

An experimental mapping method by means of fossil mollusk faunas: the Holocene Thai paleogulf

Mauro Pietro NEGRI

M.P. Negri, Università degli Studi di Milano-Bicocca, Dipartimento di Scienze Geologiche e Geotecnologie, Piazza della Scienza 4, I-20126 Milano, Italy;
mauro.negri@unimib.it

KEY WORDS - *Holocene, Mollusca, Thailand, Paleogeography, Flandrian transgression.*

ABSTRACT - *In the present work, mollusk associations are used as a tool for the reconstruction of sea level changes in the Gulf of Thailand during the Holocene transgression event (Flandrian event). The study area comprises the Lower Central Plain of Bangkok and the Petchaburi coastal plain, where mollusk assemblages were sampled in several localities exposing the Holocene sedimentary successions.*

The detailed study of recovered material, described in a previous work currently in press, led to the identification of molluscan associations, biofacies and single assemblages; each of these was attributed a restricted depth range consistent with the development of its mollusks.

The ^{14}C dating of shells allowed the separation of sampled sections into six intervals (timelines respectively at 9,000, 8,000, 6,000, 5,500, 5,000, and 4,000 years BP); each intersection between a timeline and a section was given a depth value within the range of the mollusk fauna sampled in that position. This resulted in a dataset of paleodepths for each time level and, subsequently, in the creation of six isobathymetric maps by interpolation.

The maps, showing the evolution of Thai paleogulf from the first arrival of the sea near the present shoreline to the beginning of the regression, have a small scale validity only and are subject to uncertainties due to the approximations of the method; nevertheless, the reconstruction appears consistent with both paleogulf maps based on different data (Pleistocene-Holocene contact isopachs, pollen content analyses) and recent Quaternary geological surveys conducted on the Lower Central Plain.

RIASSUNTO - [Una tecnica sperimentale di mappatura basata sulle faune fossili a molluschi: il paleogolfo olocenico thailandese] - *Nel presente lavoro le faune fossili a molluschi vengono utilizzate per realizzare una mappatura delle variazioni del livello marino durante un evento di trasgressione.*

L'area considerata comprende la parte meridionale della grande pianura alluvionale thailandese, o Lower Central Plain, e la pianura costiera di Phetchaburi. Tale area è stata interessata durante l'Olocene dall'evento trasgressivo Flandriano, che ha portato condizioni di mare basso fino a diverse decine di chilometri a nord di Bangkok, su un'estensione di oltre 14.000 chilometri quadrati.

I sedimenti fossiliferi di origine marina, appartenenti all'unità della Bangkok Clay, sono stati estesamente campionati nell'ultimo ventennio in diversi affioramenti che espongono in tutto o in parte la sequenza olocenica; lo studio dettagliato delle faune rinvenute (tutte datate tramite radiocarbonio), con le relative considerazioni paleoecologiche e stratigrafiche, è contenuto in un lavoro dell'autore attualmente in pubblicazione. Uno dei parametri utilizzati per caratterizzare le associazioni a molluschi è l'intervallo batimetrico di sviluppo delle faune, alla base della mappatura qui presentata.

Rimanendo nell'ambito dei primi 10 metri di profondità, si è cercato di ottenere per ogni associazione l'intervallo più ristretto possibile compatibile con lo sviluppo della fauna presente. Successivamente si è individuata nelle sezioni stratigrafiche la posizione di 6 linee-tempo (per corrispondenza diretta con i livelli datati, per caratteristiche faunistico-sedimentologiche o - in alcuni casi - per approssimazione). Ad ogni intersezione sezione/linea-tempo è stata quindi attribuita una fauna a molluschi ed una paleoprofondità puntuale scelta all'interno dei rispettivi intervalli batimetrici.

La ricostruzione così ottenuta mostra incertezze dovute 1) al posizionamento delle linee-tempo nelle sezioni, 2) alla necessaria interpretazione paleobatimetrica delle associazioni, 3) alla scelta dei valori di profondità puntuali, 4) alla necessità di limitare l'area di ricostruzione per evitare vistose distorsioni nell'interpolazione. Ciononostante, l'evoluzione del paleogolfo (valida a piccola scala) risulta coerente sia con quelle ricavate da altri autori utilizzando le isopache del contatto Pleistocene-Olocene o i dati pollinici, sia con i dati sedimentari evidenziati dai recenti rilievi del Servizio Geologico thailandese.

INTRODUCTION

Fossil mollusk faunas, often in association with other marine groups, are commonly used as a tool for paleoenvironmental reconstructions. All molluscan taxa can survive and reproduce only if environmental parameters fit in with their ecological requirements, including a peculiar depth range; this latter, consequently, can allow to estimate sea paleodepths, yet often at a qualitative level only. Mollusk associations are then currently referred to a particular zone (e.g. intertidal, infralittoral, circalittoral) or a part of it, as in the fundamental works concerning Mediterranean benthic bionomy (Pérès & Picard, 1964; Picard, 1965; Pérès, 1982).

More recently, the use of statistical methods allowed quantitative estimates of sea paleodepths; remarkable results were obtained by means of Detrended Correspondence Analysis (DCA), whose scores attributed to molluscan genera have been interpreted as reflecting bathymetric values (Miller et al., 2001; Scarponi & Kowalewski, 2004).

In the present work, a quantitative approach is tested by attributing punctual sea depths to fossil mollusk associations during a sea transgression event, resulting in the first attempt to use such data to draw the paleobathymetric maps of an area.

After the last glacial maximum, ended roughly around 19,000 years BP (Lambeck et al., 2002), sea level shifted to generally rising conditions, due to both continental

ice melting and thermal expansion of water. This event, the so-called Flandrian transgression, brought seawater to rise from about 120 m below the present mean sea level (Hanebuth et al., 2000; Lambeck et al., 2002) to today's conditions. Nevertheless, the rising trend was characterized by phases of rapid relative sea-level rise and subsequent stand stills. The effects of this event are particularly visible in the sediments of the wide plains of Thailand. During the peak of the Flandrian transgression, the Lower Central Plain was inundated by the sea well north the present location of Bangkok, and a similar event took place on the coastal plain of Phetchaburi. The subsequent deposition of several meters of marine and/or brackish water sediments (grouped in the Bangkok Clay Formation), often with abundant shell remains,

testifies to the progressive filling of the accommodation space created during the Flandrian transgression.

Holocene successions were extensively sampled during the last decades, and yielded very rich molluscan faunas, which have been studied in detail (Chonglakmani et al., 1983; Dheeradilok et al., 1984; Somboon, 1988; Somboon & Thiramongkol, 1992; Sato et al., 2000; Di Geronimo et al., 2002; Negri, 2002). A comprehensive paleoenvironmental reconstruction of the Holocene Thailand plain successions based on molluscan assemblages (Negri, in press) provided the database for the experimental mapping technique presented herein; for all information about the geology of the area, the sampling sites, the lists of recovered species and the detailed interpretation of the assemblages, reference can be made to this latter work.

The study area (Fig. 1) comprises about 40,000 square kilometres of alluvial plains with an extremely reduced slope (5 to 20 cm/km); at least 14,000 square km were "flooded", according to the extension of the marine Bangkok Clay Fm. These sediments, with a maximum thickness of about 20 m under the Chao Phraya River delta, include brackish, intertidal and shallow infralittoral deposits, along with the recent alluvial sediments.

