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Original Research

Diatom Assemblages in 26 December 2004 Tsunami Deposits from Coastal Zone of Thailand as Sediment Provenance Indicators

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Abstract

Tsunami deposits are often characterized by specific diatom assemblages, which may indicate sediment provenance and help identify paleotsunami deposits. In the present study diatom assemblages were studied in tsunami deposits left by the 2004 tsunami in Thailand, as well as in beach sediments, inner shelf marine sediments and freshwater ponds and streams. The assemblages in tsunami deposits had chaotic structure and consisted of species found in all the studied habitats, suggesting erosion of terrestrial and marine sediments by tsunami. The diatom frustules in tsunami deposits were generally rare and often damaged due to excessive wave force. The most common identified species were *Amphora turgida* Gregory, *Cocconeis scutellum* Ehrenberg, *Diplomenora cocconeiformis* (Schmidt) Blazé, *Eunotogramma marinum* (W. Smith) Peragallo (typical for benthos of marine and brackish environments), and taxa common in freshwaters, including *Cyclotella ocellata* Pantocsek, *Cocconeis placentula* Ehrenberg and *Encyonema silesiacum* (Bleish) D.G. Mann.

Keywords: diatoms, tsunami deposits, inner shelf, provenance, Andaman Sea

Introduction

Tsunami waves, as proved by the recent 26th December 2004 event, are serious natural hazards [1]. So, it is of the highest importance to learn about tsunami origin, propagation, run-up and its frequency. Some answers on at least two latter points may be gained from tsunami deposits left onshore. Their composition and structure may help to identify sediment source areas and sedimentation processes during tsunami run-up and backwash [2-4]. On the other hand, the occurrence of tsunami deposit layers in geological sequence may also indicate an approximated recurrence period of tsunami waves on a given coast [5, 6]. However, it is often difficult to distinguish between deposits of different origin (e.g. tsunami and storm deposits) [7-9]. Several studies have already shown that diatom assemblages serve as a useful tool in identifying of tsunami deposits as they form chaotic structured assemblages containing species from various distinctive habitats [10-14].

On December 26, 2004 a large tsunami, generated by a strong earthquake, devastated coasts around the Indian Ocean, causing considerable changes in shoreline and strong disturbances both in aquatic and terrestrial ecosystems [15-17]. A tsunami often leaves behind a characteristic sediment

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layer on land [18-22]. Several studies focused on microfossils from sediments deposited in different regions by the 2004 tsunami [23-25]. However, diatoms were studied only by Razzhigaeva et al. [26] in Indonesia. The present study was undertaken to describe the diatom assemblages from tsunami sandy deposits in Thailand. Samples for reference were subsequently collected also from beaches, the inner continental shelf and freshwater environments.

The primary objectives of the study were:

1) To identify typical diatom assemblages for tsunami deposits in Thailand; this finding proved be helpful in future search for paleotsunami at the Andaman Sea coast, as at present there are no records of historical tsunamis there.
2) To identify potential sources of tsunami deposits through comparative analysis of assemblages from different habitats.

Material and Methods

Samples (N=28) of tsunami deposits from the area flooded in 2004 were collected during a field survey in February 2005 from five areas: two near Nham Kem (Bang More and southern Kho Khao), one on Pakarang Cape and two around Patong Bay (Patong and Tri Trang) on Phuket Island (Fig. 1). Except for one site, the whole tsunami deposit layer was collected. Moreover, sediment samples from three beaches were collected at the same time. Samples of marine sediments (N=5) were taken during a February 2006 survey using a standard grab sampler from five stations along the offshore transect. Diatom samples from freshwater ponds and creeks (N=45) were collected from water and submerged objects (branches, stones etc.) during field surveys in 2007 and 2008.

All the samples were prepared for diatom identification according to Battarbee [27]. Identification of diatom species was conducted under a light microscope with Nomarskii contrast at 1000x magnification with reference to Witkowski et al. [28], Snoeijs [29-33] and Krammer and Lange Bertalot [34-37]. Due to a very low abundance of diatoms only qualitative analyses were conducted. The classification of ecological habitats of diatoms was based on Van Dam [38], Denys [39], and Witkowski et al. [28].

