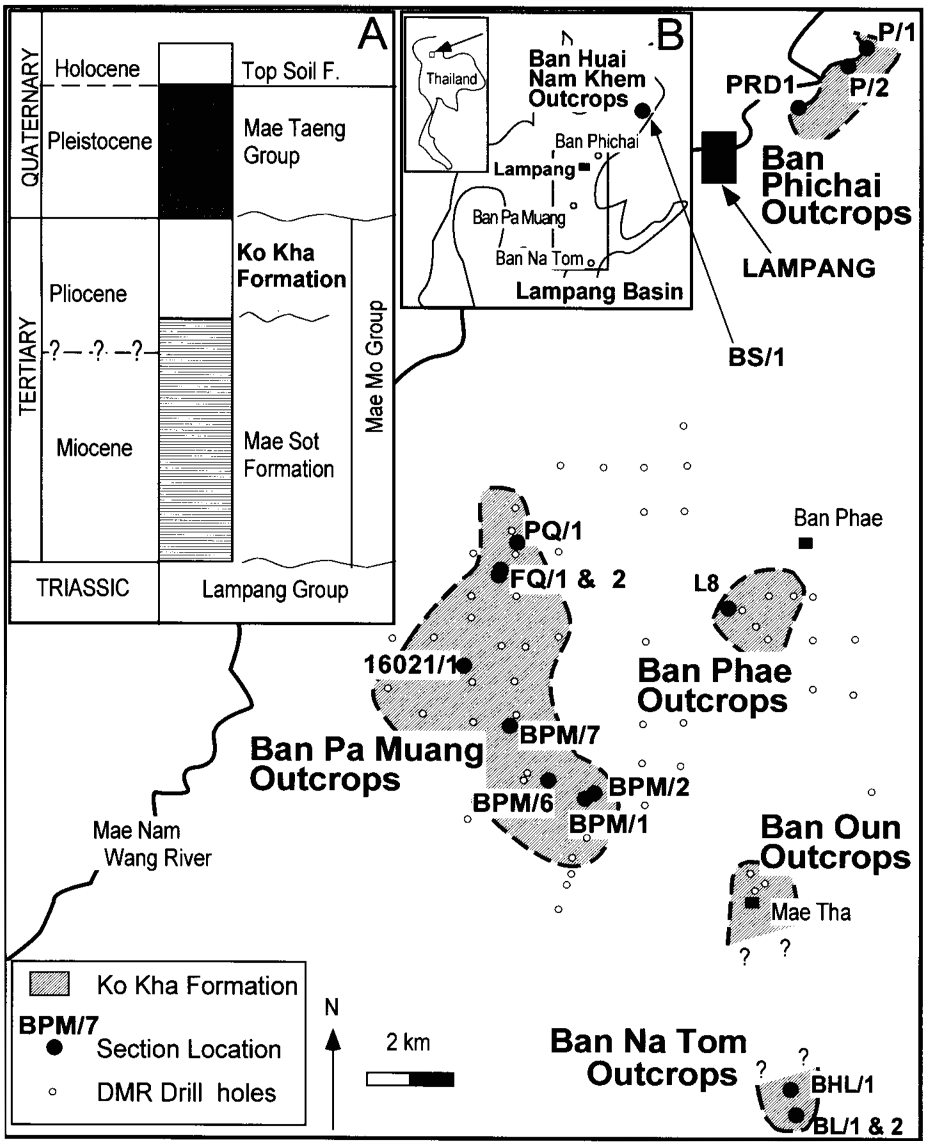

Figure 1. Location of measured sections and outcrop areas of the Ko Kha Formation, Lampang Basin. UTM grid locations: BS/1 – 0565642, 2033045; PRD1 – 0555541, 2023376; 16021/1 – 0547722, 2010476; L8 – 0554562, 2011708; BHL/1 – 0554383, 1999557. Insets: (A) stratigraphy; (B) regional location.

Basin. The Mae Mo Group is further subdivided into the Miocene Mae Sot Formation and the Pliocene Ko Kha Formation (Sripongpan, 1985). The boundary between these two units is ill-defined. The Mae Sot Formation consists of cyclic mudstone, shale, oil shale, sandstone, and lignite, which also occur in several other Tertiary basins in northern Thailand (Gardner, 1967). The Ko Kha Formation is made up of gently dipping, and faulted, light-coloured, silty clay, diatomaceous clay and diatomite (Inglethorpe et al., 1997). The Mae Mo Group is truncated by an unconformity, upon which Pleistocene river gravel and laterite of the Mae Taeng Group have developed (Kumanchan & Traiyan, 1986). A Pleistocene vesicular basalt occurs locally (Ratanasthien, 1992), and recent sediments consist of alluvial clay, sand and gravel.

This paper presents a preliminary study of the Ko Kha Formation, which includes some of the earliest diatomaceous sediments in South East Asia. Early studies of the Ko Kha Formation were carried out by Sresthaputra (in Brown et al., 1951) and Pariwatawon (1962). The latter investigation recognised the presence of freshwater diatoms. Subsequently, Piyasin (1972) reported new outcrops of diatomite, and Akutsu (1974), based on one sample, noted the presence of *Melosira* (*Aulacoseira*) *granulata* and rare *Navicula* and *Fragilaria* species. Kumanchan (1979) reported local occurrences of bentonite interbedded with diatomite. An extensive survey of the Ko Kha Formation was carried out by the Thailand Department of Mineral Resources (DMR) in the early-mid 1980's, which involved drilling 55 boreholes on a 1 km grid. In addition, six exploratory shafts were sunk in areas with known diatomite. The results of the physical and chemical analyses of the deposits are reported by Kumanchan & Traiyan (1983, 1986) and by Sripongpan (1985).

The quality of the diatomite in the Ko Kha Formation is just short of that required for industrial use. Chemical analyses show that the silica content is in the range of 72–80%, with alumina comprising up to 13%, and iron oxides forming 2–5% (Harnjavanich et al., 1995; Inglethorpe et al., 1997). This compositional range is comparable to the Moler diatomite of Denmark, which is used in the production of thermal insulation bricks, pet litter and absorbents. At present, the Lampang diatomite is quarried and sold under the trade name of 'Zeolite'.

The Ko Kha Formation sediments occur as scattered remnants (spread over an area of about 600 km^2) that have resulted from Pleistocene uplift and fluvial erosion of what may have been more extensive deposits. Today, they form small isolated hills, 10–20 m high, that are often capped by laterite (Inglethorpe et al., 1997). The distribution of these outcrops (see Figure 1) was mapped by the DMR (Kumanchan & Traiyan, 1983, 1986) using field and borehole data. Six main outcrops are present at: Ban Huai Nam Khem, Ban Phichai, Ban Pa Muang (Area A of Kumanchan & Traiyan, 1983), Ban Phae (Area B), Ban Oun (Area C), and Ban Na Tom. The latter four lie within the NNE-SSW trending Mae Tha sub-basin. The deposits have a lenticular form, with the base of the Ko Kha Formation varying by several tens of meters in altitude between the various outcrops (Sripongpan, 1985).

Methods

Fieldwork consisted of the visual logging of 16 sections from the main outcrops noted above. No samples were collected from the Ban Oun area due to lack of exposure, data being confined to DMR exploration borehole logs. A total of 188 samples were collected at about 1 m intervals, with supplementary samples gathered immediately above and below lithological boundaries. Of these samples, 97 contained diatoms, 32 included only very rare or broken taxa, and 59 lacked any diatoms at all. Iron-rich nodules, here referred to as 'rambutan' nodules, were collected from several locations for thin-section, S.E.M. and E.D.S. studies.

The diatomaceous sediments needed little pre-treatment before diatom analysis and were simply weighed and dispersed in distilled water before fixed volumes were placed on cover slips. This allowed quantitative estimates of diatom abundance to be made. Samples containing clay were additionally dispersed using sodium hexametaphosphate. Organic matter, where present, was removed with hydrogen peroxide. All samples were dried and mounted in Hyrax for optical microscopy. For scanning electron microscopy the sediment samples were gently scraped with a sharp blade and the resulting powder was mounted on carbon tape before being examined using an S.E.M. housed at the Earth Science Department of Hong Kong University. Diatom identifications were based on both optical and S.E.M. analyses, and follow the works of Akutsu (1974), Andrews (1971), Gasse (1986), and Hustedt (1957).