MATERIALS AND METHODS

The base data for the creation of the paleobathymetric maps come from the study of several samples obtained from the Bangkok Clay Formation (Negri, in press). In 16 localities, scattered on the Lower Central Plain and the Phetchaburi coastal plain (Fig. 2; Tab. 1), different types of ground excavations (such as active or abandoned quarries and pits, fish or shrimp ponds, channel digs) exposed - at least partly - the Holocene sequence. In each section, volumetric (about 30 dm³) samples were taken from shell layers whose positions in the sections are schematized in Fig. 3. A total of 335 mollusk species (159 Bivalvia, 173 Gastropoda, and 3 Scaphopoda) were recognized, together accounting for over 154,000 specimens. Shells coming from most horizons were dated some years ago by means of ¹⁴C at the Sapienza University, Rome, and U-Th (in a single case) at the University of Bern (see Tab. 2 for details), revealing ages roughly spanning from 9,000 to 600 years BP. These dates, obtained from a single sample - including a number of shells variable from 3 to 58 - for each shell horizon, were held as suitable for the reconstruction although a problem of time-averaging surely exists as regards shell layers deposited in sea transgression phases (Scarponi et al., 2008).

A statistical treatment was then applied to mollusks' abundance data, in order to recognize the occurrence of associations. It consisted in a cluster analysis performed on a Bray-Curtis similarity matrix, including only samples (= observations) and species (= variables) exceeding a significance threshold arbitrarily set at 5% of maximum abundance value referred to the richest sample and most abundant species respectively. This led to retain 20 samples (of 34 containing fossils) and 29 species. The resulting single-linked dendrogram and MDS ordination (Fig. 4) returned four major associations; of these latter,



Fig. 1 - Location of the study area (shaded rectangle). Courtesy of The General Libraries, The University of Texas at Austin (modified).

two were further subdivided into sediment-linked biofacies. The remaining assemblages, recovered from samples excluded from the analysis due to scarcity of material, were considered individually. Finally, a detailed

paleoecological interpretation allowed the assignment to each association, biofacies and single assemblage of a depth interval consistent with the development of the respective mollusk faunas.

Site	UTM long	UTM lat	Section thickness (m)	Outcrop type	Samples (nr.)
Wat Tammakai	1509641	593419	2,5	shallow pit	1
Ban Tak Daet	1524402	602433	3,5	fish ponds	3
Ban Pa Luang	1520196	599636	3,8	fish ponds	2
Ban Praksa	1587401	585874	21	quarry	3
Wat King Kaew	1596443	604678	19	quarry	2
Senanivate S	1585641	618991	18	home-building pit	4
Senanivate N	1585641	618991	19,5	home-building pit	8
Ban Ko	1604374	614874	3,7	shallow pit	2
Ban Dong Tan	1575730	623917	9,5	quarry	3
Ban Bang Dua	1575007	634182	12	quarry	2
Wat Hoi	1564335	651170	4,7	shallow pit	1
Ban Sam Tum	1566100	667607	5	sand quarry	1
Bang Sai	1567130	664691	4	quarry	1
TH18	1504817	553816	2,5	shrimp pond	1
TH33	1520442	528985	3,5	home-building pit	6
TH42	1512551	513638	1	channel dig	2
TH43	1517713	519564	1,4	channel dig	1

Tab. 1 - Basic data about Holocene sampling locations.

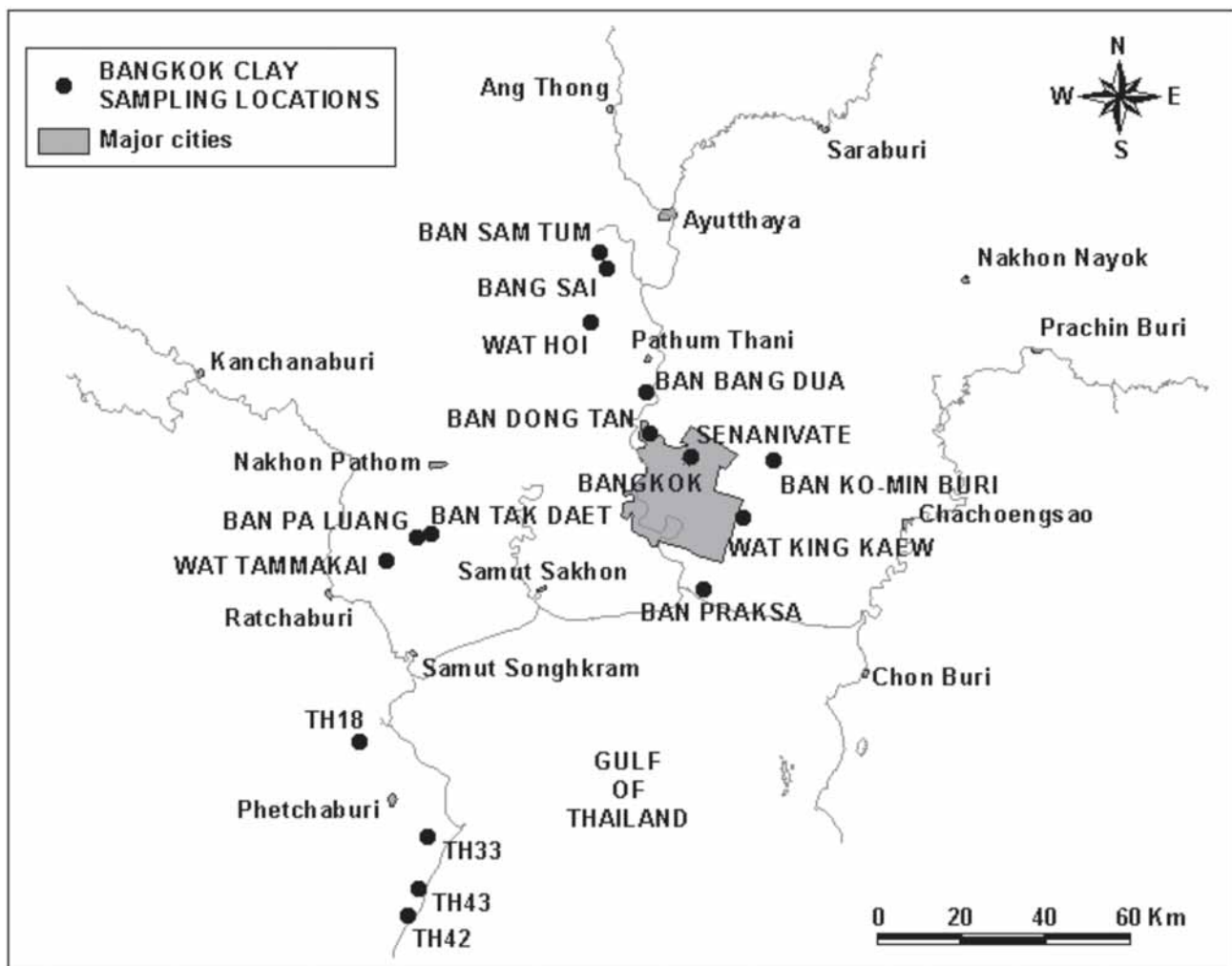


Fig. 2 - Holocene Bangkok Clay sampling locations.

