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Paleontology and magnetostratigraphy of the Eocene Krabi basin (Southern Thailand)

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Abstract: Excavations undertaken since several years in the Eocene sites of the Krabi basin (southern Thailand) has yielded six genera of reptiles and 31 different species of mammals, among which are several forms new to Southeast Asia. Nearly all vertebrate remains have been collected from lignite levels, and their study indicates a rather closed area submitted to a tropical climate. In addition to considerably increase our knowledge of the early Tertiary terrestrial vertebrate faunas of southern Asia, these Thai remains allow to propose an accurate age for this mammal fauna. They also can be related to known late Eocene and/or early Oligocene forms from Europe, North Africa, Asia, or even North America. The study of the evolutionary stages of the different taxa of the Krabi fauna, and comparisons with other well dated mammalian faunas from Eurasia and North Africa, led us to propose a late Eocene age for the mammal fauna (about ±37 to ±34 Ma).

A magnetostratigraphic study has been carried out on the late Eocene fluviatile/lacustrine Krabi deposit (southern Thailand). 87 samples in 43 different stratigraphic levels were collected from a thickness of 105 m of the section. These paleomagnetic samples were analysed, and they yielded a paleomagnetic direction. Rock magnetic experiments show that the NRM generally results from the presence of magnetite. The Krabi section that has been sampled displays only reverse polarity. The mean direction for reversed polarity samples was D = 192.34, I = -15.5 (N = 71, α_{95} = 4.7, k = 14). The correlation to the Geomagnetic Polarity Time Scale (GPTS) relies on the biostratigraphic data previously proposed for the fauna found in the same section. These correlations have been achieved by comparing variations in the sedimentary rate derived from the alternative correlation. The proposed correlation puts Krabi section in the chron C13r (34.1 Ma) or C15r (35.14 Ma). This suggests sedimentation rates of 9.4 and 26 cm/ky respectively, but the second sedimentation rate is too high for this type of sediments (lignite). Hence, the most probable correlation for the Krabi section is with chron C13r (33.54–34.65 Ma).

INTRODUCTION

The Krabi basin, in South Thailand (Fig. 1), is one of the richest and most diversified Paleogene fossiliferous localities in South Asia. Six genera of reptiles including snakes, crocodiles and turtles, and twenty eight species of mammals, among which are several new forms to Southeast Asia have been so far discovered in Krabi (Ducrocq *et al.*, 1992, 1993, 1995). The peculiar aspect of this Paleogene mammalian fauna allowed the description of several new taxa, whose importance at a phylogenetical and paleobiogeographical level can be considered as a reference for paleomammalogy. Also, these recent discoveries have led to a considerable increase of our knowledge of the early Tertiary vertebrate faunas of Southeast Asia.

The fossils have been recovered from three open pits (Wai Lek, Ban Pu Dam, Bang Mark) from which lignite is extracted before being burned by the EGAT (Electricity Generating Authority of Thailand) to produce electricity. Most of vertebrate remains come from the main lignite seam, which therefore represents a valuable landmark for the geology of the basin. It is worth noting that the small anthracotheriid artiodactyl *Siamotherium krabiense* has been found in the three pits, and no significant difference of size or morphology can be observed in the specimens from each and in nearby all levels of these pits or between the bottom and the top of each section (Ducrocq, 1992). In addition, the fossil mammals associated with *Siamotherium* remains are the same in the three pits. We therefore consider them as contemporaneous (Ducrocq, 1992).

Despite a number of geological and palynological studies, no reliable age was available for the continental deposits of Krabi basin, until fossil mammals were found there. Age estimates varied from Paleocene to Pliocene (Chaodumrong *et al.*, 1983). According to recent sedimentological studies (Bristow, 1991), the sequence exposed in Krabi indicates lacustrine conditions. In addition, the study of the mammalian community suggests that the latter lived in a tropical, probably forested environment (Ducrocq *et al.*, 1995). In the absence of available radiometric ages, the mammalian fauna of Krabi was considered as Late Eocene in age on the basis of its mammalian association.

This Late Eocene age of Krabi has been recently challenged on the basis of new interpretations of the age of the Pondaung fauna in Burma and of some Chinese localities (Holroyd and Ciochon, 1994). Consequently, Krabi has been correlated with these late middle Eocene localities. However, several new fossil taxa have been since discovered and described in Krabi (Chaimanee *et al.*, 1997; Ducrocq, in press), and we will present here several further arguments that rather indicate a younger age for the Thai fauna relative to the Pondaung fauna. In the absence of radiometric data for Krabi we analysed the magnetostratigraphy of a 105 m thick section of Bang Mark Pit of the Krabi basin in order to precise the age of the fauna.