Results

Diatoms Found in Tsunami Deposits

Altogether 60 diatom taxa (Table 1) from tsunami sandy deposit samples were identified. Concentration of diatom frustules in slides was very low. Moreover, often only damaged frustules were observed. The diatom flora was represented by taxa of different origin: marine, brackish and freshwater. Almost half of identified species were typical marine diatoms. Four taxa were classified as brackish to marine or brackish to freshwater species. The remaining 20 taxa were typical of freshwater or freshwater to brackish environments (with an optimum in fresh waters but tolerant

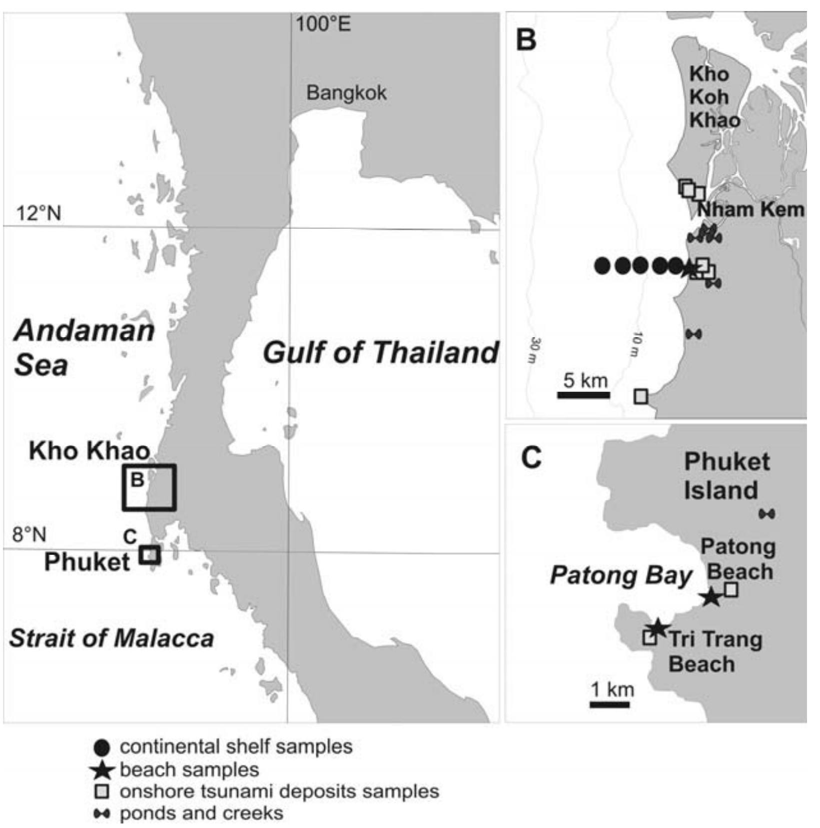

Fig. 1. Location of sample sites within the study area.

toward slightly brackish water conditions). It is worth indicating that 19 taxa within those from tsunami sediments were identified earlier in marine sediments (Table 2). Assemblages of marine, brackish and freshwater diatoms were observed at all sites. Among marine species both planktonic and benthic forms were present. The most commonly observed planktonic diatoms were *Actinoptychus senarius* and *Thalassiosira oestrupii* cosmopolitan species typical of warm marine waters. A number of species identified as benthic forms occurred in a shallow nearshore zone of littoral, such as: *Eunotogramma marinum* typical of marine, sandy littoral, *Delphineis surirelloides* and *Diploneis cafra* widely known from warm coastal waters or *Diplomenora cocconeiformis, Amphora turgida,* and *Plagiogramma pulchellum* var. *pygmeum,* also common in shallow nearshore zones. Among freshwater diatoms we observed both planctonic, e.g. *Cyclotella atomus, C. praetermissa, C. radiosa* and *Tabellaria flocculosa,* and benthic species, e.g. *Brachysira brebissoni, Cocconeis neothumensis, Navicula capitatoriadia, Navicula cryptotenella, Nitzschia dissipata* and *Nitzschia incospicua,* as well as forms representing both benthic and epiphytic habitats, e.g. *Gomphonema parvulum*.