Sample	Calibrated age (years BP)	Conventional age (years BP)	Dating method	Confidence	Material
BPL1	3560 ± 120	3670 ± 50	¹⁴ C + ¹³ C	95.4% (2σ)	Anadara granosa
BPL1	7340 ± 135	6450 ± 80	¹⁴ C + ¹³ C	95.4% (2σ)	mang. wood (reworked)
BTD2RM	4790 ± 160	4550 ± 65	¹⁴ C + ¹³ C	95.4% (2σ)	Anadara granosa
BTD1	4590 ± 195	4450 ± 65	¹⁴ C + ¹³ C	95.4% (2σ)	Paratectonatica tigrina
BTD2	5630 ± 105	5285 ± 65	¹⁴ C + ¹³ C	95.4% (2σ)	Scapharca inaequalis
BTD4	4430 ± 190	4335 ± 75	¹⁴ C + ¹³ C	95.4% (2σ)	Paratectonatica tigrina
BTN2	35460 ± 1300 (*)	34850 ± 1270	¹⁴ C + ¹³ C	95.4% (2σ)	Saccostrea cucullata
BTN3	3170 ± 90	-	U - Th	-	Paphia undulata
NC1	3970 ± 165	3995 ± 60	¹⁴ C + ¹³ C	95.4% (2σ)	Anadara granosa
PK1	5020 ± 210	4785 ± 70	¹⁴ C + ¹³ C	95.4% (2σ)	Dendostrea rosacea
PK2	5280 ± 190	4955 ± 60	¹⁴ C + ¹³ C	95.4% (2σ)	Dendostrea rosacea
PK3	4950 ± 165	4730 ± 60	¹⁴ C + ¹³ C	95.4% (2σ)	Dendostrea rosacea
(**)	6279 ± 130	-	¹⁴ C	-	mangrove wood
RAT1	3820 ± 160	3860 ± 60	¹⁴ C + ¹³ C	95.4% (2σ)	Anadara granosa
6-7m	5290 ± 160	4965 ± 60	¹⁴ C + ¹³ C	95.4% (2σ)	Planostrea pestigris
7-11m	8300 ± 150	7870 ± 75	¹⁴ C + ¹³ C	95.4% (2σ)	Polymesoda bengalensis
SEN1	4790 ± 145	4550 ± 55	¹⁴ C + ¹³ C	95.4% (2σ)	Paratectonatica tigrina
SEN3	5250 ± 190	4915 ± 65	¹⁴ C + ¹³ C	95.4% (2σ)	Planostrea pestigris
SEN5	8490 ± 150	7730 ± 80	¹⁴ C + ¹³ C	95.4% (2σ)	mangrove wood
SEN6	8420 ± 120	7700 ± 75	¹⁴ C + ¹³ C	95.4% (2σ)	mangrove wood
WatHoi	5500 ± 50	-	¹⁴ C	-	Crassostrea gigas
WKK2	3870 ± 135	3915 ± 50	¹⁴ C + ¹³ C	95.4% (2σ)	Paphia undulata
TH18	697-642	1119 ± 37	¹⁴ C + ¹³ C	68% (1σ)	Anadara granosa
TH33C	4931-4813	4648 ± 57	¹⁴ C + ¹³ C	68% (1σ)	shells
TH42A	3299-3070	3331 ± 74	¹⁴ C + ¹³ C	68% (1σ)	shells
TH42B	3070-2977	3224 ± 27	¹⁴ C + ¹³ C	68% (1σ)	Meretrix meretrix
TH43	3750-3567	3738 ± 72	¹⁴ C + ¹³ C	68% (1σ)	Placuna placenta

Tab. 2 - Radiometric ages of samples. Dating was conducted on a single sample for each level; the ages retained for the maps are the mid values of calibrated intervals. (*) = age out of calibration limits; (**) = age after Robba et al. (1993).

Full data concerning the statistical and paleontological analyses are reported in Negri (in press); depth ranges of all associations, along with relative substrate characteristics, environment type and samples included, are briefly resumed in Tab. 3. In this respect, a note is to

be made. The extremely narrow range attributed to the associations/biofacies derives from an imposed limitation rather than a surprisingly precise result of the assemblages' analysis. Actually, the sea depth on the plain was assumed *a priori* not exceeding 10 m, since the

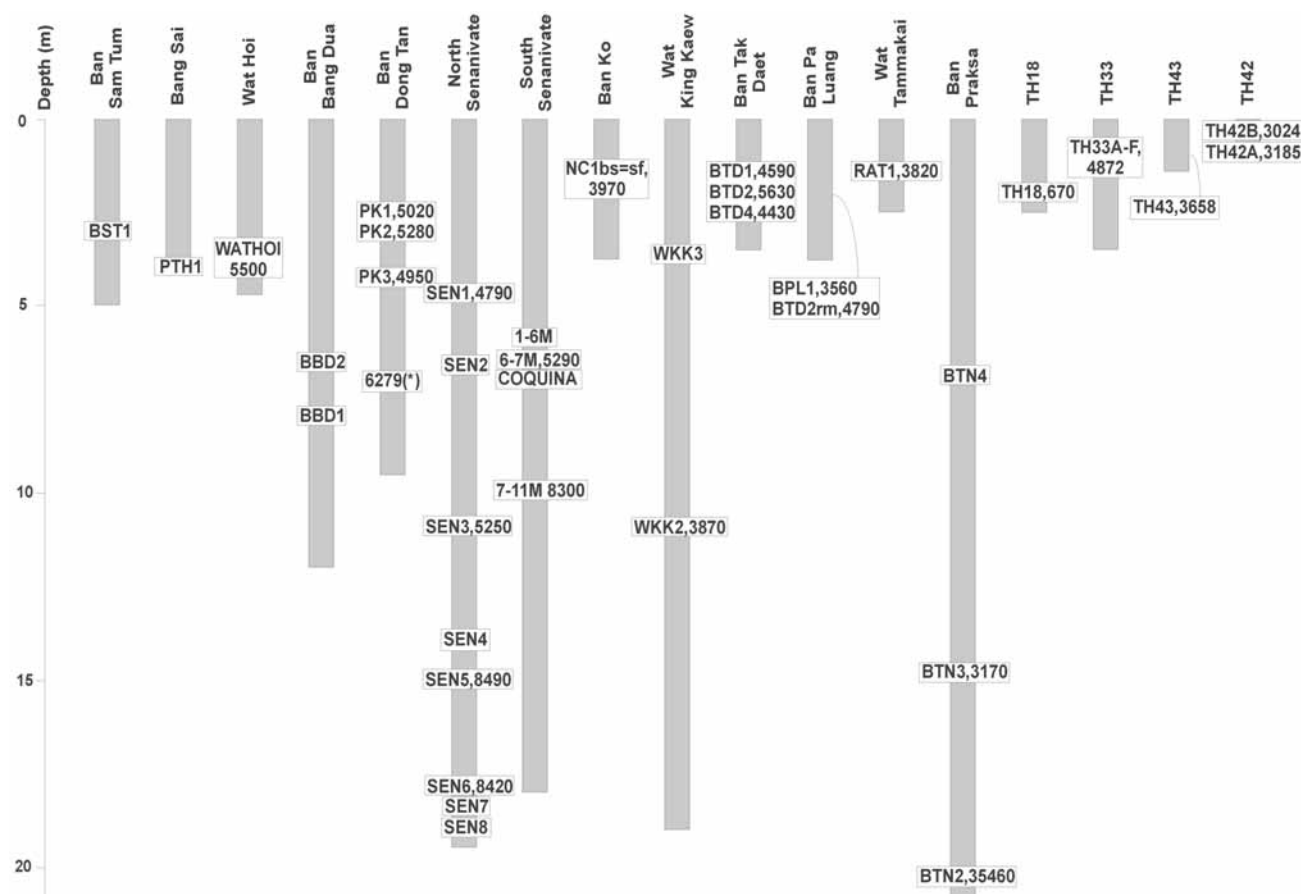


Fig. 3 - Holocene sampled sections, with the position of all samples and (when available) respective ¹⁴C ages in years BP; to preserve clarity, dates are reported without their uncertainty interval. (*) = age after Robba et al. (1993).