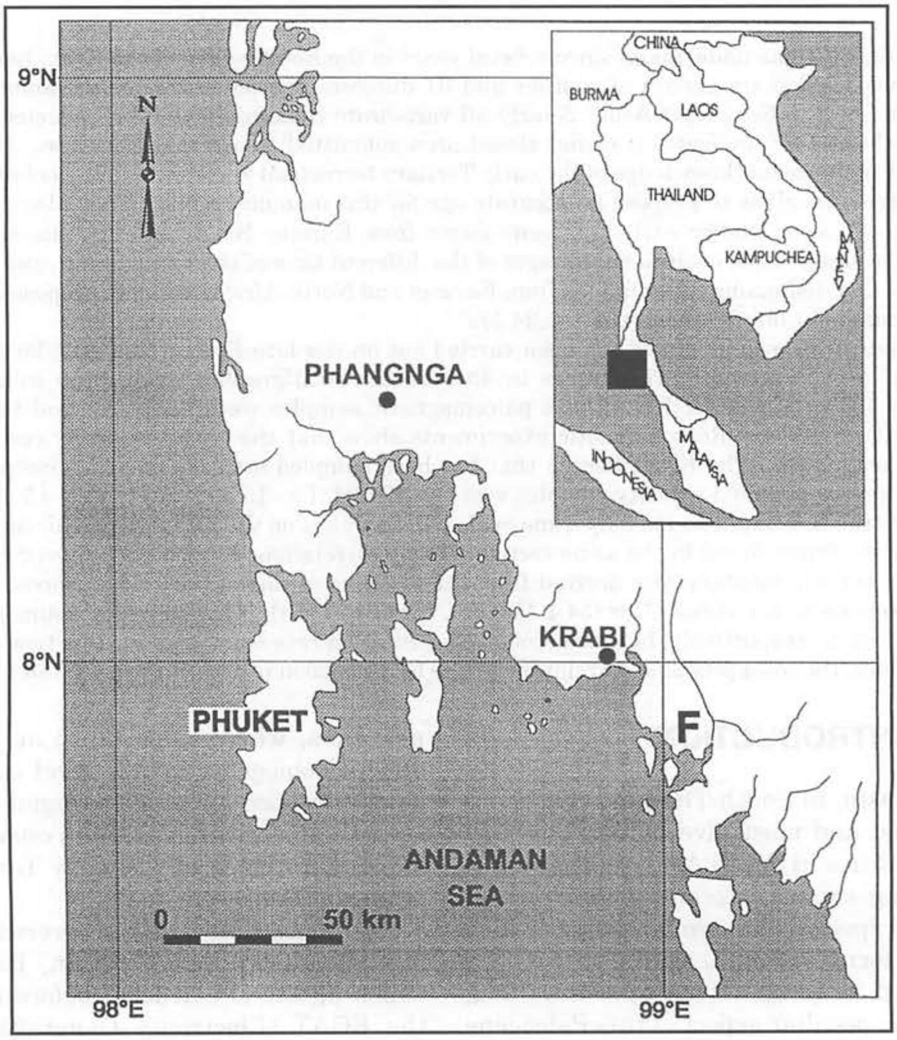

Figure 1. Location map showing the study area in the Peninsular Thailand. F: location of the sampling area in the Krabi basin.

GEOLOGICAL SETTING

The Tertiary formations

The Tertiary basins of Thailand are a prime area for prospecting the energy resources (lignite, gases natural, oil). More than 60 basins, either continental and marine, are distributed in various areas. The fossiliferous Tertiary basins are located in the peninsula (Paleogene) and in the northern part of the country (Neogene). Same basins have a considerable size, but the outcrops are generally small and are dispersed mainly because of the presence of a dense vegetation covering them.

The Krabi basin

The coal-bearing Krabi basin is situated in the Southern part of Thailand. It is bordered in North-West and South-East by major north-eastern to south-western faults (Bang Kram, Khlong Marui, Khlong Chon and Phang-Nga faults). The fluvio-lacustrine deposits are poorly exposed and usually covered by Quaternary sediments. The outcrops are generally limited in surface. However, opencast coal mines provide suitable outcrops of Tertiary sediments. A proposed provisional stratigraphy for the Krabi basin dividing the Krabi group into five formations (A, B, C, D and E) was used by Bristow (1991) in his study of the stratigraphy of Krabi.