Diatoms Found in Marine Sediments

In five samples collected along a 12km long marine transect across the inner shelf of Nam Kem area over 80 taxa were identified (Table 2). The highest number of species was observed within genera: *Amphora, Diploneis, Nitzschia* and *Thalassiosira*. The identified taxa were typical planktonic species, e.g.: *Actinocyclus octonarius, Actinoptychus senarius, Pleurosigma sp., Thalassiosira anguste-lineata, T. leptopus, T. oestrupii* and *T. pacifica*. Among benthic taxa were species typical of shallow sandy littoral zones such as: *Amphora commutata, Amphora pseudoholsatica, Eunotogramma marinum, Delphineis surirelloides, Psammodictyon panduriforme* and taxa typical for a more inner shelf (up to 21.5m depth), among others: *Amphora acuta, A. acutiscula, A. bigibba, A. coffeaeformis, Diploneis chersonensis, Diploneis didyma, D. nitescens, D. smithii, Fragillaria improbula, Lyrella hennedyi* and *L. spectabilis*.

Diatom Found in Freshwater Ponds and Creeks

Over 90 diatom taxa were indentified in 45 samples collected from ponds and creeks. In samples from sites unaffected by tsunami waves only freshwater and brackish taxa were observed, for example: *Cocconeis placentula* Ehrenberg, *Frustulia rhomboides* (Ehrenberg) De Toni, *Navicula cryptotenella* Lange-Bertalot, *Nitzschia dissipata* (Kützing) Grunow, *Sellaphora pupula* (Kützing) Mereschowsky, *Stauroneis phoenicenteron* (Nitzsch) Ehrenberg and numerous representatives of *Pinularia sp.* Ehrenberg and *Cyclotella sp.* Kützing genera. In contrast, in samples collected from ponds flooded by tsunami waves, frustules of marine diatoms were observed along with freshwater species, e.g., *Amphora psedoholsatica*, *Eunotogramma marinum, Mastogloia elliptica* (C.A. Agardh) Cleve, *M. smithii* Thwaites, *Nitzschia liebetruthii* and *Seminavis sp*. D.G. Mann. However, it must be pointed out that cells of marine diatoms were generally devoid of chloroplasts, indicating that they were transported by tsunami waves. Therefore, living populations of these species probably do not exist in these habitats.

Discussion

Diatom assemblages in the studied tsunami deposits had characteristic structure. Such assemblages composed of marine, brackish and freshwater diatoms are describe as having 'chaotic' structure in the literature [14]. The findings presented are fully in line with data showing chaotic assemblages of diatoms in tsunami deposits from Scotland, Canada and Papua New Gwinea [12, 14, 40].

In the present work the chaotic diatom composition was particularly well represented in tsunami deposits collected in transect from the Bang More. They included both typical marine species transported by tsunami waves and freshwater diatoms incorporated by backwash, which passed over terrestrial freshwater reservoirs and artificial ponds in that area. Ponds and depressions were formed by long lasting tin mining activity, common on the coastal plain of the Andaman Sea. As shown in the study, the backwash-enriched tsunami deposits included a significant number of freshwater species, such as pelagic *Cyclotella praetermissa,* benthic *Brachysira brebissonii* or *Frustulia rhomboides* typical of mentioned freshwater reservoirs. It is important to note that in a potential search for paleotsunami, freshwater species will be not so numerous in the hypothethical paleotsunami deposits because the freshwater reservoirs were probably much less common in the past in this region.

The frequent occurrence of the typical marine benthic species *Diplomenora cocconeiformis, Eunotogramma marinum* and pelagic *Thalassiosira oestrupii* within tsunami sediments (located at times almost 500 m inland) proved significant sediment transport from marine environment. Most of the identified marine species in tsunami sediments were characteristic of sandy littoral. Investigation of diatom flora of marine sediments confirmed the presence of these species in this habitat. These results show that particularly the nearshore part of the coastal zone was heavily eroded and provided an important source of tsunami deposits.