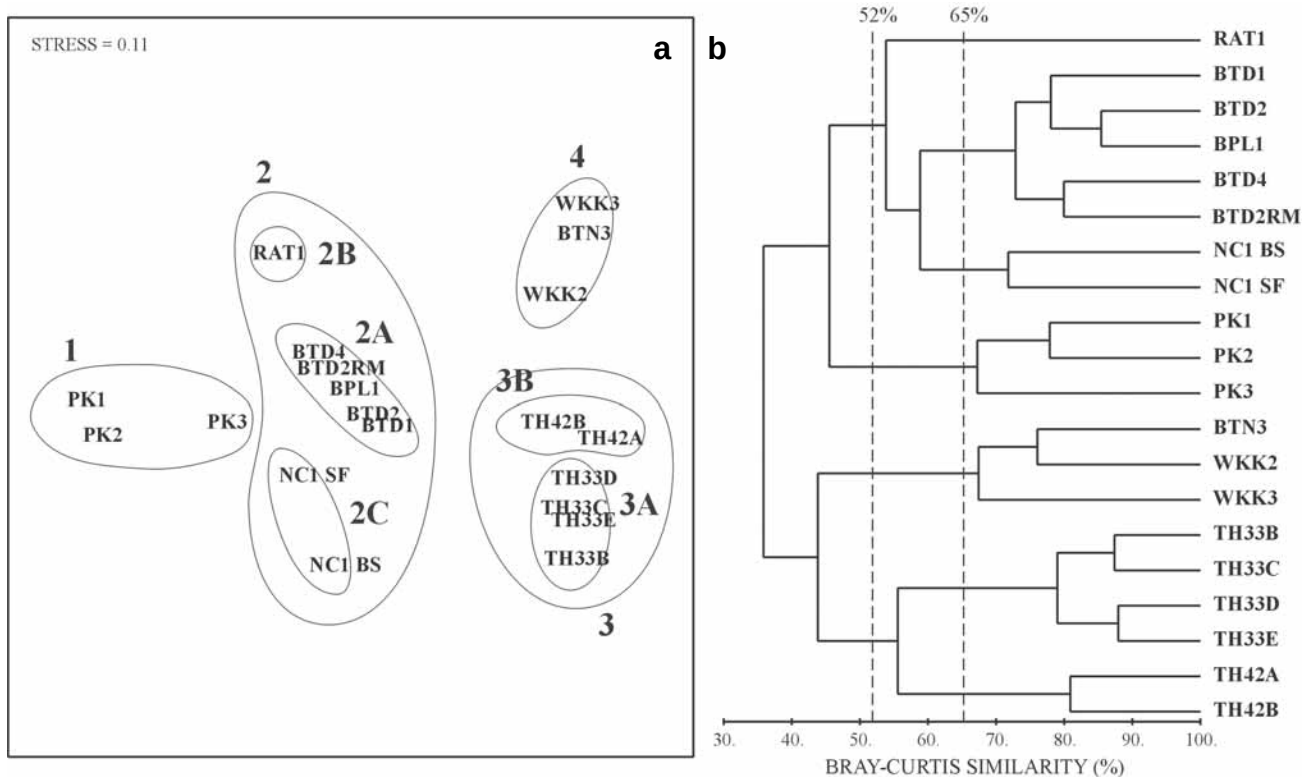


Fig. 4 - MDS ordination (a) and dendrogram (b) resulting from cluster analysis applied to abundance data. Hatched lines in dendrogram define associations and biofacies (see Tab. 3 for codes).

maximum thickness of Holocene deposits reaches about 20 m (in Senanivate, Wat King Kaew, Ban Praksa) and, otherwise, no more than about 10 m of marine sediments are found between the level corresponding to the apex of transgression and the bottom of the recent mangal soil. Consequently, the attributed ranges were restricted to span from the high tide mark and 10 m depth only; the necessary differentiation between associations (deriving from

different faunal compositions) led to give them depth intervals of few meters, and less so for the respective subfacies and the single assemblages.

The depth differentiation of associations/biofacies (within the above cited maximum interval) was realized by means of the depth ranges attributed in literature to the respective relevant (i.e. exceeding 1% of mean dominance) taxa; all data concerning the bathymetric

Tab. 3 - Summary scheme of molluscan associations and biofacies (upper section), single assemblages (middle section) and samples bare of fossils (lower section) recognized in Negri (in press). Abbreviations are Inf = infralittoral, Int = intertidal, M = mud, S = sand, H = hard substrates. As regards substrate, small letters denote minor fractions.

Name	Environment	Depth range (m)	Substrate	Samples included
1 - <i>D. rosacea</i>	Tidal flat-Inf	Int-3	M	PK1, PK2, PK3
2 - <i>C. fortisulcata</i> - <i>M. luzonica</i>	Inf	Int-5		
2A - typical facies	Inf	0-3	Sm	BTD1, BTD2, BTD4, BPL1, BTD2RM
2B - <i>C. erycina</i>	Inf	4-5	Ms	RAT1
2C - <i>A. arcuatula</i>	Tidal flat-Inf	Int-2	M	NC1bs, NC1sf
3 - <i>A. ojanus</i> - <i>N. mauritiana</i>	Sand bar	0-6		
3A - typical facies	Sand bar	3-6	Ms	TH33B, TH33C, TH33D, TH33E
3B - <i>D. derupta</i> - <i>D. rosacea</i>	Sand bar	0-2	S	TH42A, TH42B
4 - <i>T. scabra</i> - <i>A. pudica</i>	Inf	5-10	Ms	BTN3, WKK2, WKK3
SEN1	Inf	0-5	M	
SEN2	Inf	0-3	M	
SEN3	Tidal flat-Inf	Int-3	M	
1-6m, 6-7m	Tidal flat-Inf	Int-3	M	
Coquina, 7-11m	Tidal flat	Int	M	
BTN4	Inf	2-4	Ms	
WatHoi	Tidal flat	Int-1	H	
BBD1, BBD2	Tidal flat	Int	-	
TH18	Mangrove	Int	M	
TH33A	Sand bar	2-3	M	
TH33F	Sand bar	3-4	M	
TH43	Tidal flat-Inf	0-3	Ms	
BST1	Continental		Ms	
PTH1	Continental		M	
SEN4	Tidal flat	Int	M	
SEN5, SEN6	Mangrove	Int	M	
SEN7, SEN8	Continental		M	

distribution of the species were obtained from Robba et al. (2002, 2004, 2007) and are resumed in Negri (in press). In some cases, the intervals were refined by considering the intertidal/infralittoral components ratio, the contribution of stenobathymetric elements being emphasized.