In the Klong Wai Lek opencast coal mine, Bristow (1991) measured and described a 175 m of thick section. This sequence exposed in the Krabi basin is entirely fluvial, deltaic and lacustrine. Bristow recognized the following succession from bottom to top:

- Formation A (0–30 m): consists of red and yellow mottled siltstones with occasional carbonate concretions and cross-stratified coarse to very coarse grained channel sandstones.
- Formation B2 (30.5–56 m): Lignite and associated organic-rich siltstones.
- Formation B4 (56–97 m): Gray claystones, siltstones and fine to medium grained cross stratified and laminated sandstones in 10 m thick coarsening upwards cycles capped by granule to pebble grade conglomerates.
- Formation C1 (40–200 m): which is the youngest formation, is logged and contains lacustrine limestones including micritic carbonate mudstones, gastropod packstones and occasional gastropod grainstones in addition to the sandstones which occur in formation B.

In the Bang Mark coal pit, we sampled a 105 m thick section which is the maximum thickness of the outcrop (Fig. 2A). These beds we sampled are the equivalent of the formations described above by Bristow (1991).

BIOSTRATIGRAPHY

Two orders of mammals will be mainly used here in order to discuss the age of the Krabi fauna, because of their common occurrence in Eurasian localities, or because of their importance on a systematical and phylogenetical level. The Anthracotheriidae, a group of ungulates that offers a great potential for broader faunal correlations (Rasmussen *et al.*, 1992), are abundant and diversified in the Krabi Basin, as in the Pondaung locality. Particularly, the genus *Anthracotherium* is known in both Burmese and Thai localities (Ducrocq, in press). However, *Anthracotherium* from Krabi is larger and displays more derived dental features than the species from Pondaung. Conversely, dental remains of large anthracotheres described from the Gongkang Formation in South China, and dated as late Eocene to early Oligocene (Tang, 1978), are almost identical with those of the Thai anthracothere, with the exception of the larger size of the Chinese species. These observations tend to suggest that the age of Krabi is intermediate between that of Pondaung and the Chinese site, thus between late middle Eocene and early Oligocene.

A similar case can be seen in eastern Europe, more precisely in Romania, where the early Oligocene Dîncu Beds have yielded an isolated upper molar of *Anthracotherium* (Radulescu and Samson, 1989) that displays a structure identical with that of the upper molars of the Thai *Anthracotherium*. Meanwhile, the European form is distinctly larger than the Asian one, and suggests that *Anthracotherium* from Thailand is probably older.

Also, *Anthracotherium monsvialense* from the basal Oligocene of northern Italy (Dal Piaz, 1932) very closely resembles *Anthracotherium chaimanei* from Krabi in its dental morphology and size. However the Italian species exhibits some differences of structure on its upper and lower premolars that warrants the separation of both forms and makes the Italian species somewhat more derived than the Asian one (Ducrocq, 1992). An age close to the early Oligocene can therefore be considered for the Thai locality.

Other anthracotheres genera found in Krabi also suggest an age younger than late middle Eocene. That is for example the case of *Bothriogenys*, a genus also known in the Late Eocene to early Oligocene Jebel Qatrani Formation in the Fayum (Rasmussen *et al.*, 1992). A recent revision

