Soft Sediment Deformation Structures in the Andaman Flysch Group, Andaman Basin: Evidence for Palaeogene Seismic Activity in the Island Arc

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ABSTRACT

The Andaman Flysch Group is represented by four sedimentary facies: thick sandstone, thin sandstone, heterolith and shale. They were observed in seven outcrops in the Andaman Islands. Soft sediment deformation features like slumps structure/folds, convolute bedding or lamination, load and flame structures, pseudo nodules/ball and pillow structures and dish and pillar structures have been observed with regularity in these facies and independent of facies specifics. The slumps structure/folds, convolute bedding or lamination encased by undeformed beds, sand volcanoes and some load casts/pseudo-nodules shows evidence of being triggered by earthquakes in this convergent margin basin.

Keywords: *Andaman, Palaeogene, Island Arc, soft sediment deformation structures*

INTRODUCTION

The Andaman and Nicobar Islands represent an uplifted accretionary prism on the edge of a fore arc basin (Figures 1 & 2). It came into existence after the breakup of Gondwanaland, the northward movement of the Indian plate, its anticlockwise rotation and its impingement beneath the Sunda plate since Late Cretaceous time (Roy, 1992; Roy and Das Sharma, 1993). The major tectonic elements have been described from west to east as: outer arc, Andaman trench, accretionary prism, trench slope break or structural high, forearc, volcanic arc and back-arc with a spreading centre (Roy, 1992; Curray, 2005) [Figure 1]. A standardized stratigraphy of the basin, based on outcrops on the Andaman Islands, exemplifies the vertical and lateral variation in lithofacies succession (Roy, 1983; Pal et al., 2003) [Table 1]. In this sedimentary pile, ranging from Late Cretaceous-Recent, the Andaman Flysch Group, a deep marine, Late Eocene-Oligocene, siliciclastic sequence, is increasingly attracting attention for hydrocarbon exploration in view of its widespread occurrence, large volume and distinctive lithology with possibilities for reservoir occurrence all along the island arc chain and in the adjoining forearc (Figure 2).

In North-, Middle- and South-Andaman Islands, the outcrops were studied in detail in seven positions in near vertical dipping sections for sedimentary structures, facies, bed geometry and lateral facies variation (Figure 2 and Table 2). Four sedimentary facies have been identified within the flysch, which show a distinct reduction in grain size from north to south parallel to the arc chain. Observed sedimentary structures like planar laminae, ripple - cross laminae, contorted beds, flame structures, flute marks, prod and groove marks and burrows have aided in identifying gravity flow processes within the Andaman Flysch (Roy and Banerjee, 2011). Within the facies, soft sediment deformation structures (SSDS) e.g. slump structure/folds, convolute lamination or bedding, pseudo-nodules, load and flame structures, dish and pillar structures have a distinguished presence, both laterally and vertically. This paper describes the deformation features in the Andaman Flysch, discusses their genesis, reveals linkage to or independence from facies, spatial and temporal occurrence of the indicated deformation types and possible connection between some of the deformation features and documented seismic activity.

SOFT SEDIMENTARY DEFORMATION STRUCTURES (SSDS) AND SEDIMENTARY FACIES

The term SSDS has been defined earlier by several workers, but leaves some ambiguity. One of the unifying definitions providing clarity is by Van Loon (2009), who says: *"soft-sediment deformation structures in clastic sediments are deformations that occur in still unlithified sediments or in sedimentary rocks that had not yet undergone lithification before the deformation structures started to be formed."* The implication as per this definition is that SSDS is an early diagenetic feature (Van Loon, 2009) or "it reflects products of deformational processes which

Table 1. *Stratigraphy of Andaman Basin (from outcrop data) [altered after Roy, 1983 & Pal et. al., 2003]*

Stratigraphic Unit	Age	Lithology
	Pleistocene to Recent	Beach, tidal flat deposits, mudstones, coral reefs, raised beaches
Unconformity		
Archipelago Group	Pliocene	Foraminiferal mudstones, calcareous sandstones, siltstones
Unconformity		
	Early-Mid. Miocene	White nannoforam chalk, volcanic ash, calcareous sandstones, mudstones, siltstones
Unconformity		
	Early Miocene	Calcareous sandstones, conglomerates, marl, siltstones
Unconformity		
Andaman Flysch Group	Late Eocene to Oligocene	Massive to planar-laminated, buff to light grey coloured fine to coarse-grained sandstones with or without clay clast and concretions. Sand-shale alternations, shale and conglomerates
Unconformity		
Mithakhari Group	Late Cretaceous to Palaeocene	Dark grey, compact shales. Coarse-grained, ophiolite-derived greenish sandstones and polymictic conglomerates with extraneous ophiolite clasts, mud clasts, sandstone and limestone clasts
Unconformity		
	Late Cretaceous	Pink radiolarian cherts, jaspers, quartzites, white limestones and marbles
Unconformity		
Ophiolite Group		Oceanic basement - ophiolite suite

affected sediments that were not yet lithified" (Mills, 1983; Collinson, 2003).