Maps were realized on a DXF format base drawing, obtained from the digitalization of four sheets (ND 47-7, ND 47-8, ND 47-11, and ND 47-12) of the topographic map of Thailand, scale 1:250,000, by means of AutoCAD R10 software, and geo-referenced with points of coordinates (13°00' N, 99°15' E) and (14°45' N, 101°45' E).

Isobaths (in grey on the maps) were realized with Surfer 5.00 software, adopting the kriging interpolation method. This latter manages depth as a spatially continuous parameter, and estimates unknown values by weighting the influence of measured ones within an "influence zone"; so, nearby points are strictly correlated each other, while distant ones are considered statistically independent. In the maps, infralittoral (thin) isolines have a 1 m interval; the thick line represents the mean zero level, while the dotted one is placed 0.5 m above this latter and interpreted as marking the landward limit of tidal flat. The interpolation was limited landward by placing a series of hidden points (see discussion below) at a height of 2 m above mean sea level (this choice has been arbitrary).

RESULTS

The creation of the paleobathymetric maps presented herein is entirely based on data obtained from the paleoecological interpretation of molluscan assemblages.

The radiometric dating of shell material coming from the samples allowed the placement, in each section, of six opportune timelines (at 9,000, 8,000, 6,000, 5,500, 5,000, and 4,000 years BP respectively; Fig. 5). These latter were chosen in order to detail the paleogulf's evolution, in particular around the apex of transgression (between 6,000 and 5,000 BP), and compatibly with the availability of fossils; late Holocene evolution was not investigated because only very few sections yielded shells of that age.

The placement of the timelines in the sections stands as one of the uncertainty points of the reconstruction. In some instances timelines were exactly coincident with or at least very near to dated shell levels, e.g. 5.5 ky in WatHoi section or 5 ky in Senanivate pits; some others were placed capitalizing on fossil and/or sedimentary characteristics (this is the case of 9 ky timeline, which was located in several sections at the lower limit of marine sediments, i.e. at the Pleistocene/Holocene contact; another example is the 5.5 ky line, marked in the northernmost localities by the short-term appearance of levels containing mangrove remains). Timelines placed

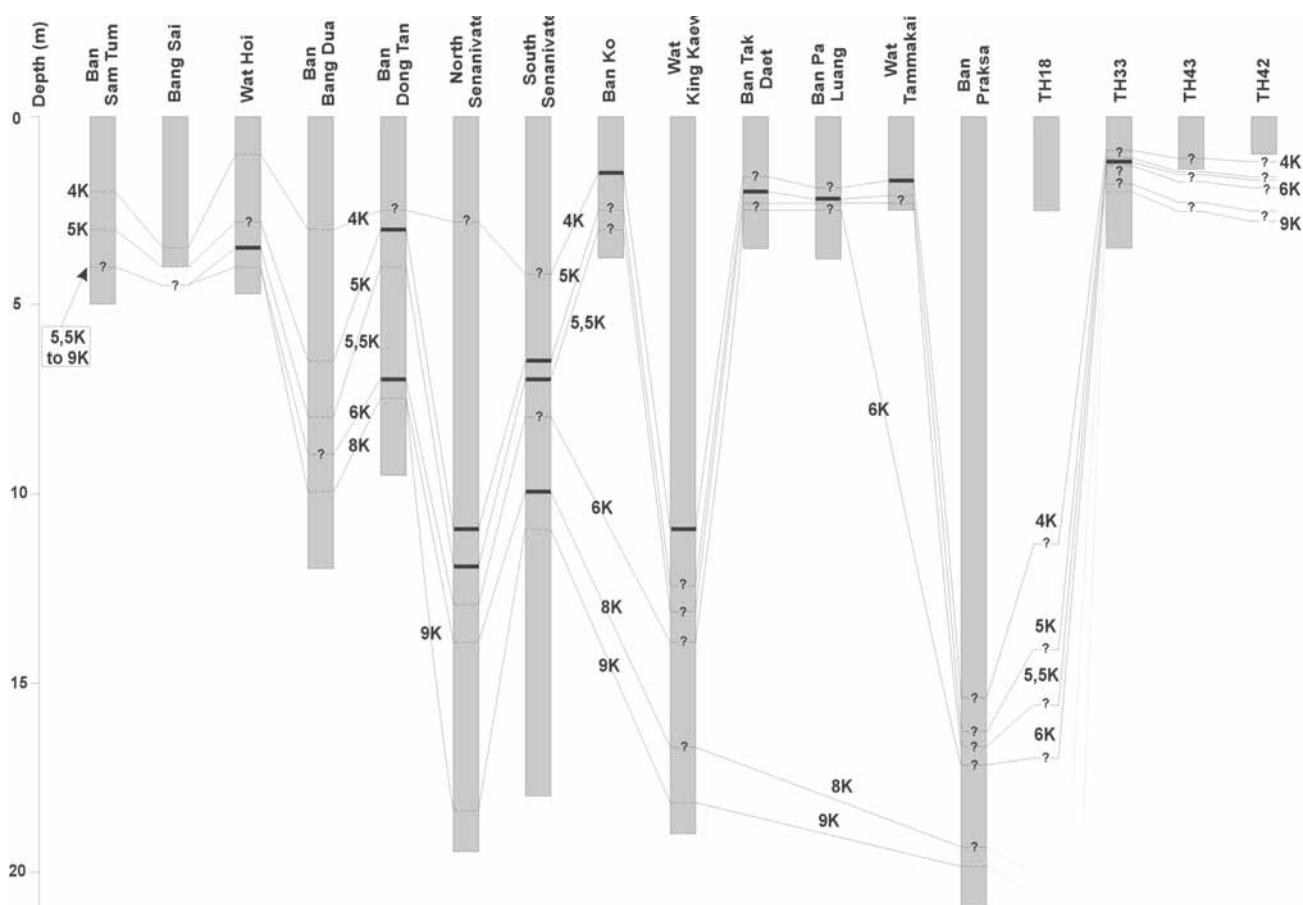


Fig. 5 - Holocene sampled sections, with the inferred position of the six timelines. Levels: bold = placed by direct ^{14}C dating; hatched = placed by fossil content and/or sediment characteristics; ? = placed by assuming a constant sedimentation rate. K = thousand years BP.

in such two ways were retained as datum points for the localization of the remaining ones by assuming a constant sedimentation rate (section by section) between the known levels; this method has revealed particularly useful where the Holocene sequence was only partly exposed (e.g. Ban Tak Daet-Ban Pa Luang or Phetchaburi Plain sampling locations) or poorly dated (Ban Praksa, Wat King Kaew). An extreme case is represented by TH18 section, a 2.5 m thick sequence of mangal mud returning a single shell level with an age of about 670 years BP; though very short, this section was retained since it represents a relevant linking point between the Bangkok and Phetchaburi plains. Here, all timelines were located by assuming as constant the sedimentation rate calculated between the surface and the shell layer; this was possible considering that a coring in a very nearby location revealed several meters of homogeneous mangal mud (personal communication by Dr. Niran Chaimanee, Department of Mineral Resources). All the assumed depths of timelines below soil level are reported on the right columns of Tab. 4.

