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Soft-sediment deformation structures interpreted as seismite from the Middle Permian of the southern Sydney Basin, southeastern Australia

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The Middle Permian Wandrawandian Siltstone of the southern Sydney Basin is well exposed along the coastline from Lagoon Head in the south to North Head in the north near Ulladulla in southern New South Wales. The unit is dominated by fossiliferous siltstone and mudstone, with abundant dropstones and minor pebbly sandstone interbeds, and contains an interval of well-preserved and extensive soft-sediment deformation structures. These deformation structures occur mainly in the middle part of the cliff sections and are bounded above and below by undeformed sedimentary units of similar lithology. A wide range of soft-sediment deformation structures have been observed, including cracks, sandstone and sandy mudstone dykes, a possible sand volcano, networks of relatively small and closely connected fissure-like structures, metre-scale complex-type slump folds, flexural stratification, concave-up depressional structures, small-scale normal faults (with displacements usually <1 m), shear planes, and breccias (pseudonodules). The slumps and associated deformations are here collectively interpreted as representing a seismite deposit attributable to penecontemporaneous deformation of soft, hydroplastic sediment layers following a liquefaction triggered by seismic shocks. The timing of the inferred earthquake events appears to correspond to the onset of a major basin-wide tectonism during the Middle Permian.

KEY WORDS: Australia, Permian, seismite, soft-sediment deformation structures, Sydney Basin, Wandranwandian Siltstone.

INTRODUCTION

As originally defined by Seilacher (1969), seismites are re-deposited sedimentary beds, following disturbance and pervasive modification by earthquakes. Together with turbidites and tsunamites, seismites are widely regarded as geological event deposits of great importance to the understanding of basin-scale tectonism and evolution. The last three decades have seen a steady increase in global research effort on seismite deposits, as evident from the publication of at least three major special journal issues (Cita & Ricci Lucchi 1984; Shiki *et al.* 2000; Ettensohn *et al.* 2002). To date, most of the knowledge on Holocene seismites and their geological counterparts has been based on case studies from Europe, North America and East Asia (see recent review papers in Ettensohn *et al.* 2002). Australian case studies have been very limited. This paper will provide the first detailed description of a possible seismite deposit from the Middle Permian Wandrawandian Siltstone in the southern Sydney Basin, eastern Australia and discuss the depositional processes responsible for its genesis.

REGIONAL GEOLOGICAL SETTING AND PREVIOUS STUDIES

The southern Sydney Basin is located in the southernmost part of the north–south-trending Bowen–Gunnedah–Sydney basin system, bordering the New England Fold Belt in the northeast and the Lachlan Fold Belt to the west (Figure 1a, b). As such, the study area is generally considered to be part of a large foreland basin system within the Tasman Fold Belt of eastern Australia. Various studies have indicated that the southern Sydney Basin evolved from a backarc extensional phase (Stage I) in the latest Carboniferous to early Early Permian, through a passive thermal sag phase (Stage II) in the late Early Permian to Middle Permian, to a typical foreland basin setting in the Late Permian to Middle Triassic characterised by tectonic stacking (from the east and northeast), flexural loading and increased compression (Stage III) (Tye *et al.* 1996).

The Permian System of the southern Sydney Basin comprises both marine and non-marine sedimentary sequences, as well as igneous rocks (Figure 1c). The marine portion of the Permian sedimentary succession