The Andaman Flysch was observed at seven outcrop positions on the Andaman Islands and soft sediment deformation structures (SSDS) were observed at several separated intervals, both spatially and temporally (Figure 2).

Slump Structure/Folds

In Area C (Figure 2), the slump structure occurs off centre as a fine–medium grained, massive 0.5m unit, overlain and underlain by undisturbed plane laminated sandstone and shales. The folds show vertical repeatability every 3-5m or, at the top of the section, around 18m above the described fold in sandstone beds. The asymmetric folds are around 10cm in height with the axis of slump overturned downslope. Laterally, in part, the slump is highly disturbed and the fold trace, undecipherable (Figure 4a).

In Area B (Figure 2), two consecutive, 2.5m of slump folds separated by undisturbed, plane parallel heterolith facies are laterally extensive throughout the outcrop (Figures 3a, b, c). The slumps occur in a heterolith section encasing fine-grained sandstone (0.2m). The asymmetrical, slumped bed, with high angle of overturn, is overlain and underlain by undisturbed, plane laminated heteroliths. In places, the slumped bed is faulted.

Convolute Lamination or Bedding

Convolute bedding has been observed frequently and periodically in a vertical stack of Andaman Flysch at in Area E (Figures 2 and 4d). They occur in all facies in the section namely the thick massive sandstone, heteroliths and shale facies, although they have been observed mostly in the heteroliths. In each case, the beds are highly disturbed and overlain and underlain by undisturbed, planer laminated heteroliths. The convolute lamination has bed sizes, usually ranging from 0.5 to 1.0m. The beds are highly deformed, contorted, disturbed and disrupted (Figure 4d). In some heteroliths, the convolute bedding is deformed into rolls, with asymmetric, overturned signatures towards the paleo-current direction (Figures 4e, f). Convolute lamination and high angled slump folds are observed in fine grained sandstone facies in Area D, South Andamans (Figures 2 & 5e).

Load and Flame Structures

An array of load casts has been observed in Area B (Figures 3d, e, f) in North Andamans, occurring in fine grained sandstone with thin shale partings or in the heteroliths in location E, South Andamans (Figure 4c) and at a sand shale interface in location F (Figure 5d). In North Andamans, the observed load casts were found in laterally continuous zones of lamination within one sandstone bed of 70cm, affecting a planar laminated bed. The pointed flames in this feature have not penetrated the overlying bed which again is a section of sandstone with thin shale partings (Figures 3d, e). Discontinuous lamination with load structure and flames not penetrating the upper bed was also observed (Figure 3f). Load structures and flames observed in the interface of siltstone and shale facies, in Area F where the shale were squeezed upwards due to the loading by the fine grained sand (Figure 5d).

Pseudo-nodules/Ball and Pillow Structures

Pendulous load casts, attached and detached nodules, flame structures in fine grained sandstone facies overlying a shale facies were observed in location F (Figure 5a). Detached pseudo-nodules (Owen, 2003) and ball and pillow structures in siltstone and shale facies were also observed in Area F, South Andamans (Figures 5b, c). Convolute