Another characteristic feature of tsunami sandy deposits is a high percentage of broken valves, which is ascribed to high turbulence during the sediment transport. According to Dawson [14], they may contribute over 75% of the total number of observed valves, phenomenon also known from previous studies by Dominey-Howes et al. [41]. Also in the present study, damaged valves were very frequent in all investigated samples. Similarly to earlier studies [e.g. 11, 12, 40] in our work it was shown that some species are more resistant to erosion and breakage, especially those belonging to centric diatoms. The most common species from this group observed in our samples were:

Table 1. Diatom taxa found in tsunami deposits in the studied areas.

Taxon	Pakarang (N=4)	Bang More (N=7)	Patong (N=7)	Tri Trang (N=3)	Kho Khao (N=7)	Habitat
1	2	3	4	5	6	7
Planothidium engelbrechtii (Cholnoky) Round et Buktiyarova		*				b-m B
Achnanthidium minutissimium (Kützing) Czarnecki					*	f-b B
***Actinoptychus senarius* (Ehrenberg) Ehrenberg**	*				*	**m P**
Achnathes sp. Bory		*				f-b B
***Amphora acutiuscula* Kützing**				*	*	**m-b B**
***Amphora coffeaeformis* (C.A. Agardh) Kützing var. coffeaeformis**				*		**m-b B**
Amphora delicatissima Kraske		*				m B
***Amphora pseudoholsatica* Nagumo et Kobayasi**				*		**m-b B**
Amphora turgida Gregory			*	*	*	m B
***Amphora* sp. 1**		*				**m B**
***Amphora* sp. 2**	*				*	**m B**
***Anaulus minutus* Grunow**		*				**m B**
Astartiella bahuensoides (Foged) Witkowski, Lange-Bertalot & Metzeltin		*				m B
Astartiella sp.1			*	*		m B
***Astartiella* sp. 2**		*		*		**m B**
Asterionella formosa Hassall					*	f-b P
Brachysira brebissoni Ross		*				f B
Cocconeis neothumensis Kramer		*				f B
Cocconeis placentula Ehrenberg	*		*	*	*	f-b B
Cocconeis sp. Ehrenberg		*				f-b B
Cyclotella atomus Hustedt		*				b-f P
Cyclotella ocellata Pantocsek	*					f P
Cyclotella praetermissa Lund		*				f P
Cyclotella radiosa (Grunow) Lemmermann			*		*	f-b P
Encyonema silesiacum (Bleish) D.G. Mann	*					f-b B
Delphineis minutissima (Hustedt) Simonsen		*				m B
***Delphineis surirelloides* (Simonsen) Andrews**					*	**m B**
***Diplomenora cocconeiformis* (Schmidt) Blazé**	*	*			*	**m B**
***Diploneis* cf. *caffra* (Giffen) Witkowski, Lange-Bertalot & Metzeltin**	*				*	**m B**
***Diploneis didyma* (Ehrenberg) Cleve**					*	**m B**
***Diploneis* sp. Ehrenberg**				*	*	**m B**
***Diploneis vacillans* (A. Schmidt) Cleve**				*		**m B**
Eunotia sp Ehrenberg.		*				f B
***Eunotogramma marinum* (W. Smith) Peragallo**	*	*				**m B**
***Eunotogramma* sp. (Weisse)**	*	*	*			**m B**

Table 1. Continued.