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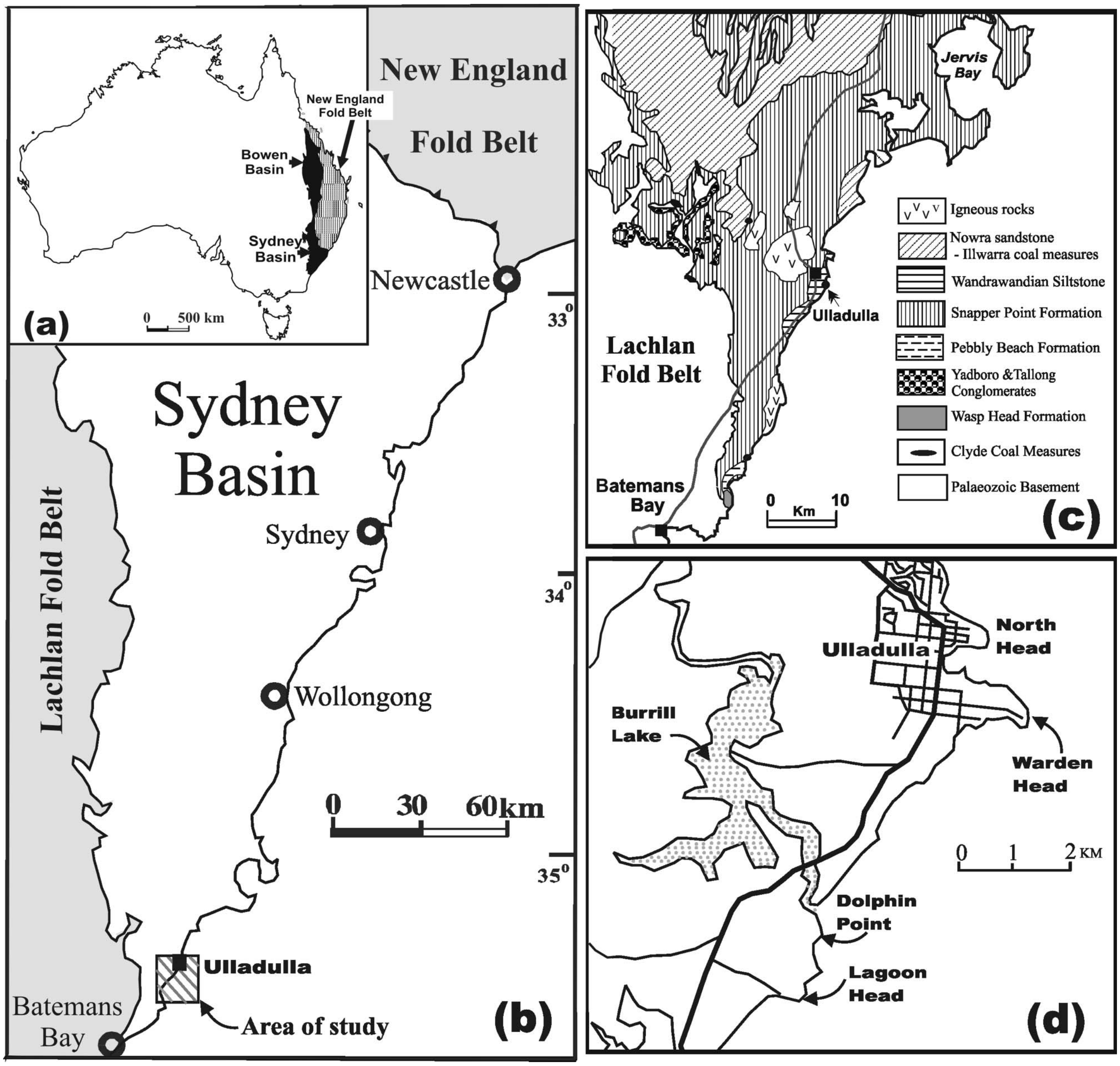

Figure 1 (a) Index map showing the location of the Sydney Basin relative to the New England Fold Belt in eastern Australia. (b) Tectonic outline of the Sydney Basin. (c) Simplified geological map of the southernmost Sydney Basin (simplified from Jones *et al.* 1986). (d) Detailed location map showing areas of study.

comprises the Wasp Head Formation of the Tallaterang Group characterising the initial backarc extensional stage, and the Shoalhaven Group manifesting thermal subsidence (tectonic stage II) and the early period of flexural loading and compression (tectonic stage III). The non-marine part of the Permian succession along the coast is represented mainly by the Late Permian Illawarra Coal Measures intercalated with some volcanic layers and intervals of volcaniclastic sediments. The emplacement of the volcanic rock bodies and abundant volcaniclastic material associated with the coal measures has been generally linked to the formation of an active subduction-related magmatic arc along the eastern coast of Australia during the Late Permian–Triassic (Carr 1998). Deposition in the Sydney Basin ceased in the Middle Triassic, when the basin sequence was deformed and uplifted by the terminal episode of the Hunter–Bowen Orogeny (Harrington & Korsch 1985).

The Wandrawandian Siltstone of the southern Sydney Basin, the focus of the present study, was thus deposited under the tectonic setting of a backarc basin on an active continental margin. The siltstone-dominated unit occurs in the middle part of the Shoalhaven Group and, unlike any other Permian unit immediately underlying or overlying it, contains widespread and well-preserved soft-sediment deformation structures.

Several previous studies have summarised the stratigraphy of the Wandrawandian Siltstone and its faunas (Gostin 1968; Dickins *et al.* 1969; Gostin & Herbert 1973; Wiles 1995; Eyles *et al.* 1998; Smith 2000), but few have attempted to discuss the origin of the soft-sediment deformation structures in the siltstone-dominated succession. Brown (1925) was probably the first to note in any detail the occurrence of these peculiar structures. Later, Gostin (1968) and Gostin and Herbert (1973 p. 66) also noted the presence of soft-sediment deformation structures in the 'Ulladulla Mudstone' (now Wandrawandian Siltstone) and described them as 'penecontemporaneous slump structures,' but did not comment on how these slumps were formed. Wiles (1995) also referred to some of the soft-sediment deformation structures including sedimentary dykes, recumbent folds and faults, and proposed a syn-depositional tectonic cause to account for these features. In a detailed recent study of the depositional environments of the Lower Permian southern Sydney Basin sequence, Eyles *et al.* (1998 p. 147) also briefly noted the slumped siltstone horizons in the Wandrawandian Siltstone and suggested that seismic shaking may have been responsible, but no further discussion was provided. More recently, Smith (2000) examined the deformation style of the sediments and especially those of the slump folds and the crinoid stems contained in the slumped beds, and proposed that the slumps moved in a general eastward direction towards the flanks of the slumped beds or lobes, but no mention was made about the original cause of the slumping.