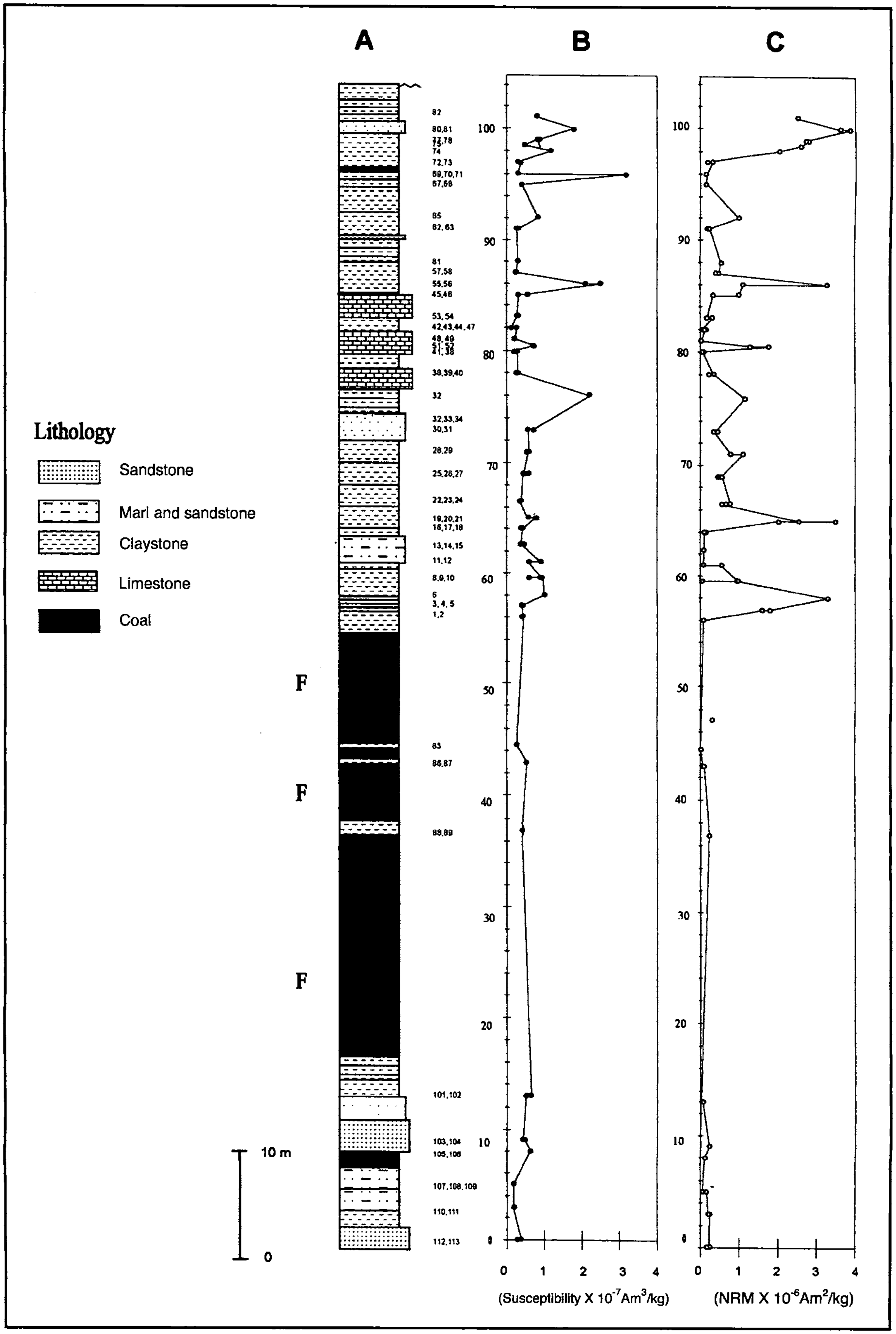

Figure 2. A: Lithology and stratigraphic position of sampling sites of the Krabi section (number on the right of the column represent the number of the samples). NRM intensities (A) and susceptibility (B) plotted against biostratigraphic and lithostratigraphic information from the study section.

of the Fayum material housed in Stuttgart and London demonstrated that the African forms clearly display a somewhat more derived dental morphology than that of the Thai species, but nevertheless indicates close affinities between the African and the Thai material (Ducrocq, 1997). The late Eocene or early Oligocene age of the Jebel Qatrani Formation thus reflects a relatively similar age for the Krabi mammals.

Finally, *Atopotherium* is a peculiar anthracothere that has been recently described from Krabi (Ducrocq *et al.*, 1996). This genus is characterized by typical anthracotheriid lower premolars and strongly selenodont lower molars. This unusual tooth structure nevertheless reflects an advanced condition that can be observed for example in Oligocene artiodactyles like *Elomeryx* or *Brachyodus*, and therefore tends to refute a late middle Eocene age for Krabi and suggests a somewhat younger age.

Primates recently described in Krabi (Chaimanee *et al.*, 1997) also favour an age younger than late middle Eocene for the Thai fauna. *Siamopithecus eocaenus* is an anthropoid primate that seems to be closely related to *Pondaungia* from Burma and *Moeripithecus* from the Sultanate of Oman. However, the Thai anthropoid displays some dental features that suggest a somewhat more derived condition than that of the Burmese form (stronger bunodonty, loss of paraconid, loss of conules on upper molars, better developed hypoparacrista). On the other hand, comparisons with *Moeripithecus* reveals that the Omani and the Thai forms are morphologically close, although *Moeripithecus* is more advanced than the Thai species in its wider and more developed upper premolars, its upper P3/ lacking a connection between the protocone and the hypocone, its lower molars with shorter trigonid and more centrally situated hypoconulid, and in its M_3 with more reduced hypoconulid (Ducrocq, in press).