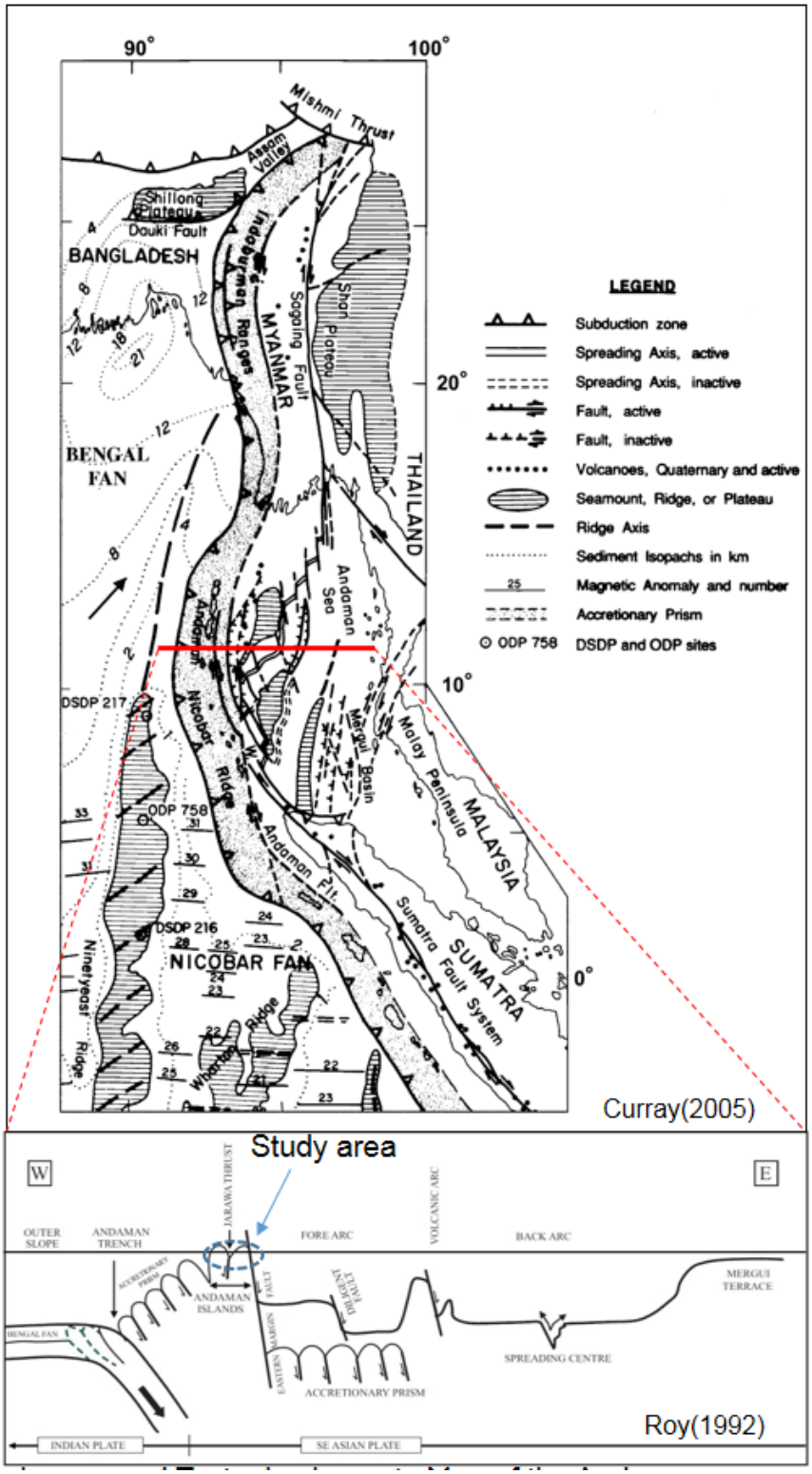


Figure 1. *Tectonic map and tectonic elements map of the Andaman Sea region (after Curray, 2005 & Roy, 1992)*

laminations were observed in the pseudo-nodules and they were stacked in multiple haphazard positions isolated within a matrix leading to expressions of ball and pillow structures (Figures 5b, c). They may also be expressed as pendulous load casts (Owen, 2003) with intervening flame structures widening upwards. Here the pseudo-nodules are detached and aligned along one plane in several layers (Figure 5f). The detached pseudo nodules show a chaotic internal structure (Figures 5b, c).

Sand Volcanoes/Burst through Structures

A sand volcano/burst through structure has been observed in a sequence of very fine sandstone and alternating heterolith facies, with isolated heteroliths lobes formed by sandstone dykes moving upwards due to upward escape of water (Figure 5f). Note that the sequence is inverted in Figure 5f. The central plug of sand from the sandstone facies below has cut through the heterolith facies above. The upward conical sand volcanoes have just stopped the juncture of the alternating sandstone facies at the top. The heterolith lobes appear to be rotated

***Table 2**. Interpreted genesis of deformation structures observed in various outcrops across North, Middle and South Andamans*

Fig No	Deformation structure	Area	Interpreted Genesis
3a	Slump structure/ folds	North Andamans	seismogenic
3b	Slump structure/ folds	North Andamans	seismogenic
3c	Slump structure/ folds	North Andamans	seismogenic
3d	simple load casts	North Andamans	
3e	simple load casts	North Andamans	
3f	pendulous load casts	North Andamans	
3g	dish structure	North Andamans	
3h	Flame structure	North Andamans	
4a	Convolute bedding	Middle Andamans	seismogenic
4b	Water escape structure	Middle Andamans	
4c	simple load casts	South Andamans	
4d	Convolute bedding	South Andamans	seismogenic
4e	Convolute lamination	South Andamans	seismogenic
4f	Convolute lamination	South Andamans	seismogenic
5a	Pendulous load casts, attached and detached Pseudonodules,	South Andamans	seismogenic
5b	Detached Pseudonodules	South Andamans	seismogenic
5c	Detached Pseudonodules	South Andamans	seismogenic
5d	Flame structure	South Andamans	
5e	Convolute lamination	South Andamans	
5f	Sand volcanoes	South Andamans	seismogenic

and intervening fine sandstone facies is disturbed. The example in Figure 5f is very similar to one described by Montenat et al. (2007). The rotated heterolith lobes are 1cm in height and 3cm in length (Figure 5f).