A correspondence analysis (Greenacre, 1993) was carried out for diatoms that accounted for >1% of the flora in at least 3 samples. Given the very low diatom diversity in the Ko Kha Formation (only 17 species occurring), this approach left only 10 common diatoms for the analysis. The resulting correspondence analysis maps were then used to relate sample scores according to similarities in diatom floras and to distinguish diatom assemblages (Gasse & Tekaia, 1983; Reavie & Smol, 1997).

Lithology

Biogenic and clastic deposits

Diatomite has been widely reported from a variety of lakes and palaeolakes. However, the terminology is commonly confused and often major misidentifications occur with volcanic tuff and white clay variously being referred to as 'diatomite'. This has also been the case for parts of the Ko Kha Formation. Here, we adopt a classification (see Figure 2) that uses simple point counting, and which is based on the common components that are associated with diatoms. Lacustrine

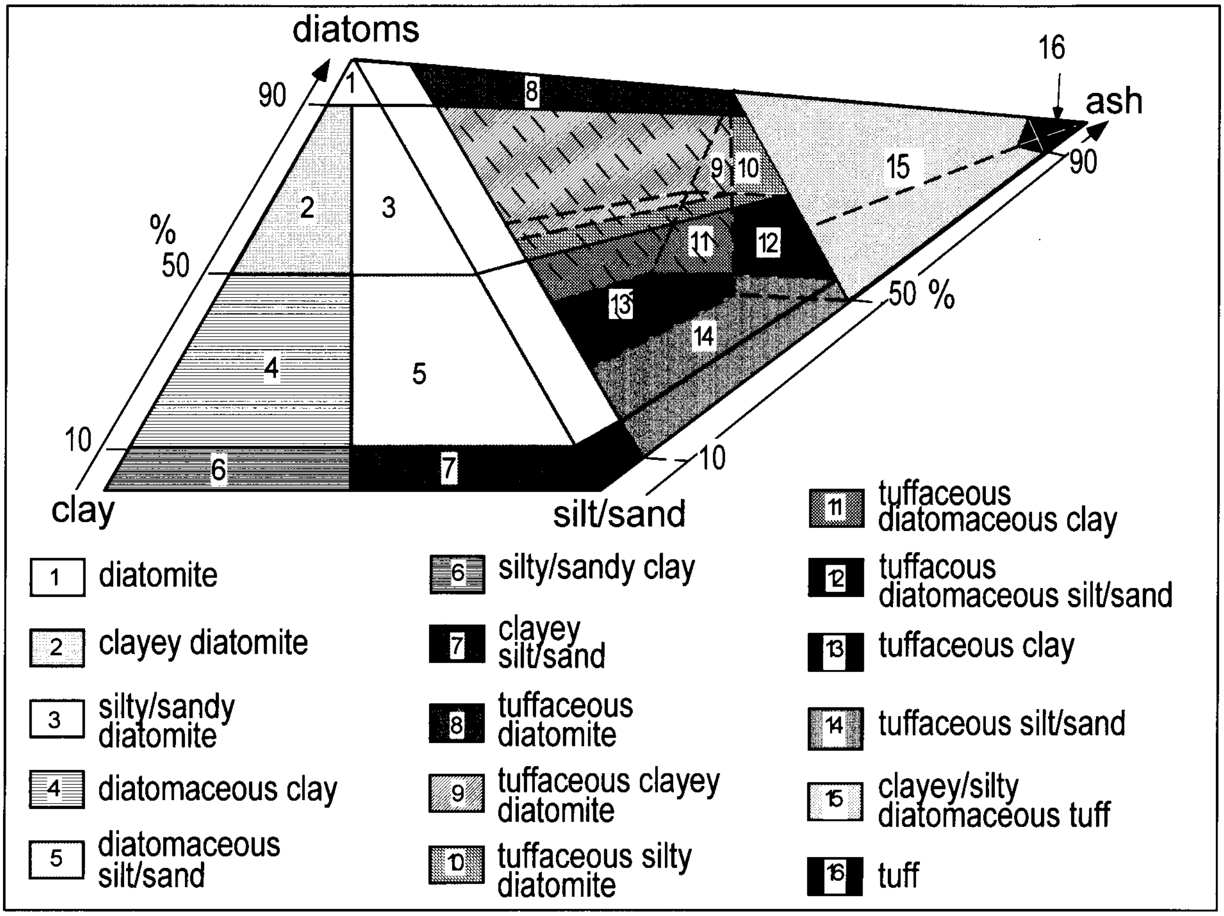

Figure 2. Classification of common diatomaceous sediments based on a four component system (see text for discussion).

diatoms are largely found in fine-grained sediments (Owen, 1981) and rarely occur with coarse sand or pebble deposits (except as fragments). Typically, they form part of four component systems, consisting of clay, fine-grained clastics (silt, fine- and, less commonly, medium-grained sand), ash and diatoms. Diatoms are generally not common in sediments with evaporite minerals, such as trona, gaylussite and natron. This is partly due to dissolution after burial, but also reflects their scarcity in lakes with alkalinities >150 meq l^{-1} (Holdship, 1976). Occasionally, diatoms are associated with carbonate-rich deposits (Gasse, 1975). In contrast, they are often present in volcanic basins, where ash forms a significant portion of the total sediment load and may contribute dissolved silica, which is needed for diatom growth.

The Ko Kha Formation includes several, largely fine-grained, sediment facies: diatomite and winnowed diatomite, clayey diatomite, diatomaceous clay and silt, and 'rambutan'-bearing clay. In general, the formation is dominated by both whole and fragmentary diatoms (see Figure 3), rare sponge spicules, and clay. Volcanic ash occurs sporadically in lenses, with bentonite occurring in a few outcrops, particularly towards the margins of the Lampang Basin. Massive bedding is common, although lamination is locally prominent (see Figure 3B). Scattered clay- and iron-stained root structures, suggestive of shallow water deposition, occur at a number of intervals.

In the Ko Kha Formation, SiO_2 (75–80%) is composed of diatoms, with dissolution of frustules restricted to only a few, localised, horizons. Fragmentation is common, with some deposits showing extensive breakage and others, in contrast, containing long, well preserved, *Aulacoseira* chains. The amount of Al_2O_3 (10–12%) appears to reflect clay content, which Kumanchan & Traiyan (1986) report includes smectite, kaolinite and illite. In general, clay content tends to be greatest in the upper part of the studied sequences. Fe_2O_3 is widespread, but generally accounts for <5% of the sediment (Inglethorpe et al., 1997).

Iron precipitation

Sediment staining with iron oxides is a prominent and common feature of the Ko Kha Formation, occurring in well-defined horizons, generally conformable with bedding (see Figure 3B). Inglethorpe et al. (1997) discuss its occurrence and origins, noting that it may have developed during lacustrine deposition, but preferring an explanation related to solution and redeposition, with the overlying laterites providing the major source of iron. The latter possibility is supported by the occurrence of red staining along joints and immediately above impermeable clay-rich horizons.

Iron is also present in a distinctive 'rambutan'-bearing clay (see Figure 4A) that is conformable with bedding in all outcrops. It may represent a local marker horizon in the southern Ban Pa Muang area (as shown in Figure 5). This horizon consists of red to yellow-olive green, sub-spherical nodules (rambutan nodules), up to 2 cm in diameter, in a dark grey or red-stained clay matrix. E.D.S. spectra shows that iron is abundant in the rambutan nodules and also indicates the presence of less common silica and minor alumina, which may suggest the presence of nontronite, or perhaps a mixture of two very fine phases. Calcium was present in small amounts in one analysis.