The subsequent step was the attribution of a numerical paleodepth to each timeline in the respective sections. Both faunal content and sediment type in correspondence to (or in the vicinity of) each of these levels allowed their attribution to one of the recognized mollusk associations, biofacies or assemblages of Tab. 3. Normally, all homogeneous intervals in the sections were considered as representing the same environmental conditions and consequently hosting the same fauna. So, each level fell within a definite depth range. For the construction of the maps, single depth values were chosen within these intervals, and are reported in Tab. 4 (middle columns). The choice of a value in an interval was of course arbitrary, and this stands as another point of uncertainty of the method. As a starting point, all timelines were attributed the median values of the assigned intervals; subsequently, such values were more or less modified (remaining anyway in the limits of the respective interval) on the basis of

1) the faunal composition of the nearest assemblages: the intertidal/infralittoral taxa ratio was used in order to choose a shallower (higher ratio) or deeper (lower ratio) value in the range;

2) the vicinity to lithological variations: a timeline falling near a sediment change denoting a sea deepening was attributed a depth in the lower part of the range, and *vice versa*.

For example, a hypothetical association (originally interpreted as dwelling in the 0-5 m depth range) was assigned a value of 1 m, 2.5 m, or 4 m if recovered just below a mangrove soil, in the middle of a homogeneous sediment package or just above an infralittoral bottom respectively.

However, correlations with nearby sites were considered in all cases, in order to avoid “step-like” discontinuities over short distances.

The result of the reconstruction is visible in the six maps (Figs. 6a-f) showing the estimated evolution of the paleogulf from the arrival of the sea at the latitude of the present shoreline to the beginning of the regressive phase. It is of note that the 1 m equidistance between isobaths was only adopted in order to make the maps more readable, since the very shallow Holocene sea on the plains would have become “invisible” by using a wider interval. So, the precision of the maps is only apparent and not related to that of the paleoecological reconstruction; this latter has an error margin at least coincident with the whole depth range attributed to each association/biofacies.

Moreover, these maps have a small-scale validity only; this is primarily due to the restricted number of available sampling locations (i.e., points on the maps), particularly on the east side of the area. When drawing the isobaths by interpolation, the use of relatively few points on the plots led necessarily to relevant distortions on the edges of the reconstructions. An attempt to minimize distortions was made by placing a line of points with a fixed depth of 2 m above sea level. Such points were located around the paleogulf in areas that remained surely emerged during the whole Holocene, by using the presumable position of the coastline obtained on palynological data (Somboon, 1990; Somboon & Thiramongkol, 1992). In particular, they were placed just landward of brackish water pollen occurrences. This procedure allowed to “cut” the isolines traced by the interpolation on the mainland and likely to alter the reconstruction also in the gulf zone.

Site	Sea paleodepth (m)						Timeline depth in the section (m)					
	4k	5kA	5,5k	6k	8k	9k	4k	5kA	5,5k	6k	8k	9k
Wat Tammakai	-4	-5	-5	-4	0	1	-1,7	-2,1	-2,3			
Ban Tak Daet	-2	-3	-3	-2	0,5	1	-1,6	-2	-2,3	-2,5		
Ban Pa Luang	-2	-3	-3	-2	0,5	1	-1,9	-2,2	-2,3	-2,5		
Ban Praksa	-8	-8	-7	-6	-3	0	-15,5	-16,4	-16,8	-17,3	-19,1	-20
Wat King Kaew	-7	-7	-6	-5	-2	0,5	-11	-12,5	-13,2	-14	-16,8	-18,3
Senanivate S	-2	-2	-1	0	0	1	-4,2	-6,5	-7	-8	-10	-11
Senanivate N	-3	-4	-3	-2	0	0,5	-2,8	-11	-12	-13	-14	-18,5
Ban Ko	-1	-3	-3	-2	0,5	1	-1,5	-2,5	-3			
Ban Dong Tan	-0,5	-1,5	-0,5	0,5	1	1	-2,5	-3	-4	-7	-7,5	-7,5
Ban Bang Dua	0,5	-0,5	0	0,5	1	1	-3	-6,5	-8	-9	-10	-10
Wat Hoi	1	1	0	1	1	1	-1	-2,8	-3,5	-4	-4	-4
Ban Sam Tum	1	0,5	1	1	1	1	-2	-3	-4	-4	-4	-4
Bang Sai	1	0,5	1	1	1	1	-3,5	-4	-4,5	-4,5	-4,5	-4,5
TH18	-4	-5	-4	-3	0	1	-11,4	-14,2	-15,7	-17,1		
TH33	-3	-5	-4	-3	0,5	1	-0,9	-1,1	-1,2	-1,3	-1,8	-2
TH42	-3	-5	-4	-3	0	1	-1,2	-1,6	-1,7	-1,9	-2,5	-2,8
TH43	-3	-5	-4	-3	0	1	-1,1	-1,4	-1,5	-1,7	-2,2	-2,5

Tab. 4 - Depth of timelines in each section (right) and suggested sea depths (left). K = thousand years BP.

DISCUSSION

The evolution can then be summarized as follows. The first arrival of the sea at the latitude of the present coastline seems to date back at about 11,000 years BP, according to the ^{14}C age of peat recovered under the Chao Phraya delta (Somboon, 1988). At 9,000 years BP (Fig. 6a) the prograding sea had already encompassed the

present-day shoreline, though with a very low depth (2-3 m) in the Northern Gulf; the extension of tidal flats was roughly the same as today, but for a 10-20 km more northern position of their edges.

At 8,000 years BP (Fig. 6b) the situation had radically changed. The sea decidedly deepened (over 8 m between Phetchaburi and Ko Si Chang Island) and the mean shoreline moved northward and westward, touching