Dish and Pillar Structures

Dish structures were observed in massive sandstone facies in all the investigated outcrops, particularly at location B (North Andamans) and location E (South Andamans). Typically the dish features are 30-50cm in length and either singly concave or bi-concave. Associated pillar structures were marked by grooved, vertical surfaces of 20-40cm in length (Figure 4b). Typically in massive thick sandstones, the dish and the pillars occur singly.

Sedimentary Facies

In a very broad sense, the Andaman Flysch comprises thick sandstone facies (1-10m thick, fine to coarse grained, massive to plane laminated, often with concretions and clasts), thin sandstone facies (10-30cm thick, fine grained, tabular, with plane parallel lamination), heterolith/heterolithic facies (very fine sandstone/siltstone-shale alternations, 10cm – 1m thick with planar and cross laminations) and shale facies (hemipelagics, 10cm – 1m thick,

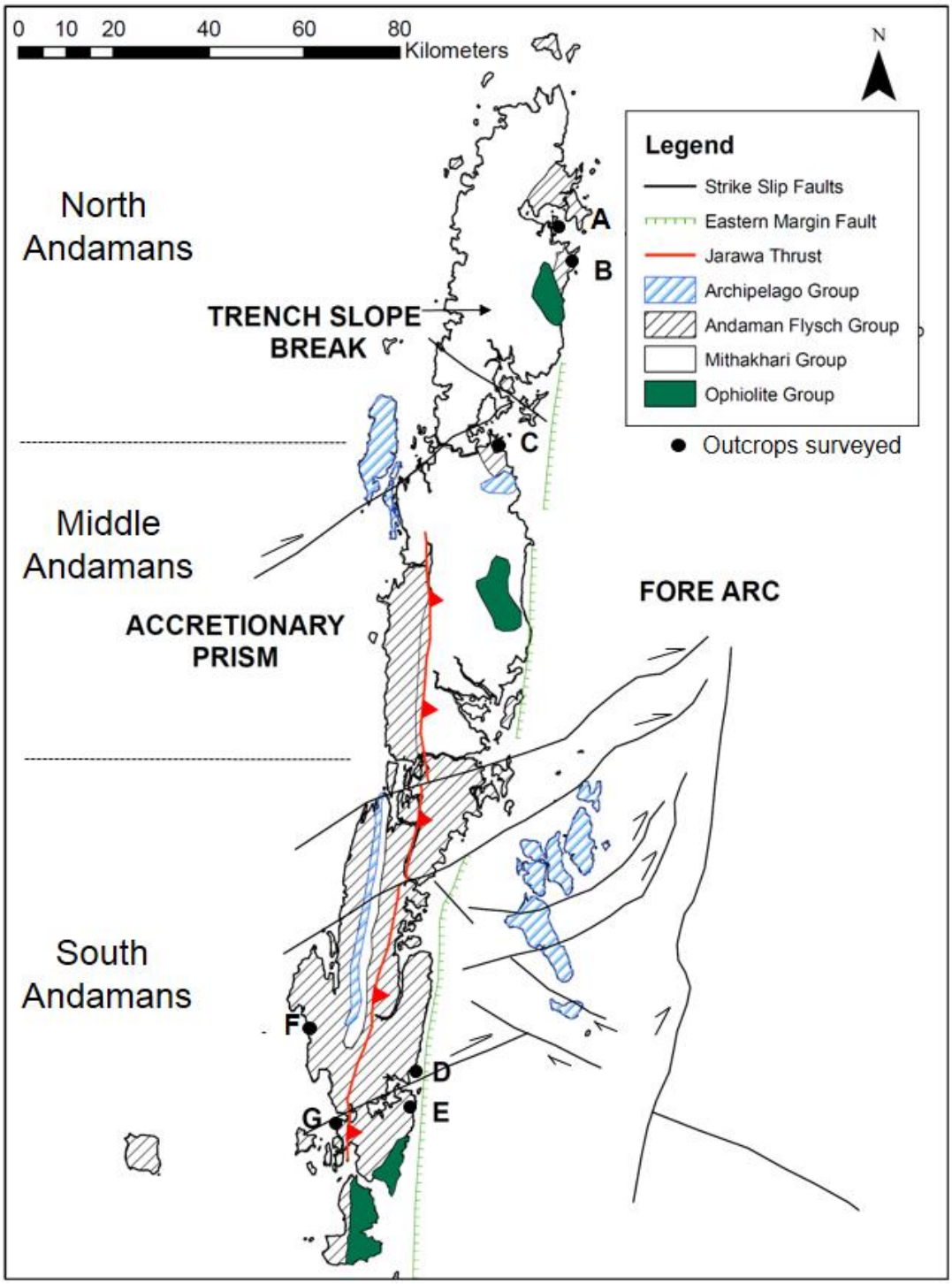


Figure 2. *Geological map of Andaman Islands with referred outcrop positions. Map altered after Roy and Chopra (1987), Roy and Das Sharma (1993) and Pal et al. (2003)*