The nodules often posses a distinct, sub-spherical or highly irregular, red-coloured nucleus, which S.E.M. study shows to be either amorphous or to be composed of a honeycomb texture (see Figure 4E). In hand specimen, the outer cortex consists of red, and yellow-olive green, radial structures. Optical microscopy shows that the inner part of the cortex consists of many silica bundles that grow competitively outwards (as

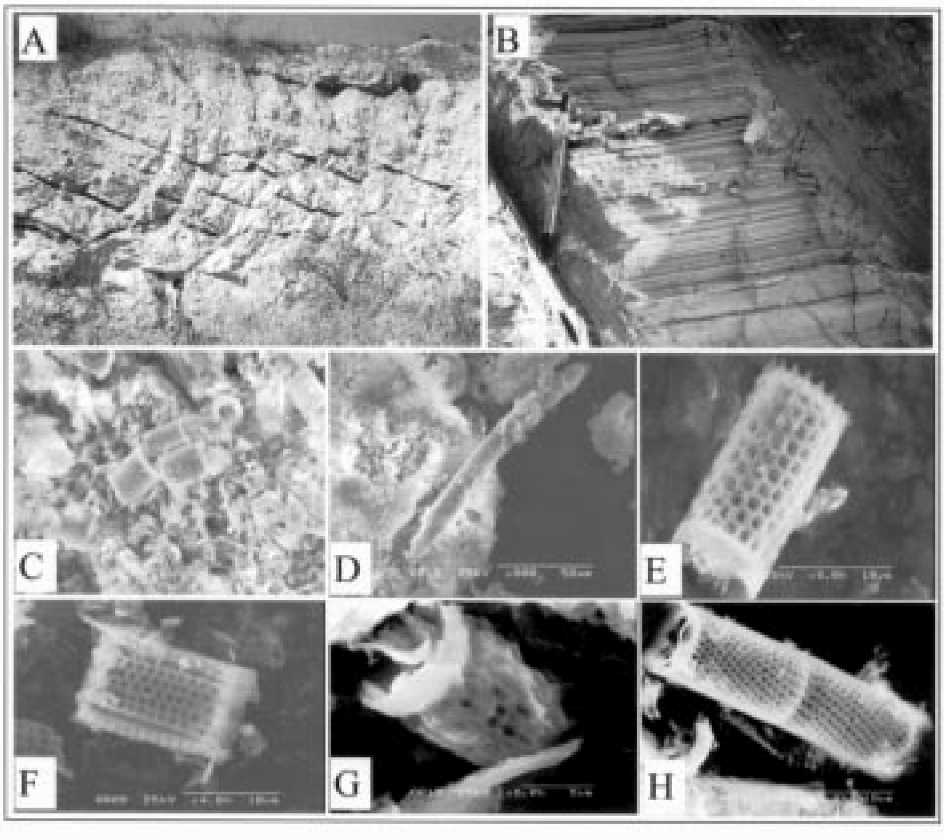

Figure 3. Major lithological and biological features of the Ko Kha Formation. (A) Massive diatomites showing normal faulting and gentle uniclinal dip. The dark layers are clay beds; (B) laminated diatomite showing thin iron-stained (dark grey) horizons; (C) diatomite showing both well preserved and broken *Aulacoseira*; (D) sponge spicule; (E) well preserved *A. granulata* var. *valida*; (F) well preserved *A. granulata*; (G) *A. goetzeana* (?) showing effects of dissolution; (H) *A. ambigua*.

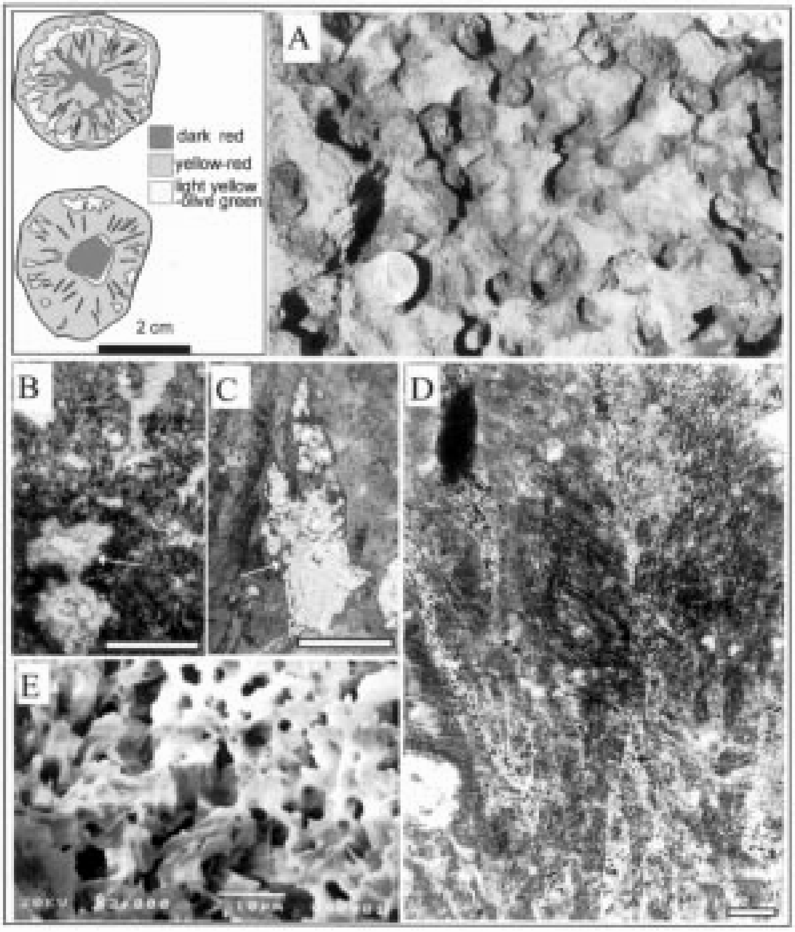

Figure 4. Morphology of the 'rambutan' nodules. The sketches show an inner dark red, sub-spherical to irregular, nucleus, surrounded by a cortex of radial, yellow-red and yellow-olive green, bundles. Towards the outer margins, a concentric colour banding is occasionally developed. (A) field appearance of a rambutan bed; (B–D) show optical microscope views of rambutan nodules with 0.5 mm scale bars; (B) irregular dissolution void (arrow) with authigenic quartz crystals; (C) finely laminated quartz lining a dissolution cavity (arrow); (D) Cross section of rambutan nodule (outer part at top) showing distinct growth lines forming 'feather-like' structures. Small dark acicular crystals are haematite, which tends to be concentrated along the median line of feathers; (E) S.E.M. image of honeycomb structure in the nucleus.

shown in Figure 4D). Better-developed bundles widen symmetrically from the centre, taking over available space. This results in a 'feather-like' pattern accen– tuated by the presence of growth lines in the outer cortex, which may suggest rapid crystallisation. Very small, dark acicular crystals of hematite(?) are common, often forming the median line of feathers, as well as thick spikes at the outer tip. The distribution of these acicular crystals appears to be controlled by the available space between the competitively growing minerals. Along the edge of the rambutan nodules, a number of dissolution voids are frequently present. These are usually lined with authigenic quartz, either as coarse crystals or as fine layers (see Figure 4B-C).

The rambutan nodules are of uncertain origin. The iron was probably transported in a reduced state in ground-water and precipitated rapidly as oxides. This might have occurred at the time of lacustrine deposition, or was perhaps related to aqueous iron transport after burial. E.D.S. data, although not definitive, tends to suggest that an Fe-clay may be present, which might suggest that the clay incorporated reduced iron during nodule growth.