The late middle Eocene anthracotheres and primates from Pondaung and correlated Chinese localities therefore display more primitive conditions than those from Krabi. On the other hand, early Oligocene taxa from Europe, North Africa and China can be distinguished from those of Krabi by their somewhat more advanced condition. Also, the Thai fauna is characterized by the occurrence of mammals that are known otherwise only from late Eocene and Oligocene deposits. That is the case for example of a pteropodid megabat, a group that was so far first discovered from the early Oligocene of Europe (Ducrocq *et al.*, 1993), and of the carnivore *Nimravus* which first occurrence dates from the late Eocene or early Oligocene in Asia (Ducrocq, 1992).

PALEOMAGNETIC ANALYSIS

Sampling and laboratory procedures

Samples were collected with a water-cooled rock drill and oriented with a magnetic compass. Two to three cores were sampled in 43 different stratigraphic levels (86 samples) along a 105 m section (Fig. 2A). Two 2.2 cm specimens were cut from each core. Average spacing between level was 2 m, but varied between 0.3 m and 20 m, depending on the thickness of lignite beds and lithology.

Initially, a test of two weeks in terrestrial field is carried out on all samples. Thereafter, the samples were demagnetized gradually by thermal processing.

At least two specimens per sampling level was thermally demagnetized. The alternating field and thermal demagnetization was applied with a temperature increment of 20–50°C up to a maximum temperature of 500–550°C, in a magnetically shielded laboratory-built oven. The Natural Remanent Magnetization (NRM) of each sample was measured on a 2 axis CTF cryogenic magnetometer at the Paleomagnetic Laboratory of the University of Montpellier II. The initial magnetic susceptibility of each sample was measured with a Brington MS2 susceptibility bridge after each thermal demagnetisation step to record any mineralogical alteration during heating. Orthogonal vector plots and stereographic projections were used for analysis of remanence directions and polarities. Component directions were computed using least-squares analysis. Sites mean directions were determined with standard Fisher statistics.

NRM demagnetisation

The NRM and susceptibility of the studied fluvio-lacustrine sediments average 1.1 x 10^{-7}Am^2/kg and 3.5 x 10^{-8} kg/m^3. The samples from the lignite display lower NRM intensities (2 x 10^{-9} Am^2/kg) due to the weak ferromagnetic mineral concentration. These magnetic parameters vary according to the nature of the lithology, and they appreciably increase towards the top of the main lignite layer (Fig. 2B, C). All samples were stepwise demagnetized by both heating (10–12 steps) and alternating fields lower than 50 mT. The processing by alternating field gives valuable results, but most of the samples were demagnetised by heating. The thermally demagnetized specimens showed a stable behaviour during demagnetisation (Fig. 2A, B and C). The measured remanence directions are stable, but in some samples they become scattered at higher temperatures (over 500°C), which has been caused by chemical/mineralogical alterations due to heating. Furthermore, these demagnetizations showed that samples can have at least two distinct magnetic components.

The demagnetisation diagrams are of good quality for 86%, in the 14% remaining, their quality is lower. The northern dip of about 30°–40° of the layers can be used to distinguish primary and secondary magnetization components. A secondary component, certainly of viscous nature, is isolated between 100 and 200°C (Fig. 3 A, B and C). The stereographic projection of the direction of this normal polarity component in geographic coordinates shows that it is close to the present-day field. The Zijderveld diagrams of samples of lower quality do not show a linear decay to the origin but move successively toward the reversed quadrant of the diagram (Fig. 3F). We assume that the primary component is partly printed over by a secondary component caused by a overlapping blocking temperature spectra. When plotted on a stereographic diagram, remanence vectors progressed along a great circle toward a reversed primary component (Fig. 3G).

The evolution of susceptibility during heating shows that in some samples it begins to increase from 200 to 400°C (Fig. 3D) indicating a transformation of magnetic minerals; on other samples, the susceptibility is stable until the last stage of the processing.