plane laminated). Sediment deformation examples are not confined to single facies – they occur equally throughout all facies of the Andaman Flysch. Only the load structures, pseudo-nodules, ball and pillow structures and flame structures occur in the interface of thick sandstone facies overlying the shale facies. Convolute lamination, on the other hand, was observed in all facies in location E (Figure 2). Of particular note is that, beds having slump folds and convolute lamination were encased by completely undisturbed beds, which exhibited plane parallel lamination.

DISCUSSION

Simplistically, load structures comprise two main forms: load casts with flame structures and pseudo-nodules (see Allen, 1982 & Owen, 1987). The load casts with a continuous upper layer are divisible into simple and pendulous categories. The pseudo-nodules could either be attached, detached or create floating ball and pillow structures. In Andaman Flysch in Area A, flame structures emanate from below into a fine-grained sandstone which was squeezed upwards into an encompassing

conglomerate (Figure 3h) due to density loading and liquidization (Owen, 2003). Continuous laminations in attached load casts in a fine grained sandstone with flames remaining at the top of the bed, are simple and pendulous load casts (Figures 3d, e, f). Simple load structures in heteroliths caused shale to be squeezed up in the flame and in yet another case of load cast variety (Figure 4c) isolated by

by Owen (2003). Similarly, detached nodules and ball and pillow structures in which the sandstone balls are floating in a shale matrix are well exemplified in Figures 3b and 3c. The deformation mechanism, driving force and trigger required to cause the load structures, are attributed to stress exceeding the sediment strength due to liquidization (Owen, 2003). Concave upward dishes have been



Figures 3a, b, c. *Recumbent-folded and box-folded sandstone facies encased in shale facies. Note that the heterolithic facies above and below them are undisturbed and having plane parallel laminations.* ***Figs. 3d, e.*** *Simple and* ***(3f)*** *pendulous load casts in fine to medium-grained sandstone facies overlain by heterolithic facies.* ***Fig. 3g.*** *Dish structures in fine-grained sandstone.* ***Fig. 3h.*** *Flame structure of fine-grained sandstone (light shade) encased in conglomerate facies (dark shade). Note: Figs. 3a to 3g are from Area B, North Andamans. Fig. 3h is from Area A, North Andamans*

sandstone load structures while simple classical flames of shale formed between sandstone loads (Figure 3d). Pendulous load casts with 'sandstone bulbs' sinking into the underlying shale have been attached to the main sandstone facies above, by a narrow neck or if detached, form attached and detached pseudo-nodules (Figure 5a) as described

observed in thick, massive, sandstone beds which are attributed to dewatering processes, a resultant of expulsion of pore water from a bed. They are often caused by a thin clay barrier within the bed, which is exemplified by the coarse- to fine-grained sandstones of the Andaman Flysch. Slump folds can occur due to post seismic liquefaction or