Stratigraphy

Sixteen lithological logs are shown in Figure 5. These are grouped by location (see Figure 1) into: the southern

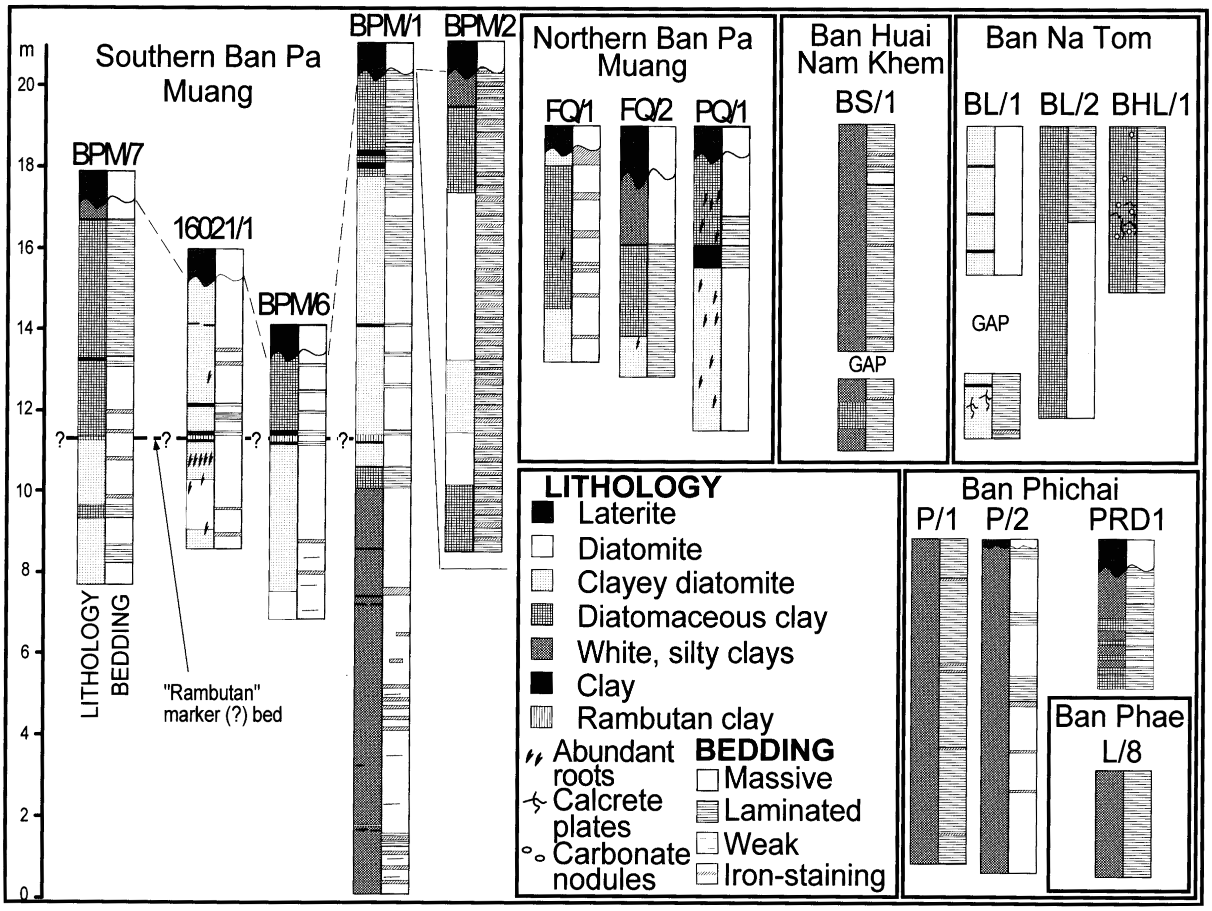

Figure 5. Lithological field logs for sixteen sections in the Ko Kha Formation. See Figure 1 for locations. The 'rambutan' marker bed is only one possible correlation line. See text for discussion.

and northern Ban Pa Muang outcrops, the Ban Na Tom, Ban Phichai, Ban Huai Nam Khem and Ban Phae outcrops. The stratigraphy of these five major areas is briefly outlined below.

The Ban Pa Muang Outcrops

The Ban Pa Muang outcrops are the most extensive in the Lampang Basin (see Figure 1) and have been divided into two parts. The southern exposures (as shown in Figure 5) contain a distinctive rambutan-bearing clay that is used in Figure 5 as a tentative marker bed (see discussion section). However, other than this horizon, lithological correlation is poor. The longest sediment succession available for study is a composite sequence composed of sections BPM/1 and BPM/2, which are separated by a short distance with no exposure. The local dip suggests that BPM/1 underlies BPM/2 by a few metres.

Section BPM/1 (as shown in Figure 5) consists of 10 m of white silty clay (lacking any diatoms) that passes upwards into diatomaceous clay and clayey diatomite. The sediments are mainly massive, but contain occasional lamination that tends to increase towards the top of the sequence. The diatomaceous clay in the upper 2.5 m of BPM/1 is unconformably overlain by a massive pisolitic laterite. Section BPM/2 consists of similar, but more diatomaceous, and highly laminated sediments (see Figure 5).

Diatoms first appear in this composite sequence at about 10 m, except for one horizon at 1.5 m (see Figure 6). *Aulacoseira granulata* (Ehr.) Simonsen dominates below the rambutan horizon, with *A. granulata* var. *valida* (Hust.) Simonsen dominating immediately above. At about 14 m these coarsely ornamented taxa give way to more delicate species that include: *A. ambigua* (Grun.) Simonsen, *A. italica*

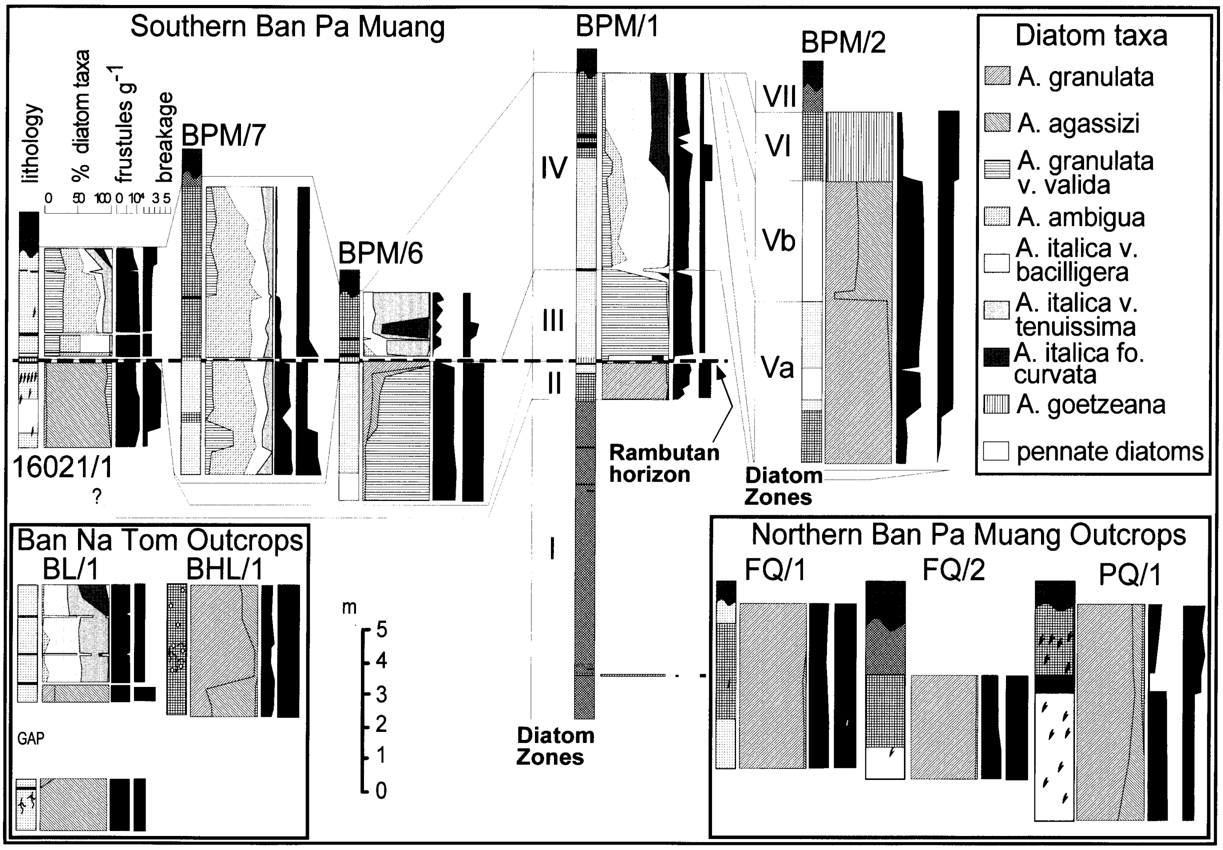

Figure 6. Diatom composition, abundance and breakage data for 10 sections in the Ko Kha Formation. Breakage is a subjective assessment, with scale as follows: 1 – breakage minor; 3 – breakage common; 5 – breakage abundant. Key to lithology given in Figure 5. See Figure 1 for locations. BPM/2 lies a short distance from BPM/1. Local dip relationships suggest that it overlies BPM/1 by a few meters. See text for discussion of the diatom zones.

var. *tenuissima* (Grun.) Simonsen, and *A. italica* var. *bacilligera* (Grun.) Simonsen. In contrast, all of section BPM/2, which is interpreted as overlying BPM/1, is dominated by robust taxa such as *A. granulata, A. agassizi* (Ost.) Simonsen, and *A. goetzeana* (O. Müller) Simonsen.