An other component is isolated between the temperatures ranging from 200° to 500–550°C, and its direction is easily given (Fig. 3A, B and C). In 71 out of the 86 studied specimens, a direction for primary component can be determined. The polarity of this component was found to be reverse in all samples. A total of 71 characteristic directions was obtained from the original 86 samples treated. The overall mean direction in tilt corrected coordinates is Decl. = 192.34°, Incl. = -15.5°, and likely represents a record of the Late Eocene geomagnetic field.

For Eurasia, the coordinates of the geomagnetic pole between 30 and 50 Ma, are $\lambda = 78$ and $\varphi = 140$ ($\alpha_{95} = 7$) (Besse and Courtillot, 1991). The coordinates of the Krabi site are 8°N, 99°E, and the directions associated with that pole are Inc. = 31.4° and Decl. = 8.2°. The average variations that we calculated in this study are not different from those deduced from the geomagnetic pole, the declination having not significantly rotated. A feasibility study undertaken by Fuller *et al.* (1991) in the Krabi and Petchaburi basins gave similar results (Decl. = 205.3°; Incl. = 40.1° and Decl = 199.1°; Incl. = -15°).

Figure 4C displays the magnetostratigraphy obtained in the present study for the Krabi section. Correlation of the polarity calculated here with the Geomagnetic Polarity Time Scale of Cande and Kent (1995) has been performed, considering the late Eocene age suggested by mammals remains.

CORRELATION TO THE GPTS

For Southeast Asia, no radiometric dating of the Eocene continental formations is available and correlations between the continental and marine formations are also missing. The Krabi section shows only one reversed polarity. The correlation of the Krabi section with the geomagnetic Polarity Time Scale of Cande and Kent (1995) can be made on the basis of the biochronologic age obtained from the study of the mammal fauna, and also by taking into account the geological context of these continental sediments.

The Krabi fauna is very diversified, and comparisons with other Southeast Asian, European and of North African faunas, allow its attribution to the late Eocene. There is no evidence for major hiatuses in the sampled section, and thus a constant average sedimentation rate is assumed for this section. The late Eocene lasted 3.3 Ma, from 37 to 33.7 Ma (Berggren *et al.*, 1995). For the late Eocene part of the GPTS of Cande and Kent (1995), four Chron with reversed polarities of variable duration (C16r, C16n.1r, C15r and C13r) occur. The sedimentation rate for each Chron was therefore calculated (Table 1) in order to determine which Chron can be most likely correlated with Krabi.

Correlation I place the Krabi section in Chron C13r (33.54–34.65 Ma) with a sedimentation rate of 9.4 cm/ka. This sedimentation rate is weak, but can correspond to this environment seen the nature of its sediments. Correlation II with C15r gives a sedimentation rate of 26.2 cm/ka. Correlation in the fluviatile deposits of Samos (Greece), the sedimentation rate was calculated as 12 cm/ka (Sen and Valet, 1986). Although, fluvial formations often have a high sedimentation rates (Sen, 1988), the nature of the sediments in the Krabi section (lignite, siltstones, limestones and sandstones) indicates that the correlation III and IV provide very high sedimentation rates (58.3 and 37.9 cm/ka) close to those of purely fluvial environments. For example in the Siwaliks of Pakistan, the sedimentation rate in fluviatile sediments lies between 13 and 49 cm/ka, these sediments being produced by tectonic activity and the climatic changes (Johnson *et al.*,

Table 1. Sedimentation rate and correlation with Krabi section.

Duration	Sedimentation Rate (cm/ka)	Correlation
C13r(1.11 Ma)	9.4	I
C15r (0.40 Ma)	26.2	II
C16n.Ir (0.18 Ma)	58.3	III
C16r (0.27 Ma)	37.9	IV