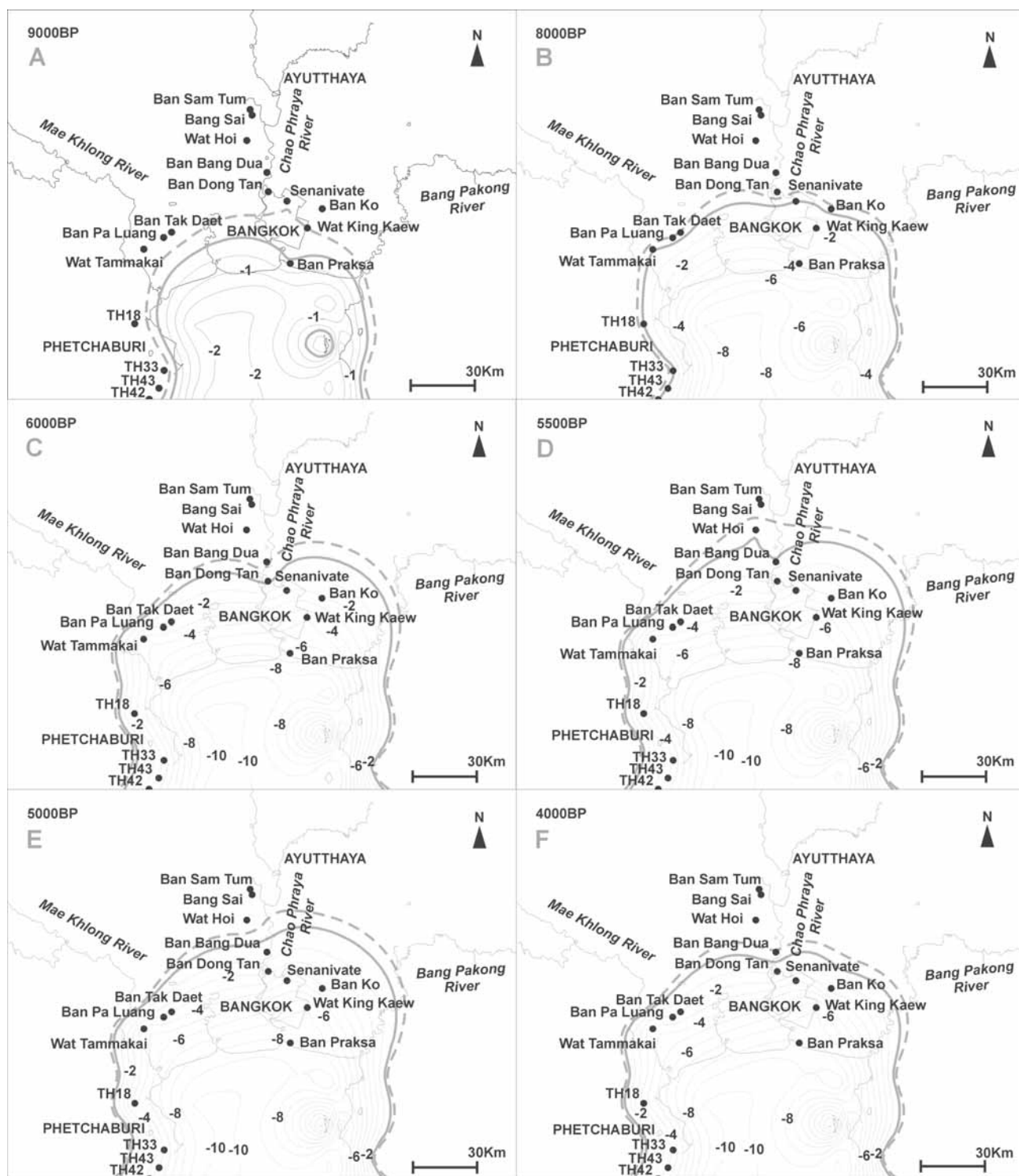


Fig. 6 - Sequence of maps showing the bathymetric reconstruction of Thai paleo-gulf. Full dots are sampling locations; grey lines represent isobaths (thin lines; depths in meters), coastline (thick line) and landward edge of tidal flat (hatched line).

almost all the localities between Wat Tammakai and Ban Ko on the Lower Central Plain, and all the Phetchaburi plain sites. The tidal flat appeared narrower than a thousand years before, and nearly all the Bangkok area was included in a very shallow (0-3 m) infralittoral context.

At 6,000 years BP (Fig. 6c) infralittoral conditions involved all sampled sites, but for the ones located north of Bangkok along the Chao Phraya fluvial axis. The estimated sea depth slightly exceeded 10 m in the Gulf and 7 m on present-day's mainland; the whole Bangkok metropolitan area was well below mean sea level. The edge of the wide tidal flat moved as far north as Ban Bang Dua. It is worth noting that in this latter zone the reconstruction draws a southward-directed, wedge-shaped protuberance: this could be well interpreted as a representation of the Chao Phraya deltaic front. Eastward, the large lobe visible on the map is clearly an approximation of the interpolation; nevertheless, it somehow matches with the extent of brackish water sediments recently detected by Thai Geological Survey (cf. the Quaternary geological map on Negri, in press).

The 5,500 BP timeline (Fig. 6d) marks the age of the transgression apex. Environmental conditions were quite similar to these of five hundreds years before, except for the area north of Bangkok. Here, the tidal flat limit reached northward an intermediate latitude between Wat Hoi and Bang Sai. Wat Hoi was included in a very wide intertidal plain that - once again - attained its maximum extent in correspondence to the Chao Phraya axis; the Chao Phraya delta is also visible on the map.

The Wat Hoi section bears a great importance as a marker of the transgression apex: its peculiar molluscan population, dated at $5,500 \pm 50$ years BP (Chonglakmani et al., 1983), is almost exclusively made by millions of specimens of the giant oyster *Crassostrea gigas* (Thunberg, 1793). This distinctive bivalve, recovered at Wat Hoi in more than 1 m thick banks, can be regarded as a highstand phase indicator; it is mostly restricted to intertidal belts even with somewhat brackish waters (Robba et al., 2002). Moreover, the large and elongated shells clustering in banks are typical of closed embayments with freshwater input (Hayasaka, 1961). These ecological requirements allowed determining the paleodepth of the assemblage with a high precision degree (cf. Chonglakmani, 1983; Negri, 2002, in press).

Even at the time of its maximum expansion, the Holocene sea seems to have attained definitely shallow depths - hardly exceeding 8 m - on the present mainland. Bang Sai and Ban Sam Tum, whose sections show continental sedimentation evidences only, remained at all times outside the submerged area; so, their position well marks the northern limit of the sea invasion.

At 5,000 years BP (Fig. 6e) the situation was essentially unchanged. Only in the northern part of the area some differences are noted in respect to the apex map: here, in fact, the coastline was starting moving southward under the pressure of the Chao Phraya alluvial sedimentation. In about five hundreds years, Wat Hoi returned to a continental context, and the northern tidal flat narrowed and settled at a slightly lower latitude.

A thousand years later (Fig. 6f) the regressive phase of the cycle was manifest on all the edges of the

paleogulf, while in the southern area infralittoral conditions remained substantially unchanged. The shoreline moved as far south as a latitude between Ban Dong Tan and Ban Bang Dua, this latter locality marking the tidal flat limit. At this stage - and in more recent times - the regression of the sea mixes with the coastal progradation, the sediment discharge of the Chao Phraya and of the other Thai rivers playing a fundamental role.

CONCLUSIONS

The mapping methodology presented in this work stands as an experimental method to draw isobathymetric maps by means of molluscan faunas data. As previously stated, the maps bear a small-scale validity only, due to both the scarcity of sampling sites and the necessary use of approximations. These latter can be summarized as follows:

1) *timelines were not sampled in all sections*. The positioning of the timelines in the sections is necessarily an interpretation, depending from the availability of datable fossil levels;

2) *several timelines were placed by deduction*. Where fossil levels corresponding to timelines lacked, these latter were placed in most cases capitalizing on their peculiarities as regards faunal and sediment characteristics;

3) *some timelines were placed by assuming constant sedimentation rates*. This procedure was adopted for that timelines impossible to place by direct dating or ecological deduction;

4) *single paleodepth values were used*. The points on which isolines are based were attributed a single value within the depth range of the respective molluscan faunas; the choices, although made within restricted intervals and carefully weighted, were in any case arbitrary;

5) *interpolation was limited*. In order to minimize huge distortions, surely emerged areas during the Holocene transgression event were excluded from the interpolation.

Nevertheless, the reconstruction seems to be quite affordable when compared to other paleogulf maps obtained on different and independent data. A comparison can be made with the reconstructions made by Nutalaya & Rau (1981) on the Pleistocene-Holocene contact isopachs, and by Somboon (1990) and Somboon & Thiramongkol (1992) mainly on palynological data. Moreover, the presented interpretations appear to be coherent with data coming from recent Thai Quaternary geological surveys (cf. Negri, in press), in particular with regard to the extent of intertidal and brackish water sediments at the apex of transgression.