The remaining sections (BPM/6, BPM/7 and 16021/1; Figure 6) in the southern Ban Pa Muang area are difficult to correlate lithologically, though they all contain the rambutan bed. *A. granulata* var. *valida* and *A. agassizi* give way to varieties of *A. italica* and *A. ambigua*, except at BPM/7 where the latter flora dominates throughout.

The northern Ban Pa Muang outcrops (sections FQ/1, FQ/2 and PQ/1; see Figures 5 and 6) lack the distinctive rambutan clay. Clayey diatomite at the base of all three sections passes upwards into diatomaceous clay and silty clay. Diatoms are dominated by *A. granulata* and *A. agassizi* throughout. All of the sequences are capped by Pleistocene laterite.

The Ban Na Tom outcrops

Three sections (BL/1, BL/2 and BHL/1) from the Ban Na Tom outcrops are shown in Figure 5. Correlation is very uncertain. The sections are variously dominated by diatomaceous clay and clayey diatomite. Calcrete plates and concretions occur in BHL/1 and in the lower part of BL/1. These resemble calcrete reported from Pleistocene diatomite in the Olorgesailie Formation of southern Kenya (Owen & Renaut, 1981), where it was attributed to periodic drying of a shallow lake.

Two sections were sampled for diatoms (see Figure 6). The lower part of BL/1 was dominated by *A. agassizi*, which gives way to *Aulacoseira italica* fo. *curvata* (Ehr.) Simonsen, *A. italica* var. *bacilligera, A.*

italica var. *tenuissima*, with *Staurosira construens* (Ehr.) Williams & Round occurring at the top. *A. granulata* var. *valida* is common in two clay horizons at 4.3 m and 6.6 m. The flora in BHL/1 is very different, with *A. granulata* and *A. agassizi* dominating throughout the section.

The Ban Phichai, Ban Huai Nam Khem and Ban Phae outcrops

The Ban Phichai, Ban Huai Nam Khem and Ban Phae outcrops occur in different parts of the Lampang Basin (Figure 1), but all contain similar diatom-poor sediments.

Three sections were measured in the Ban Phichai area (P/1, P/2 and PRD1; Figure 5). At the northernmost outcrops, bedding dips to the south or south-east, whereas southern exposures dip to the north. One section (BS/1, Figure 5) was examined at Ban Huai Nam Khem (see inset B, Figure 1 for location). There, dips form part of an arc (open to the north), with north-easterly trends at BS/1, northerly values about 1 km south of BS/1, and westerly dips about 1.5 km to the east of BS/1. At section BS/1, irregular wavy beds are present that may reflect contemporary slumping. Only one section was studied, at a small restricted outcrop, at Ban Phae (L8, Figure 5).

All of the sections noted above are dominated by well-laminated, white, silty clay. Diatoms are rare (usually broken) or absent, with *A. granulata* dominating. Diatomaceous clay occurs in a 40 cm interval near the base of BS/1, and at several levels in the lower half of PRD/1 (Figure 5). However, even in these units diatoms are not common and consist entirely of broken *A. granulata*.

The diatom floras

Correspondence analysis (CA), using axes 1 and 2 (45% of varience) and 3 and 4 (31%), suggests that five main diatom floras are present (Figure 7). These represent a variety of lake conditions ranging from fresh to moderately alkaline, and varying from shallow to relatively deep. The five diatom assemblages are dominated by: *Aulacoseira granulata*; *A. agassizi*; *A. goetzeana; A. granulata* var. *valida;* and *A. ambigua* plus *A. italica* var. *tenuissima* and var. *bacilligera*. Species diversity is very low with only 17 taxa being recorded. Other microfossils are absent, except for occasional sponge spicules.

1. *The* A. granulata *assemblage*

This assemblage is heavily dominated by *A. granulata*, which forms a monospecific flora in several samples. The only other diatoms occurring are occasional *A. granulata* var. *valida* (0–6%) and absent to common *A. agassizi*, which dominates in assemblage '2'. The CA presented in graph 'B' (Figure 7) distinguishes these diatom floras along axis 3. Samples 7, 9-11, 22 (section BHL/1) and 59 (section BPM/2) appear to contain mixtures of these two assemblages. Benthic diatoms have not been observed.

A. granulata and its varieties are usually well developed in tropical freshwater lakes (Richardson, 1968, 1969; Kilham & Kilham, 1975). Gasse (1986) provides detailed ecological data for this species and its varieties based on studies of African lakes. She notes that *A. granulata* is a freshwater, planktonic species favoured by a conductivity range of 47–1300 μScm^{-1}, with a medium pH range (6.5–9), a low to medium alkalinity (0.4–9 meq l^{-1}), and silica content of >10 mg l^{-1}.

A. granulata is a heavily silicified diatom that probably requires turbulent conditions to remain in the plankton (Kilham & Kilham, 1975), or relatively shallow water bodies. The lack of benthic species in the assemblages dominated by this diatom argues against shallow water, whereas a turbulent (wind-induced?) palaeoenvironment would be supported by the high degree of diatom breakage that often occurs. In many outcrops where *A. granulata* dominates well-preserved fine laminae are also common, which perhaps implies relatively low energy conditions on the lake floor and no bioturbation. We suggest that palaeolakes typified by this assemblage, and by lamination, may have been relatively deep and perhaps stratified, with wind-stirred surface layers and calm bottom waters. Such palaeolakes could also have been subject to transport of diatoms by bottom water currents (during which breakage may have occurred). A possible recent analogy may occur in southern Lake Malawi, Africa, where wind induced cooling of surface water causes sinking and the development of strong bottom currents that redistribute both sediments and diatoms (Owen & Crossley, 1992).

2. *The* A. agassizi *assemblage*

A. agassizi dominates, commonly forming >90% of the flora. *A. granulata* forms 0–8% and *A. granulata* var. *valida* comprises 0–6% of the assemblage. As noted above, there are samples with transitional floras be-