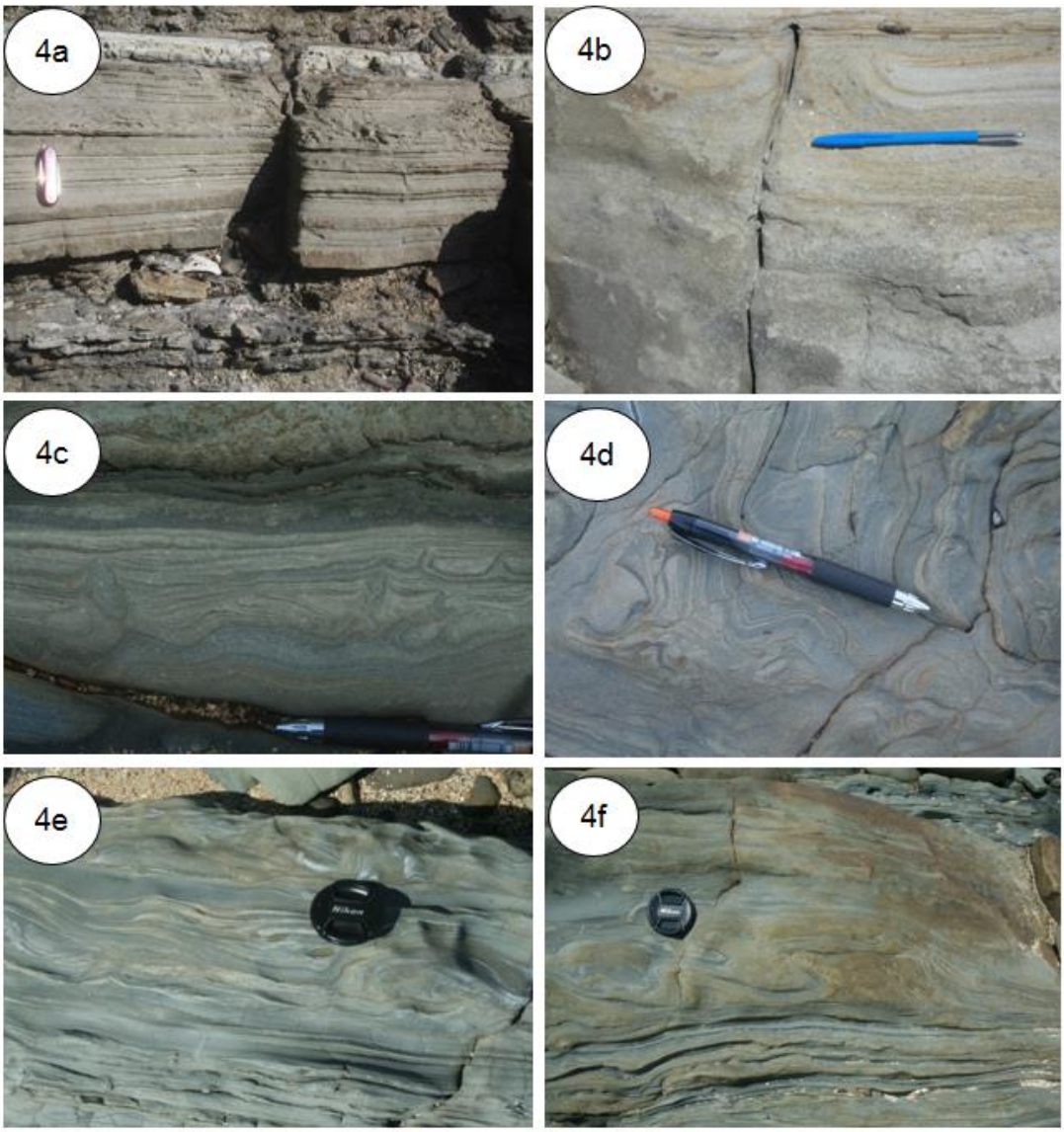


Figure 4a. *Convolute bedding in fine-grained sandstone. Note that the beds above and below show parallel lamination.* ***Fig. 4b.*** *Water escape structures with pipes in very fine-grained sandstone.* ***Fig. 4c.*** *Simple load cast in sand-shale/ heterolithic facies with a portion of shale being squeezed up and cut off by the sandstone load structures.* ***Fig. 4d.*** *Convolute bedding in heterolithic facies.* ***Figs. 4e, f.*** *Convolute laminations, recumbent folds within sand-shale heterolithic facies. Note: Figs. 4a, b are from Area C, Middle Andamans and Figs. 4c to 4f are from Area E, South Andamans*

gravitational collapse of under-consolidated sediments (Mills, 1983). The sand volcanoes show release of pore water pressure from a liquefied unit, possibly following a shock (Collinson et al., 2006). In a sequence of alternating heterolith and sandstone facies, the sands have moved up a dyke, cutting through the heterolith above and then stopped. Dewatering and upward escape of water through the sand is attributed to shocks. Three series of sand volcanoes (Figure 5f) in quick vertical succession are ascribed to shocks occurring in quick, rapid successions.

Criteria for Seismites; Their Triggering Mechanisms

Triggering mechanisms to deform unconsolidated sands are ground water movements, wave action and seismic shaking (Owen, 1987). Soft sediment deformation structures are usually attributed to deformation mechanism linked to fluidization or liquefaction (Owen, 1987; Owen and Moretti, 2011). Liquefaction in soft sediment deformation can be caused by seismic shaking, effects of water waves, rapid sediment accumulation and ground water movements triggered by seismic shaking (Owen and Moretti, 2011). Soft sediment deformation studies have proposed criteria for recognizing “seismites”, as products formed due to seismically induced liquefaction. Owen and Moretti (2011) suggested a six fold criteria to recognize seismites: (1) a large areal or lateral extent; (2) lateral continuity; (3) vertical repetition; (4) morphology comparable with structures described from earthquake-affected layers; (5) proximity to faults; (6) zonation of complexity with short distance from a fault. Recognition of layers as seismites and types of seismites have also been well described in other works (Montenat et al., 2007; Moretti and Van Loon, 2014).