On the other hand, a relevant difference exists in respect to the above-cited paleomaps, i.e. the maximum extension reached by the sea in correspondence to the Chao Phraya axis. The northward invasion of the sea, even including the wide intertidal belt, seems to have stopped south of Bang Sai. So, the Holocene coastline - according to malacological data - should not have reached the latitude of the ancient Thai capital Ayutthaya. This could require a different interpretation of some archaeological evidences that seemed to depict the city as a marine harbor

sometimes during its history; however, a conclusion in this respect requires much more exhaustive studies, which are well beyond the proposals of this work.

ACKNOWLEDGEMENTS

This paper follows the presentation of the work at the meeting “VII Giornate di Paleontologia”, held in Barzio (Lombardy, Italy) from June 6th to 10th, 2007. It derives from studies on material obtained from several research campaigns in Thailand; in this respect, logistic facilities and support during fieldwork provided by the Geological Survey Division, Department of Mineral Resources, Bangkok, Thailand, mainly in the person of Dr. Niran Chaimanee, are acknowledged. I kindly thank Prof. Elio Robba (University of Milano-Bicocca) for hints and suggestions, and Prof. Daniela Basso (University of Milano-Bicocca) for help in statistical treatment of base data. I am very grateful to suggestions offered by the reviewers in the formal reviews of the paper.

REFERENCES

- Chonglakmani C., Ingavat R., Piccoli G. & Robba E. (1983). The last marine submersion of the Bangkok Area in Thailand. *Memorie di Scienze Geologiche*, 36: 343-352.
- Dheeradilok P., Chaimanee N., Piccoli G. & Robba E. (1984). On the Quaternary stratigraphy and fossils of Senanivate housing project area, Bangkok Metropolis. *Memorie di Scienze Geologiche*, 36: 413-426.
- Di Geronimo I., Sanfilippo R. & Chaimanee N. (2002). The Quaternary Fauna from Ban Pak Bo (Western Thailand). In Mantajit N. (ed.), *Proceedings of the Symposium on Geology of Thailand*, DMR, Bangkok: 342-349.
- Hanebuth T., Statterger K. & Groote P.M. (2000). Rapid flooding of the sunda shelf: a late-glacial sea-level record. *Science*, 288: 1033-1035.
- Hayasaka S. (1961). The Geology and Paleontology of the Atsumi Peninsula, Aichi Prefecture, Japan. *Science Reports of the Tohoku University*, ser. 2 (Geology), 33 (1): 1-103.
- Lambeck K., Yokoyama Y. & Purcell T. (2002). Into and out of the Last Glacial Maximum: sea-level change during Oxygen Isotope Stages 3 and 2. *Quaternary Science Reviews*, 21: 343-360.
- Miller A.I., Holland S.M., Meyer D.L. & Dattilo B.F. (2001). The Use of Faunal Gradient Analysis for Intraregional Correlation and Assessment of Changes in Sea-Floor Topography in the Type Cincinnati. *The Journal of Geology*, 109: 603-613.
- Negri M.P. (2002). L'evoluzione olocenica della Lower Central Plain di Bangkok (Tailandia) sulla base delle faune fossili a molluschi. PhD thesis, Università degli Studi di Milano, Italy.
- Negri M.P. (in press). The fossil mollusk-faunas: their bearing on the Holocene evolution of the Lower Central Plain of Bangkok (Thailand). *Journal of Asian Earth Sciences*. doi:10.1016/j.jseas.2009.04.003
- Nutalaya P. & Rau J.L. (1981). Bangkok: the sinking metropolis. *Episodes*, 1981 (4): 3-8.
- Pérès J.-M. (1982). Structure and dynamics of assemblages in the Benthic. In Kinne O. (ed.), *Marine Ecology 5, Ocean Management, Part I*, John Wiley & Sons: 119-180.
- Pérès J.-M. & Picard J. (1964). Nouveau manuel de bionomie benthique de la Mer Méditerranée. *Recueil des Travaux de la Station Marine d'Endoume*, 31: 1-137.
- Picard J. (1965). Recherches qualitatives sur les biocoenoses marines des substrats meubles dragables de la région marseillaise. *Recueil des Travaux de la Station Marine d'Endoume*, 52: 3-160.
- Robba E., Chaimanee N., Dheeradilok P., Jongkanjanasontorn Y., Piccoli G. & Pilo Boyl A. (1993). Late Quaternary molluscan communities from the Bangkok Clay, Thailand. *Proceedings Biostratigraphy of Mainland Southeast Asia: Facies & Paleontology*: 427-437.
- Robba E., Di Geronimo I., Chaimanee N., Negri M.P. & Sanfilippo R. (2002). Holocene and recent shallow soft-bottom mollusks from the Northern Gulf of Thailand area: Bivalvia. *Bollettino Malacologico*, 38 (5-8): 49-132.
- Robba E., Di Geronimo I., Chaimanee N., Negri M.P. & Sanfilippo R. (2004). Holocene and recent shallow soft-bottom mollusks from the Northern Gulf of Thailand: Scaphopoda, Gastropoda, additions to Bivalvia. *La Conchiglia, International shell magazine*, year 35, suppl. 309: 1-290.
- Robba E., Di Geronimo I., Chaimanee N., Negri M.P. & Sanfilippo R. (2007). Holocene and recent shallow soft-bottom mollusks from the Western Gulf of Thailand: Pak Phanang Bay and additions to Phetchaburi fauna. *Bollettino Malacologico*, 42 [2006], suppl. 6: 1-98.
- Sato Y., Saito Y. & Suzuki Y. (2000). Molluscan assemblages for reconstruction of Late Quaternary sea-level change, lower central plain, Thailand. In Sinsakul S., Chaimanee N., Tiypairach S. (eds.), *Proceedings of the Comprehensive Assessments on Impacts of Sea-Level Rise*, Geological Survey Division, DMR, Bangkok: 110-119.
- Scarponi D., Kaufman D., Bright J. & Kowalewski M. (2008). Quantifying time-averaging in 4th-order depositional sequences: radiocarbon-calibrated amino-acid racemization dating of Late Quaternary mollusk shells from Po Plain, Italy. *Geological Society of America Abstracts with Programs*, 40 (6): 502.
- Scarponi D. & Kowalewski M. (2004). Stratigraphic paleoecology: Bathymetric signatures and sequence overprint of mollusk associations from upper Quaternary sequences of the Po Plain, Italy. *Geology*, 32 (11): 989-992.
- Somboon J.R.P. (1988). Paleontological study of the recent marine sediments in the lower central plain, Thailand. *Journal of Southeast Asian Earth Sciences*, 2 (3-4): 201-210.
- Somboon J.R.P. (1990). Geomorphology of the Chao Phraya Delta, Thailand. Ph.D. thesis, University of Kyoto, Japan.
- Somboon J.R.P. & Thiramongkol N. (1992). Holocene highstand shoreline of the Chao Phraya delta, Thailand. *Journal of Southeast Asian Earth Sciences*, 7 (1): 53-60.

Manuscript received 20 August 2007

Revised manuscript accepted 23 April 2009