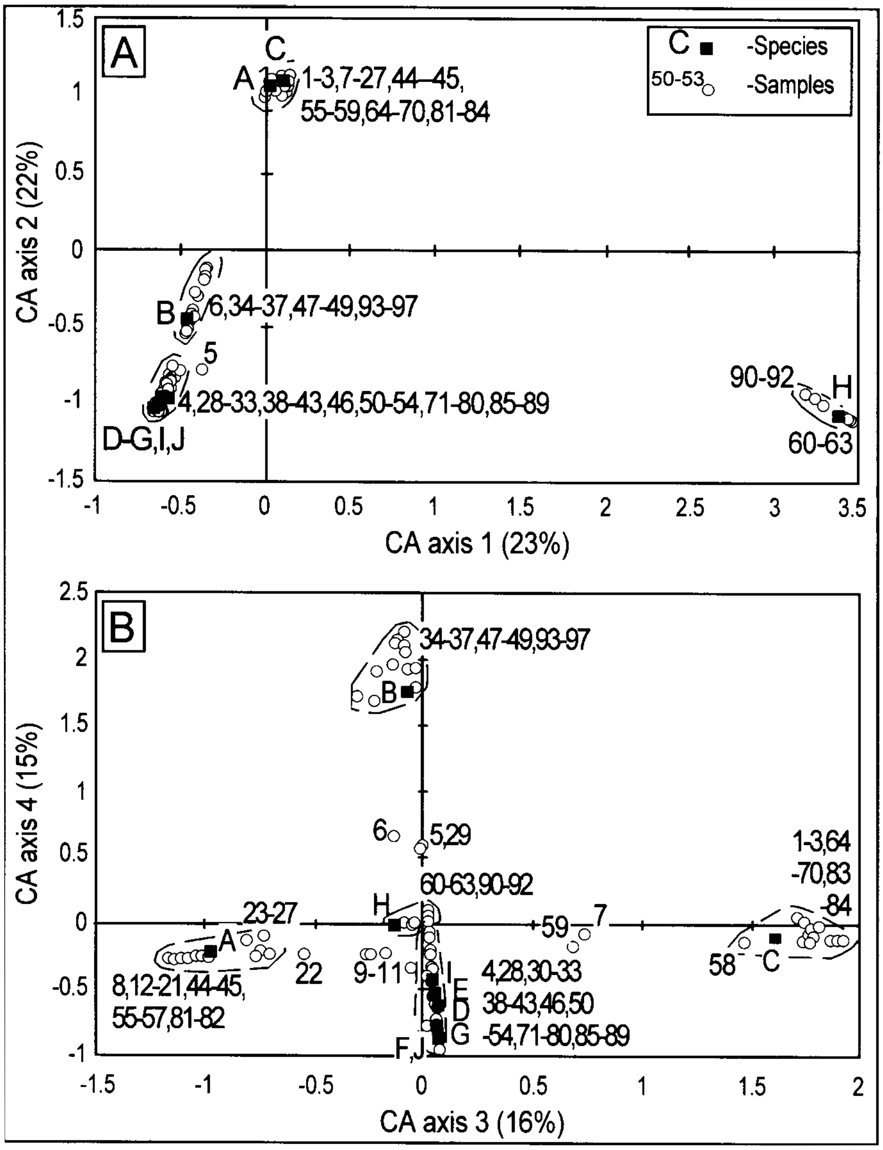

Figure 7. Correspondence analysis of the diatoms and samples from the Ko Kha Formation. (A) *A. granulata*; (B) *A. granulata* var. *valida*; (C) *A. agassizi*; (D) *A. ambigua*; (E) *A. italica* var. *bacilligera*; (F) *A. italica* var. *tenuissima*; (G) *A. italica* fo. *curvata*; (H) *A. goetzeana*; (I) *S. construens*; (J) *P. brevistriata*. Numbers represent samples. Inspection of the figures show five diatom assemblages are present. See text for discussion.

tween assemblages '1' and '2'. The only other taxa present were very rare *Navicula* and *Cymbella*.

Gasse (1986) notes that *A. agassizi* is planktonic and mainly found in broad shallow lakes. Chemical preferences are for low conductivity (<200 µScm^{-1}), low alkalinity (<2.9 meq l^{-1}), and medium pH (7–8). Horizons rich in this flora therefore suggest fresh water conditions. This assemblage tends to occur in sediments that also contain root structures and/or calcrete (e.g. sections 16021/1 & BL/1, see Figure 6). Both the diatom and sediment data suggest shallow water conditions, which may represent either the margins of a larger, deeper, lake, or perhaps part of a shallow water body.

3. *The* A. goetzeana *assemblage*

A. goetzeana forms 92–100% of the flora. Other diatoms present include *A. agassizi*, *A. granulata,* and very rare

A. distans. No other taxa were observed. *A. goetzeana* is a freshwater planktonic diatom favoured by medium to low alkalinities of <10 meq l^{-1} (Richardson et al., 1978). Gasse (1986) notes that it occurs in two African lakes with alkalinities of 0.7–1.4 meq l^{-1}. It is only dominant at the top of section BPM/2, where it occurs in low abundance in diatomaceous clay. Breakage is very common and the water body in which it was laid down was probably similar to that noted for assemblage '1' above, but perhaps representing slightly more dilute conditions.

4. *The* A. granulata *var.* valida *assemblage*

A. granulata var. *valida* comprises 79–97% of the assemblage. Other common diatoms include: *A. granulata* (0–18%), *A. agassizi* (0–5%), and *A. italica. var. bacilligera* (0–5%). Very rare *Navicula*, *Cymbella* and *Gomphonema* are present in a few samples.

A. granulata var. *valida* tends to occur in moderately alkaline lakes where dissolved sodium is abundant (Gasse, op. cit.). Typical chemical parameters reported for this variety are: conductivity >1900 µScm^{-1}, pH >8.5, alkalinity >14.6 meq l^{-1}, and silica >54 mg l^{-1}. Horizons dominated by this taxon tend to also contain abundant broken diatoms, and are dominated by massive clayey diatomite and diatomaceous clay. Transitional floras grading into assemblage '5' also occur.

The *A. granulata* var. *valida* assemblage suggests moderately alkaline water (Gasse, op. cit.). Lake depth must have been deep enough to favour a planktonic population, but not sufficiently shallow to allow a benthic flora to develop. The lack of lamination perhaps reflects water mixing and turbulence down to the lake floor and/or bioturbation.

5. *The* A. italica *var*. bacilligera, A. italica *var*. tenuissima, A. ambigua *assemblage*

This assemblage is more complicated than those noted above. *A. italica* var. *bacilligera* (15–92%), *A. italica* var. *tenuissima* (0–80%), and *A. ambigua* (0–72%) dominate to varying degrees, but generally occur in similar proportions. They form a distinct grouping in the CA (Figure 7), together with *A. italica* fo. *curvata* (0–70%, but generally 0–15%), *Staurosira construens* (0–18%) and *Pseudostaurosira brevistriata* (Grun.) Williams & Round (0–18%). Where present, the latter three taxa tend to occur towards the top of successions dominated by this assemblage. Rare *Navicula*, *Gomphonema*, *Nitzschia* and *Cymbella* are also present, but together account for < 1% of the flora in all samples.

Andrews (1971) notes that *A. italica* and its varieties are often littoral diatoms in small water bodies, but that they may occur in the plankton of larger lakes. Hustedt (1957) reports the species as being oligohalobous and alkaliphilous. Gasse (op. cit.), who examined 98 African water bodies, found *A. italica* var. *bacilligera* dominating only in Lake Tana, where conductivity values (137–240 µScm^{-1}) and carbonate alkalinity (1.5–1.9 meq l^{-1}) were very low, and pH (7.5–8.4) was medium. *A. ambigua* is planktonic, but favoured by shallow water (Gasse, op. cit.). Richardson et al. (1978) suggest it indicates low alkalinity (<5 meq l^{-1}).

Staurosira construens is the only common pennate taxon. This diatom is usually associated with shallow lakes and swamps. Although it occurs under a wide range of conditions, it is mostly found in fresh waters, with medium pH and alkalinity (Haworth, 1976; Gasse, op. cit.). *Pseudostaurosira brevistriata* tolerates a wide range of conditions, but is common only in circum-neutral, slightly alkaline lakes (Gasse, op. cit.). *Gomphonema* and *Cymbella* are usually epiphytic and suggest the presence of aquatic macrophytes.

The ecological data suggests that assemblage '5' may have developed in a shallow, fresh water, environment. The occurrence of pennate diatoms supports this inference, and the tendency for pennate floras to be more common towards the top of the successions suggests a shallowing trend.

Discussion

Stratigraphic relationships

Establishing stratigraphic relationships within the Ko Kha Formation, even on local scales, is often problematic. In many localities there are few lithological clues that can be used in relating sections that lie within only a few hundred meters of each other. However, a local lithological correlation, based on a distinctive 'rambutan'-bearing clay, can be suggested for the southern Ban Pa Muang area (Figure 1). The rambutan nodules (described earlier) are probably secondary in origin, having formed soon after deposition of the clay, or perhaps resulting from later diagenetic alteration. However, at all sections: the clay is conformable with bedding; only one rambutan-bearing clay occurs at any single location; and a distinctive set of three equally spaced thin clay layers (not shown in figures due to scale difficulties) are present above the rambutan bed.

This is unlikely to be a coincidence and suggests that the nodules are confined to one primary depositional unit. Figure 5 shows the location of this tentative marker horizon, which is confined to sections BPM/1, BPM/6, BPM/7 and 16021/1. It is estimated to extend over an area of about 30 km^2.