We have examined these criteria in light of attributes suggested by Owen and Moretti (2011) for the Andaman Flysch, to answer the question, "are the soft sediment structures in Andaman Flysch due to seismic responses?" The Andaman Flysch is spread all along the arc chain i.e. 600 km longitudinally, parallel to the island arc chain as exposed on the main Andaman group of islands (200 km long, Figure 2) and exposures in Little Nicobar and Great Nicobar group of islands. The present study involved seven outcrops well-distributed over 200km longitudinally. Thus a large area is implied, where liquefaction is operative. The outcrops are not continuous on the Andaman Islands, due to strong tectonic deformations, associated with the uplift of this subduction complex as the Andaman Islands and the beds are near vertically dipping at most exposures. Vertical repetition of soft sediment deformation features has been recorded from outcrop E where the beds were logged. In fact, the occurrence of the deformation features indicates some semblance of cyclicity occurring every 30m or so apart, except in some beds with strong deformation features in adjacent beds in Areas B and E. The Andaman Islands came into existence due to convergence of the Indian plate and its subduction beneath the SE Asian plate since Late Cretaceous times (Figures 1 & 2; Table 1) [Roy and Chopra, 1987; Roy, 1983; Roy, 1992; Roy and Das Sharma, 1993; Curray, 2005]. All the outcrops studied are close to the Jarawa thrust running N-S right across the centre of the Andaman Island (Roy and Chopra, 1987; Roy and Das Sharma, 1993) [Figure 2]. The zonation of complexity with respect to an adjacent fault cannot here be examined for the Andaman Flysch. Few wells have been drilled in the