1	2	3	4	5	6	7
***Fallacia* sp. A. J. Stickle & D.G.Mann in Round et al. 1990**			*		*	**m B**
Fragilaria brevistriata Grunow	*					f-b P
Fragilaria construens (Ehrenberg) Grunow	*					f-b P
Frustulia rhomboides (Ehrenberg) De Toni					*	f B
Gomphonema angustum Agardh.					*	f-b B
Gomphonema parvulum Kützing					*	f-b B
Navicula capitoradiata Germain					*	f-b B
Navicula cryptotenella Lange-Bertalot					*	f-b B
Navicula sp. Bory				*		f B
***Nitzschia laevis* Hustedt**				*		**f-b B**
***Nitzschia* cf. *liebetruthii* Rabenhorst**		*				**m B**
Nitzschia morosa Cholnoky			*			m B
Nitzschia dissipata (Kützing) Grunow					*	f-b B
Nitzschia inconspicua Grunow		*				b-f B
Nitzschia palea Kützing					*	f-b B
Nitzschia sp. 3 Hassal					*	f B
***Plagiogramma* cf. *pulchellum* var. pygmaeum (Greville) Peragallo**	*				*	**m P**
Planothidium cf. *dispar* (Cleve) Witkowski & Lange-Bertalot		*				b B
Planothidium engelbrechtii (Cholnoky) Round & Bukhtiyarova						b-m B
Rhaphoneis surirella (Ehrenberg) Grunow		*				m B
Rhaphoneis sp. Ehrenberg	*	*	*		*	m B
***Staurosira construens* (Ehrenberg) Grunow**		*				**f B**
Tabellaria flocculosa (Roth) Kützing		*				f P
***Thalassiosira leptopus* (Grunow) Hasle & Fryxell**				*		**m P**
***Thalassiosira oestrupii* (Ostenfeld) Hasle**		*			*	**m P**

(f) – freshwater, (f-b) – freshwater-brackish, (b) – brackish, (m) – marine, (B) – benthic, (P) – pelagic
In bold are labeled species identified also in marine sediments.

Eunotogramma marinum and *Plagiogramma pulchellum* var. pygmeyum. Surprisingly, damage was also done to valves of centric diatoms from *Thalassiosira genera*. The most resistant species frequently observed in many samples was *Diplomenora cocconeiformis* belonging to araphid diatoms.

Despite the small numbers of diatoms in assemblages from tsunami and marine sediments, a high diversity of diatom assemblages in terrestrial reservoirs was observed. Occurrence of some brackish and marine species in these water basins is attributed to tsunami waves. Elevated salinity of its waters may support the existence of some taxa related to marine environments. However, our study showed that although they were transported by tsunami waves, their populations probably did not develop. On the other hand, due to lack of pre-tsunami studies on coastal freshwater bodies, more studies on live microphytobenthos are crucial to assess properly both the ability of brackish and marine taxa to exist in such conditions, as well as the length of coastal basin recovery periods.

Conclusions

The present study shows one of the first attempts to study diatoms in potential source areas and in deposits left by the 2004 Indian Ocean tsunami in Thailand. Diatom assemblages in sandy tsunami deposits reflect the unique sedimentation processes and sediment source patterns associated with deposition of the material transported in turbulent, high-energy conditions by tsunami waves. The assemblages were deficient in taxa and consisted of damaged frustules.

Table 2. Diatom taxa found in marine sediments at different depths.

	Sampling sites				
Taxon /water depth [m]	**2.5**	**8.5**	**12**	**14**	**21.5**
1	2	3	4	5	6
Achnantes cf. *danica* (Fogel) Grunow					*
Achnanthes cf. *lorenziana* Bory					*
Achnanthes sp. Bory				*	
Achnanthes sp. 1				*	
Actinocyclus octonarius Ehrenberg				*	
Actinoptychus senarius (Ehrenberg) Ehrenberg		*			
Amicula specululum (Witkowski) Witkowski	*				
Amphora acuta Gregory					*
Amphora acutiuscula Kützing					*
Amphora bigibba Grunow var. interrupta Grunow					*
Amphora cf. *grassa* Gregory				*	*
Amphora coffeaeformis (C.A. Agardh) Kützing var. coffeaeformis					*
Amphora commutata Grunow			*		
Amphora costata W. Smith					*
Amphora cf. *lunata* Óstrup					*
Amphora pseudoholsatica Nagumo et Kobaysi			*		
Amphora eunotia Cleve				*	
Amphora sp. 1			*		
Amphora sp. 2			*		
Amphora sp. 3					*
Anaulus minutus Grunow	*				
Astartiella sp.Witkowski, Lange-Bertalot & Metzeltin			*		
Caloneis cf. *bicuneata* (Grunow) Wolle				*	
Caloneis egena (A. Schmidt) Cleve		*		*	
Campylodiscus sp. Ehrenberg		*			
Cocconeis cf. *disculoides* Hustedt				*	
Cocconeis scutellum Ehrenberg					*
Cocconeis sp. C.G.Ehrenberg				*	
Delphineis surirelloides (Simonsen) Andrews			*	*	
Diplomenora cocconeiformis (Schmidt) Blazé	*	*			
Diploneis cf. *caffra* (Giffen) Witkowski, Lange-Bertalot & Metzelin			*	*	
Diploneis chersonensis (Grunow) Cleve					*
Diploneis didyma (Ehrenberg) Cleve					*
Diploneis sp. Ehrenberg			*	*	
Diploneis cf. *litoralis* var. clathrata Óstrup					*
Diploneis nitescens (Gregory) Cleve					*
Diploneis smithii (Brébisson) Cleve					*
Diploneis vacillans (A. Schmidt) Cleve var. vacillans			*	*	
Diploneis vacillans (A. Schmidt) Cleve var. renitens A. Schmidt				*	