An alternative correlation scheme based on diatom data, for the same sections, is given in Figure 6. Diatom Zone I lacks any diatoms except at a single horizon near the base of the section. Zone II includes two diatom assemblages, with *A. granulata* occurring to the south-east (BPM/1) and *A. agassizi* to the north-west (16021/1). Zone III is dominated by the *A. granulata* var. *valida* assemblage and is confined to sections BPM/1 and BPM/6, though it might occur at depth below BPM/7. Zone IV is widespread and comprises assemblage 5, which includes *A. ambigua*, *A. italica* var. *tenuissima* and *A. italica* var. *bacilligera*. Zone V occurs in BPM/2 (a short distance from BPM/1, but with part of the intervening sequence not visible). This zone commences with *A. granulata* (Va), with *A. agassizi* becoming dominant in Zone Vb. Zone VI consists of the *A. goetzeana* assemblage. Zone VII is devoid of diatoms.

The reliability of the rambutan bed as a marker horizon remains uncertain at the present time. However, if it does represent a time line, then the diatom zones may be diachronous. Indeed, there is a tendency for the rambutan bed to be present in successively higher diatom zones in a north-westward direction, with it occurring in the basal part of diatom Zone III in BPM/1, the upper part of Zone III in BPM/6, and in the middle part of Zone IV in BPM/7. It occurs at the junction of Zones II and IV in 16021/1 (further to the north-west), where Zone III and part of Zone IV are missing, perhaps due to non-deposition and/or erosion.

Palaeogeography

Previous studies (e.g. Sripongpan, 1985) have assumed that all of the Ko Kha Formation sediments were laid down in a single large palaeolake, with the deposits since being modified by mild crustal movements and eroded by recent river systems. However, the Ko Kha Formation includes a wide variety of diatomaceous and fine-grained clastic sediments with considerable variability between sections that may reflect deposition in a series of isolated palaeolakes.

For example, bedding directions at the Ban Phichai outcrops (northern Lampang Basin) dip towards a local 'basin centre'. A similar situation also occurs at the nearby Ban Huai Nam Khem area. Although there have been mild post depositional earth movements, these patterns tend to suggest that deposition occurred in two relatively small neighbouring palaeolakes (or within two distinct sub-basins of a single palaeolake) along the same graben structure. Primary depositional dips appear to be evident at a quarry face (400 m long), 1.5 km east of Ban Huai Nam Khem. There, the sediments dip at 30–35° at the eastern end of the exposure and are near-horizontal to the west, without any faulting of the intervening strata. At the same locality, the deposits also tend to thicken westwards. These local variations suggest deposition in a small lake basin rather than sediment accumulation on the edge of a very large single palaeolake. The rapid westward increase in bed thickness might reflect the local depositional regime, or perhaps differential local subsidence. Contemporary earth movements are more clearly indicated by the occurrence of soft sediment deformation at the site of section BS/1 (Ban Huai Nam Khem).

Sediments from the Ban Phichai and Ban Huai Nam Khem areas (and also at Ban Phae) (Figure 1) contain only rare broken diatoms or none at all, whereas well preserved floras are found only in the Ban Pa Muang and Ban Na Tom regions. This may also reflect deposition in separate water bodies.

A tentative reconstruction of the relationships between the diatom zones, and possible palaeoenvironments, for the Ban Pa Muang outcrops is given in Figure 8A. This model lacks accurate height control, but the relative sediment thicknesses and diatom floral data would suggest that a basin centre lay close to the BPM/1-BPM/2 composite section, in the south-east of the Ban Pa Muang area. A further complication is that the diatom zones may be diachronous, if the rambutan bed noted earlier should prove to be a valid time marker horizon.

In general, lacustrine sedimentation, at Ban Pa Muang, began with the deposition of non-diatomaceous sediments of Zone 1. Zone 2 represents a fresh water 'Type 1' lake (Figure 8B), with *A. granulata* developing in the deeper south-eastern area, and *A. agassizi* growing in the shallower margins. Zone 3 is dominated by diatom assemblage '4' and is confined to the inferred basin centre. The flora suggests a moderately alkaline 'Type 2' lake (Figure 8B), perhaps with inefficient overflow caused by regression into the basin centre. Alternatively, the mildly elevated alkalinity might relate to variable groundwater and/or surface inflows (Renaut, 1990; Renaut et al., 1994), given that the Lampang Basin at the time of deposition contained a wide variety of lithologies. Zone IV

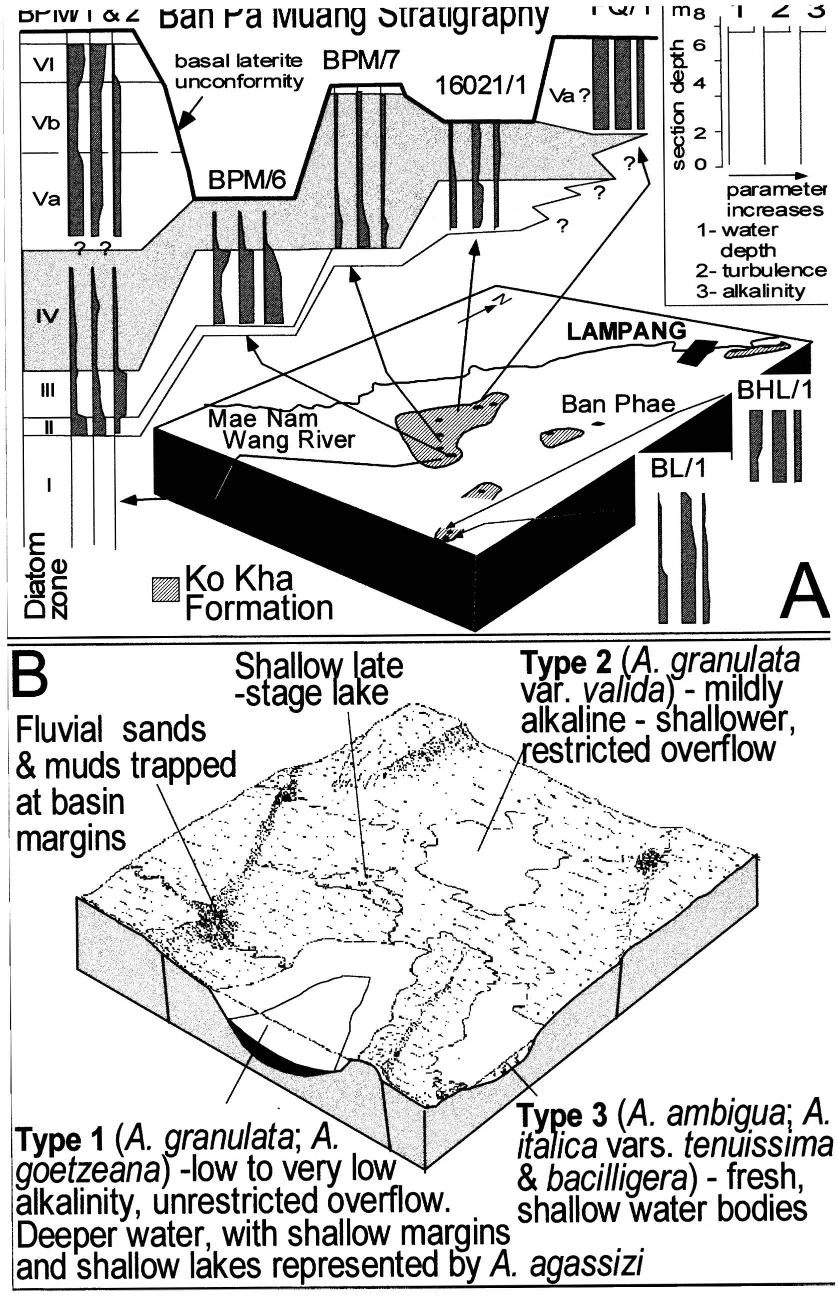

Figure 8. Inferred diatom stratigraphy and palaeoenvironments of the Ko Kha Formation. (A) suggested reconstruction of diatom zones for the Ban Pa Muang area, with graphs showing changes in relative water depth and alkalinity (based on diatom species), and turbulence (based on diatom species & breakage data). (B) simplified palaeogeographic model showing the coexistence of several palaeolakes of variable depth and alkalinity. Three ‘lake types’ are recognised. See text for discussion.

comprises diatom assemblage ‘5’, and suggests a shallow, freshwater ‘Type 3’ lake (Figure 8B). In contrast, Zones V and VI probably reflect lake deepening and the re-establishment of a ‘Type 1’ water body. The northern Ban Pa Muang outcrops (e.g. FQ/1, Figure 8A) may correlate with Zone Va, though given the difficulties in correlation, this remains somewhat conjectural.