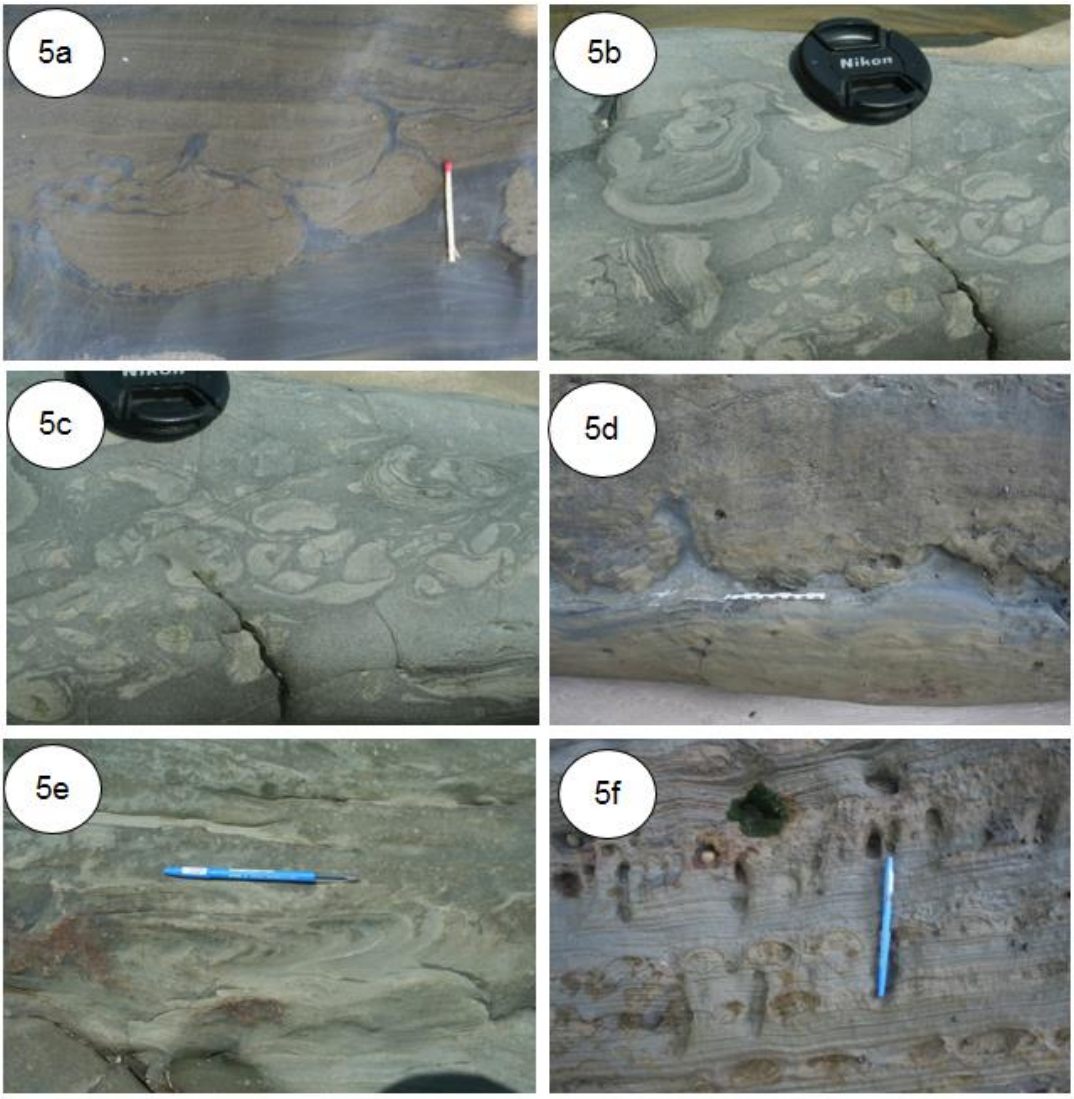


Figure 5a. *Pendulous load casts, attached and detached nodules, flame structures in fine-grained sandstone facies overlying a shale facies.* ***Figs. 5b, 5c.*** *Detached pseudo-nodules and ball and pillow structures in siltstone and shale facies. Convolute laminations observed in the pseudo-nodules.* ***Fig. 5d.*** *Load structures and flames observed in the interface of siltstone and shale facies.* ***Fig. 5e.*** *Convolute lamination and recumbent folding observed in fine-grained sandstone facies.* ***Fig. 5f.*** *Sand volcanoes exhibiting burst out structure with heterolithic balls separated by expulsion of fine-grained sandstone facies. The sedimentary sequence is inverted. Note: Figs. 5a to 5d are from Area F, South Andamans. Fig. 5e is from Area D, South Andamans. Fig. 5e is from Area F and Fig. 5f is from Area G, South Andamans*

forearc further away from the plate boundary and there are no published data on deformation structures from drilling data.

Recognition of liquefaction as deformation mechanism and determining the trigger for liquefaction (Owen and Moretti, 2011) holds the key to identification of SSDS affected by seismogenic causes. The slump folds in Area B and convolute laminations in Area C attributed to liquefaction, encased by undisturbed heterolith/sandstone facies with planar lamination, supports the supposition of a seismogenic trigger. These deformation structures occur below the storm wave base and are frequently repeated in quick succession vertically, suggestive for seismogenic causes (Mazumder et al., 2006).

Earthquakes associated with convergent margin systems are well known. The Andaman Islands have often been subjected to quakes small and large, the last big one being the Banda Aceh earthquake in 2004. Soft sediment deformation features are also present in Neogene exposures in Ritchies Archipelago, to the east of the main Andaman Islands. Hence it can be assumed that earthquakes were happening to this region periodically and could leave expressions periodically as some of the soft sediment deformation structures recorded.

All observed slump folds and convolute lamination of observed beds, are distinctly isolated from the undeformed, underlying and overlying beds. This is a positive indication that the concerned SSDS are related to seismic activity (Figures 3a, b, c; Table 2). Moreover, many of these SSDS attributed to fluidization due to seismogenic activity are observed in multiple outcrops of the Andaman Flysch, e.g. in Areas B, E and F from the studied areas. Pillow structures are often related to seismic activity (Montenat et al., 1987; Mazumder et al., 2009). The sand volcanoes are interpreted as triggered due to aftershocks in quick succession as a result of seismogenic activity.

Conversely, some of the observed fluid escape structures *viz*. simple load structures and dish and pillar structures may be attributed to localised fluidization. So, although admittedly not all SSDS, or the identifying criteria are initially seismogenic, some pre-shock structures can be reactivated by seismic shocks (Van Loon, 2014, Moretti and Van Loon, 2014). For this to be true, it is believed that all of them should be part of an early diagenetic process in a pre-lithification stage. Some of the water escape structures observed in the outcrops are assigned to non-seismogenic SSDS (Table 2).

CONCLUSIONS

1. Soft sediment deformation structures (SSDS) have been observed to be present both vertically and laterally from seven examined outcrops of the Andaman Flysch on the Andaman Islands.
2. The SSDS, e.g. slump structure/folds, convolute lamination or bedding, pseudo nodules, load and flame structures, dish and pillar structures, are a distinctive feature of the Andaman Flysch.
3. The SSDS has been distributed in all the five broad facies of the Andaman Flysch *viz*. thick sand stone facies, thin sandstone facies, heterolithic facies, shale facies. Occurrence of convolute lamination in all the facies of the same outcrop (Area E, South Andamans) deserves mention.
4. The Andaman Flysch is laterally extensive, close to the plate boundary, close to an active thrust and oblique faults to the plate margin. The deformation features like slump folds and convolute lamination are encased by beds with no deformation, sand volcanoes are frequently observed within the Andaman Flysch both vertically and spatially. These are positive indicators of these SSDS being earthquake-induced and the products may be termed 'seismites' (Table 2).
5. Some observed fluid escape structures, like load and flame structures, dish and pillar structures could be attributed to local fluidization.

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