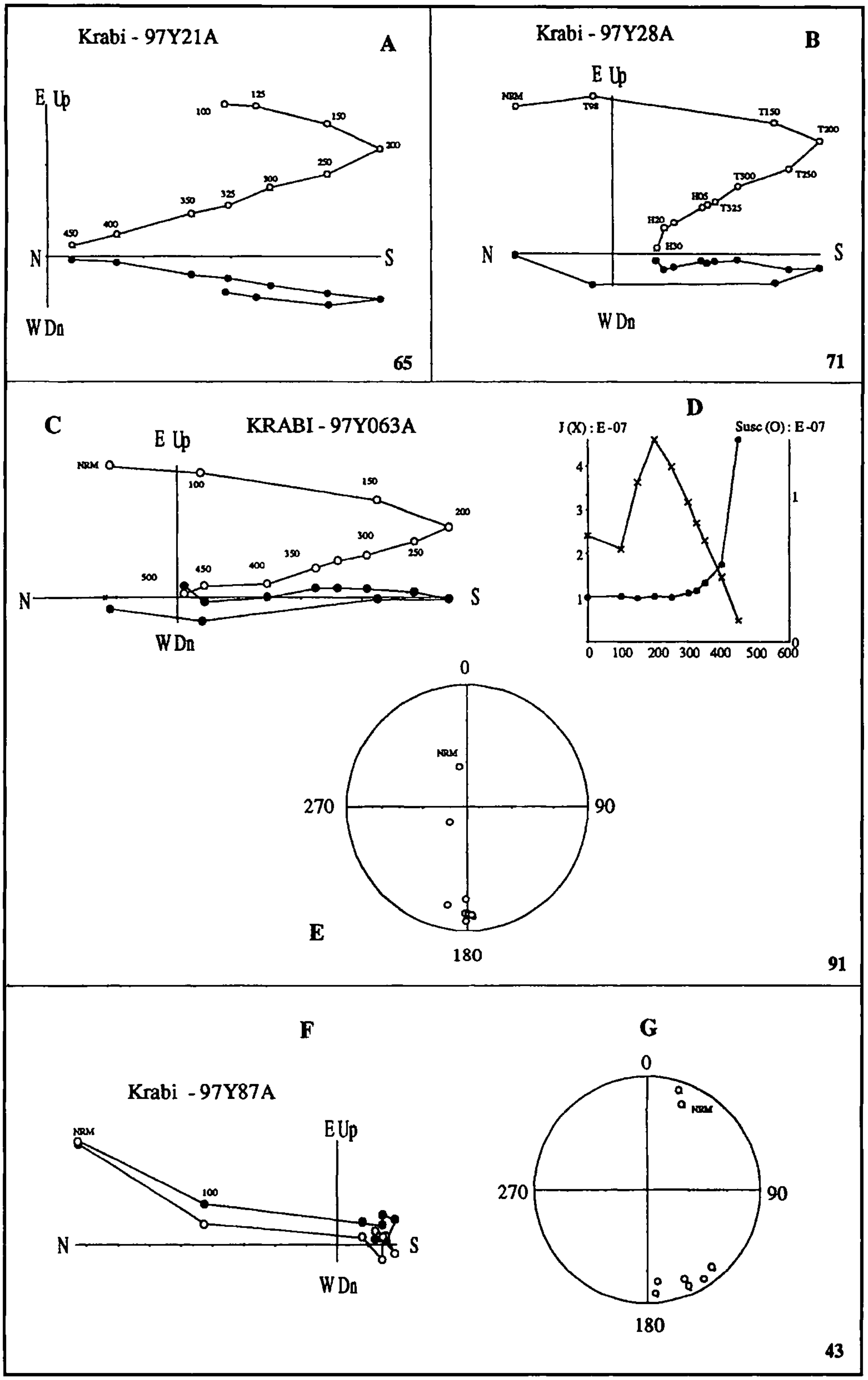

Figure 3. Demagnetization vectors plots and stereographic projections of selected samples from the Krabi section. Plots A, show results of stepwise thermal demagnetisation and plot B shows a combined alternating field (H) and thermal (T) demagnetisation. C: an other example of thermal demagnetisation, D: Diagram of evolution of magnetization and susceptibility according to the temperature; for this sample, note the increase in susceptibility between 300 and 400°C. E: Stereographic projection of the same sample. F: Example of sample of lower quality, G: Stereographic projection. For all Zijderveld diagrams, open circles represent vertical projection and the solid circles represent horizontal projection. Stratigraphic levels are in the lower right-hand corner.