Figure 8B shows a simplified model that may represent the general situation in the Lampang Basin during Pliocene times. The basin was broken into several active grabens by normal faults. The irregular topography that developed would have allowed small lakes to develop with individual depositional histories, and perhaps subsidence rates. The dominance of clays and biogenic materials indicates that coarse clastics were either not being generated or that such materials were trapped at the margins of the Lampang basin, perhaps due to a very low gradient that at least partially resulted from earlier basin infilling during deposition of the underlying fluvial and lacustrine sediments of the Mae Sot Formation. An overall increase in clay content toward the top of the Ko Kha Formation may imply an increased recharge from rivers, which would have introduced more fine-grained clastic material to all of the palaeolakes in the basin.

In general, the Pliocene palaeolakes of the Lampang Basin preserve a local record of diatomaceous sedimentation dominated by *Aulacoseira* taxa. The low species diversity may be typical of the region and time period. However, a more complete understanding of these floras must await studies of other late Tertiary lake basins in South East Asia.

Acknowledgements

This study was funded by a Faculty Research Grant (FRG/95-96/I-01) of the Hong Kong Baptist University. Field and logistic support was provided by the Economic Geology Division, Department of Mineral Resources in Thailand, which at the time was under the direction of Mr. Boonmai Inthuputi. We would like to thank Khun Preecha Nupairoj, our driver and field aide, for his excellent support. Thin sections of the rambutan nodules were prepared by Khun Pramuanpong Sindhusen of the Department of Land development in Bangkok.

References

Akutsu, J., 1974. On the fossil diatoms from Amphoe Mae Chaem, Changwat Lampang, Thailand. In Kobayashi T. & R. Toriyama (eds.), Contributions to the Geology and Palaeontology of Southeast Asia. The University of Tokyo Press, 14: 161–163.

Andrews, G. W., 1971. Early Miocene none-marine diatoms from the Pine Ridge area, Sioux County, Nebraska. U.S. Geol. Surv. Prof. Paper, 683-E, p. 15.

Brown, G. F., S. Buruvas, J. Charaljavanaphet, N. Jalichandra, W. D. Johnston, V. Srethaputra & G. C. Taylor, 1951. Geological reconnaissance of mineral deposits of Thailand. U.S. Geol. Surv. Bull. 984-I, p. 183.

Gardner, L. S., 1967. The Mae Moh lignite deposits in northwestern Thailand. Rept of Investigation No. 12, Dept. Miner. Res., Thailand, p. 72.

Gasse, F., 1975. L'évolution des Lacs de l'Afar Central (Ethiopie et T.F.A.I) du Plio-Pléistocène à l'actuel. D.Sc. thesis, Univ. of Paris, p. 403.

Gasse, F., 1986. East African diatoms. Taxonomy, ecological distribution. Biblio. Diatomol. 11, p. 201.

Gasse, F. & F. Tekaia, 1983. Transfer functions for estimating paleoecological conditions (pH) from East African diatoms. Hydrobiologia, 103: 85–90.

Greenacre, M. J., 1993. Correspondence analysis in practice. Academic Press, London, p. 195.

Harnjavanich, P., T. Chotikrai, S. Chotipanich & K. Suramana, 1995. Characteristics and mineralogy of diatomites, Lampang. Proceedings, Department of Mineral Resources Annual Technical Meeting, (in Thai), Jan. 1995, Bangkok: 459–473.

Haworth, E., 1976. Two late-glacial (Late Devensian) diatom assemblage profiles from northern Scotland. New Phytol., 77: 227–256.

Holdship, S. A., 1976. The paleolimnology of Lake Manyara, Tanzania: a diatom analysis of a 56 m core. Ph.D. thesis, Duke University, p. 220.

Hustedt, F., 1957. Die diatomeen flora des flusssyestems der Weser im gebiet der Hansestadt Bremen. Abh. Naturw. ver. Bremen. 34(3): 18–140.

Inglethorpe, S. D. J., C. Utha-aroon & C. Chanyavanich, 1997. An inventory of diatomite deposits of the Lampang Basin, northern Thailand. Proceedings of the International Conference on Stratigraphy and Evolution of Southeast Asia and the South Pacific, Aug. 1997, Bangkok: 669–685.

Kilham, S. S. & P. Kilham, 1975. Melosira granulata (Ehr.) Ralfs.: morphology and ecology of a cosmopolitan freshwater diatom. Verh. Intern. ver. Limnol. 19: 2716–2721.

Kumanchan, P., 1979. Bentonite (in Thai). Geol. Soc. Thailand Special Issue, Bangkok: 1–6.

Kumanchan, P. & A. Traiyan, 1983. Diatomite. Proceedings of the Conference on Geology and Mineral Resources of Thailand (Section B: Mineral resources), Department of Mineral Resources, Bangkok: 1–8.

Kumanchan, P. & A. Traiyan, 1986. Research on geologic environment, chemical compositions, physical properties and the uses of diatomite from the Lampang Basin, northern Thailand. Economic Geology Division Report, 2nd edition, Department Mineral Resources, Bangkok: p. 27.

Owen, R. B., 1981. Quaternary diatomaceous sediments and the geological evolution of Lakes Turkana, Baringo and Bogoria, Kenya Rift Valley. Ph.D. thesis. University of London. p. 465.

Owen, R. B. & R. Crossley, 1992. Spatial and temporal distribution of diatoms in sediments of Lake Malawi, Central Africa, and ecological implications. J. Paleolim. 7: 55–71.

Owen, R. B. & R. Renaut, 1981. Palaeoenvironments and sedimentology of the middle Pleistocene Olorgesailie Formation, southern Kenya Rift Valley. Palaeoecol. Afr. 13: 147–174.

Pariwatawon, P., 1962. Diatomite deposits in Changwat Lampang, (in Thai), Department Mineral Resources, Bangkok, p. 7.

Piyasin, S., 1972. Geology of the 1:250,000 Changwat Lampang sheet (in Thai) Rept. Invest. No. 14, DMR, Bangkok, p. 98.

Piyasin, S., 1978. Geological report of petroleum drillhole IL-3(15), Lampang Basin project, Division of Exploration and Production, Defence Energy Department, Ministry of Defence, Bangkok, p. 98.

Polachan, S. & N. Sattayarak, 1989. Strike-slip tectonics and the development of Tertiary basins in Thailand. In Thanasuthipitak T. & P. Ounchanum (eds.), Proceedings of the International Symposium on Intermontane Basins: Geology & Resources, Bangkok: 243–253.

Ratanasthien, B., 1992. Neogene events recorded in coal fields in northern Thailand. Proceedings of the Technical Conference on Development Geology for Thailand into the Year 2000, Chulalongkorn University, Bangkok: 462–476.

Reavie, E. D. & J. P. Smol, 1997. Diatom-based model to infer past littoral habitat characteristics in the St. Lawrence River. J. Great Lakes Res., 23(3): 339–348.

Renaut, R.W., 1990. Recent carbonate sedimentation and brine evolution in the saline lake basins of the Cariboo Plateau, British Columbia, Canada. Hydrobiologia, 197: 67–81.

Renaut, R. W., D. W. Stead & R. B. Owen, 1994. The saline lakes of the Fraser Plateau, British Columbia, Canada. In Gierlowskii-Kordesch E. & K. Kelts (eds), Global Geological Record of Lake Basins, Cambridge University press, Cambridge, 1: 419–423.

Richardson, J. L., 1968. Diatoms and lake typology in East and Central Africa. Intl. Rev. ges. Hydrobiol. 53: 299–338.

Richardson, J. L., 1969. Characteristic planktonic diatoms of the lakes of tropical Africa. Intl. Rev. ges. Hydrobiol. 54: 175–176.

Richardson, J. L., T. J. Harvey, & S. A. Holdship, 1978. Diatoms in the history of shallow East African lakes. Pol. Arch. Hydrobiol. 25: 341–353.

Sripongpan, P. 1985. Lithostratigraphy and depositional environment of diatomite deposits in the southeastern part of the Lampang Basin, Changwat Lampang, M.Sc. thesis. Dept. of Geology, Chulalongkorn University, Thailand, p. 114.