Table 2. Continued.

1	2	3	4	5	6
Diploneis weissflogii (A. Schmidt) Cleve		*		*	
Eunotogramma marinum (W. Smith) Peragallo	*			*	*
Eunotogramma sp. Weisse	*				
Fallacia forcipata (Greville) Stickle & D.G.Mann	*				*
Fallacia pygmaea (Kützing) Stickle & D.G.Mann					*
Fallacia scaldensis Sabbe & Muylaert	*				
Fallacia sp. A. J. Stickle & D.G.Mann			*		
Fragillaria improbula Witkowski & Lange-Bertalot					*
Fragilaria sp.1	*				
Fragilaria sp.2		*			
Fragilariopsis sp. Hustedt	*				
Hyalodiscus scoticus (Kützing) Grunow	*				
Grammatophora oceanica Ehrenberg				*	*
Lyrella hennedyi (W. Smith) Stickle & D.G. Mann					*
Lyrella spectabilis (Gregory) D.G. Mann					*
Lyrella sp. Karayeva				*	*
Mastogloia cf. cyclops Voigt					*
Mastogloia sp. Thwaites				*	
Navicula sp. Bory			*		
Nitzschia sp. 1					*
Nitzschia laevis Hustedt	*				
Nitzschia liebetruthii Rabenhorst					*
Nitzschia sp.1	*				
Nitzschia sp.2	*				
Nitzschia sp.3		*			
Nitzschia sp.4					*
Petroneis marina (Ralfs) D.G. Mann					*
Pinnularia cf. *quadratarea* (A. Schmidt) Cleve					*
Planothidium cf. *dispar* (Cleve) Witkowski & Lange-Bertalot					*
Planothidium polaris (Ǿstrup) Witkowski & Lange-Bertalot					*
Plagiogramma cf. *pulchellum* var. pygmaeum (Greville) Peragallo & Peragallo	*				
Pleurosigma sp. W. Smith		*			
Psammodictyon cf. *panduriforme* (Gregory) D.G. Mann				*	*
Staurosira construens var. venter (Ehrenberg) Hamilton	*				
Synedra fasciculata Kützing					*
Thalassiosira anguste-lineata (A. Schmidt) Fryxell & Hasle					*
Thalassiosira cf. eccentrica (Ehrenberg) Cleve		*			
Thalassiosira leptopus (Grunow) Hasle &t Fryxell		*			
Thalassiosira oestrupii (Ostenfeld) Hasle		*		*	*
Thalassiosira pacifica Gran & Angst				*	

Their structure was chaotic due to the co-existence of diatoms transported by tsunami waves from various freshwater, brackish and marine habitats. Among diatom identified in tsunami deposits, the most common were marine species, suggesting that the primary erosion zone was the shallow, nearshore zone. The set of features typical of tsunami deposits common for samples from various locations along the coast, makes them a reliable proxy for identifying paleo-tsunami records.

The study also demonstrates the occurrence of brackish and marine species in freshwater basins in flooded areas indicating the impact of a tsunami event on environmental conditions of these reservoirs

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