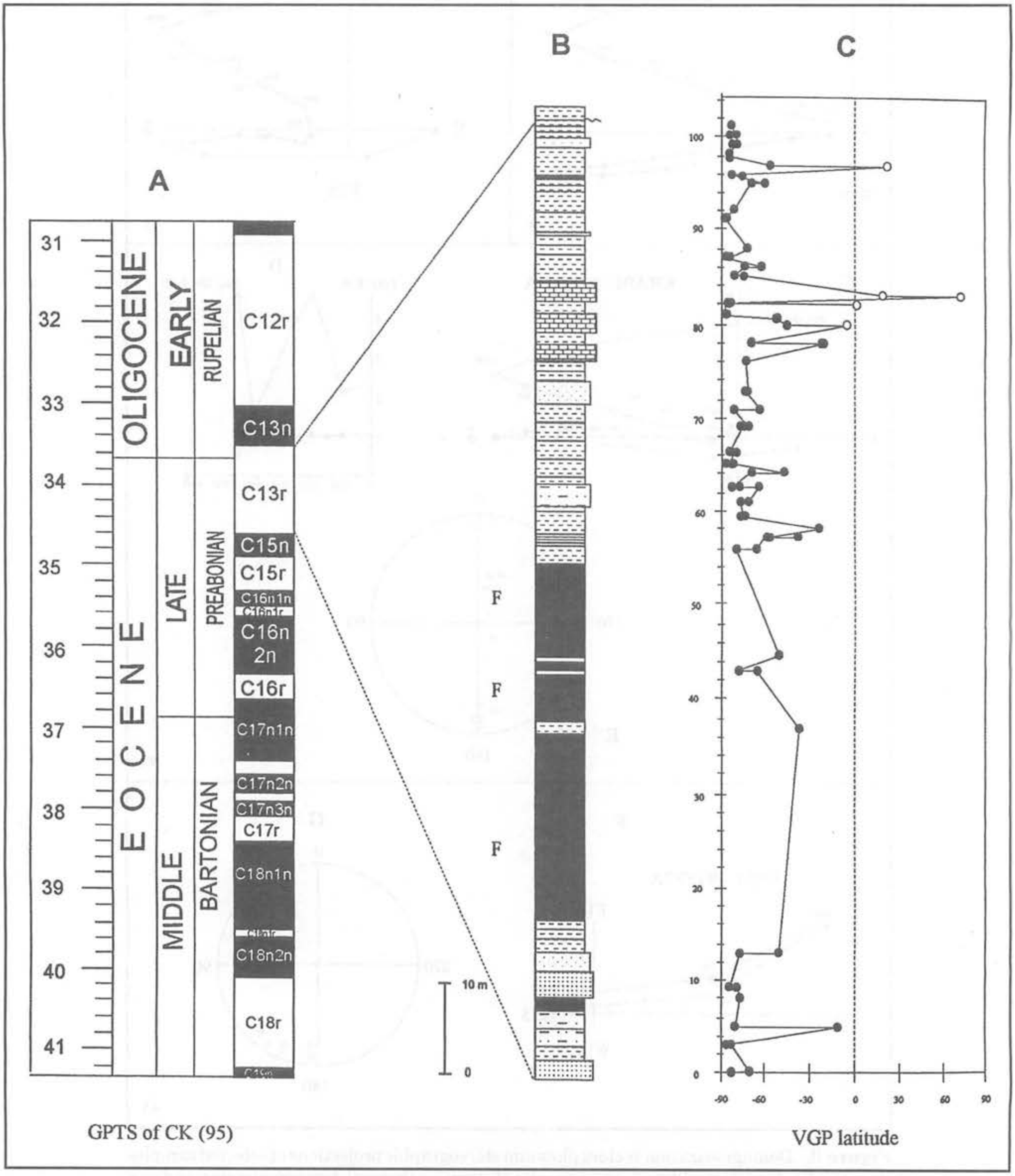

Figure 4. Magnetostratigraphy, lithology and correlation to the geomagnetic polarity time scale of Cande and Kent (1995) (GPTS). A: Segment of the GPTS; B: Lithology displays variations in clays, limestones and lignite; C: Latitude of virtual geomagnetic pole (VGP), the open circles represent the samples not included in alpha sites.

1982). Consequently, the last two hypothesis of correlation should be abandoned. Taking into account the lithology of these deposits, the first hypothesis, i.e. correlation with Chron C13r seems much possible.

CONCLUSIONS

A paleomagnetic analysis of a 105 m thick section of fluviolacustrine sediments from the Krabi basin has provided a magnetostratigraphic framework that allowed to correlate its late Eocene mammal fauna to the Geomagnetic Polarity Time Scale. Thermal demagnetization of samples resulted of consistent remanent direction with expected Eocene direction for this area. Two out of four potential correlations of the resulting polarity record to the GPTS are proposed. Correlation I places the Krabi section in Chron C13r (approximately 35 Ma) and correlation II places the Krabi section in Chron C15r. The calculated sedimentation rates indicate that the most probable correlation for the Krabi section (Fig. 4A) is therefore with Chron C13r (33.54–34.65 Ma). This result agrees with the inferred late Eocene age proposed for the Krabi mammal fauna on the basis of the mammalian remains.

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