In this paper, we attempt to present a new interpretation of the soft-sediment deformation structures based on both our field observations as well as comparisons with similar structures that have been reported in several overseas case studies. Our main conclusions are that these structures most likely represent earthquake event deposits (seismite) emplaced on a seismically active continental margin. To this end, our conclusions concur with the earlier suggestion made by Eyles *et al.* (1998).

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT

Originally named by David and Stonier (1891) based on a diamond drillcore sunk near Wandandian, the Wandrawandian Siltstone (=the 'Ulladulla Mudstone' of Harper 1915; Brown 1925: see Tye *et al.* 1996) is well exposed along the coast from Lagoon Head to North Head of the Ulladulla Bay in the southern Sydney Basin (Figure 1d). In general, the unit dips gently ($<10^\circ$) in an east-to-northeast direction, and is dominated by fossiliferous siltstone and mudstone, with abundant dropstones and minor pebbly sandstone interbeds (Figure 2). The measurable thickness of the siltstone in the study area ranges from 20 to $\sim$60 m, although it appears to thicken in an east-to-northeast direction. In the study area, neither the base nor the top boundary of the Wandrawandian Siltstone is exposed, but according to Gostin and Herbert (1973), in the context of the regional stratigraphy of the southern Sydney Basin, the siltstone unit conformably overlies the Snapper Point Formation and is separated from the overlying Nowra Sandstone by a minor erosional surface.

The age of the Wandrawandian Siltstone as a whole has been variably inferred from its rich marine invertebrate faunas, ranging from late Early Permian (Dickins *et al.* 1969; Briggs 1998) to early Middle Permian (Reid 2003). Our preliminary assessment of the abundant brachiopod faunas in the Wandrawandian Siltstone, especially in view of the bipolar distribution of the *Terrakea* species abundantly occurring in the unit and elsewhere in the southern Sydney Basin (Weldon & Shi 2007), appears to favour a Roadian – Wordian age (Guadalupian, Middle Permian).

Detailed field observations suggest that the Wandrawandian Siltstone in the study area, especially the cliff succession at Warden Head, can be divided into three units based on lithology and sedimentary structures (Shi & McLoughlin 1997) (Figure 2). At Warden Head, the basal unit (Unit A) is exposed on the shore platform extending from the base of the Warden Head cliff eastward to an unknown depth and distance out to sea. This basal unit is dominated by fine pebbly sandstone and siltstone with bioturbated structures, clusters of concentrated pebbles [i.e. dump structures of Bennett *et al.* (1996), suggestive of glacial origin], and occasional large boulders (erratics) up to 1.5 m in diameter. At Warden Head and Dolphin Point, several sandstone beds, some of which contain brachiopod and bivalve fossils, occur in the upper part of this unit, near the boundary with the overlying unit (Figure 2). On the platform itself at Warden Head, there are abundant shallow-marine benthic invertebrate fossils, notably brachiopods, crinoids, bryozoans and bivalves, in descending order of abundance. Most of these fossils form shell concentrations in isolated pockets (areas usually $<1\ m^2$ in size), some of which are mixed with poorly sorted angular polymictic pebbles. Most of the brachiopod shells are seen still with their two valves articulated together, and spinous productids (e.g. *Terrakea*) still have long, delicate spines attached to their shell surfaces.

The middle unit (Unit B in Figures 2, 3a, 4a), dominated by fine-laminated siltstone and mudstone, is a chaotic interval comprising large, laterally extensive depositional slumps and other associated soft-sediment deformation structures (see below for details). Compared with the underlying basal unit, the sediments of the slumped beds of the middle unit are generally finer and contain fewer pebbles, but with more abundant shelly fossils, some of which are heavily concentrated to form coquina beds. Of particular note is that some crinoid stems in this unit are severely deformed with their individual ossicles displaced (offset) with respect to one anther albeit remaining connected (Smith 2000). The lower contact of this middle chaotic unit with the underlying unit is usually sharp and locally may be marked by undulose shear planes (interpreted as glide planes, see below). At Warden Head and Dolphin Point, several thrust faults have also been observed separating the middle unit from the underlying beds. The upper contact of the middle unit is also well defined by a sharp change in either lithology or sedimentary structures. For example, at the southern end of Warden Head, the upper boundary of the middle unit is immediately overlain by a prominent, wedge-shaped normal-graded

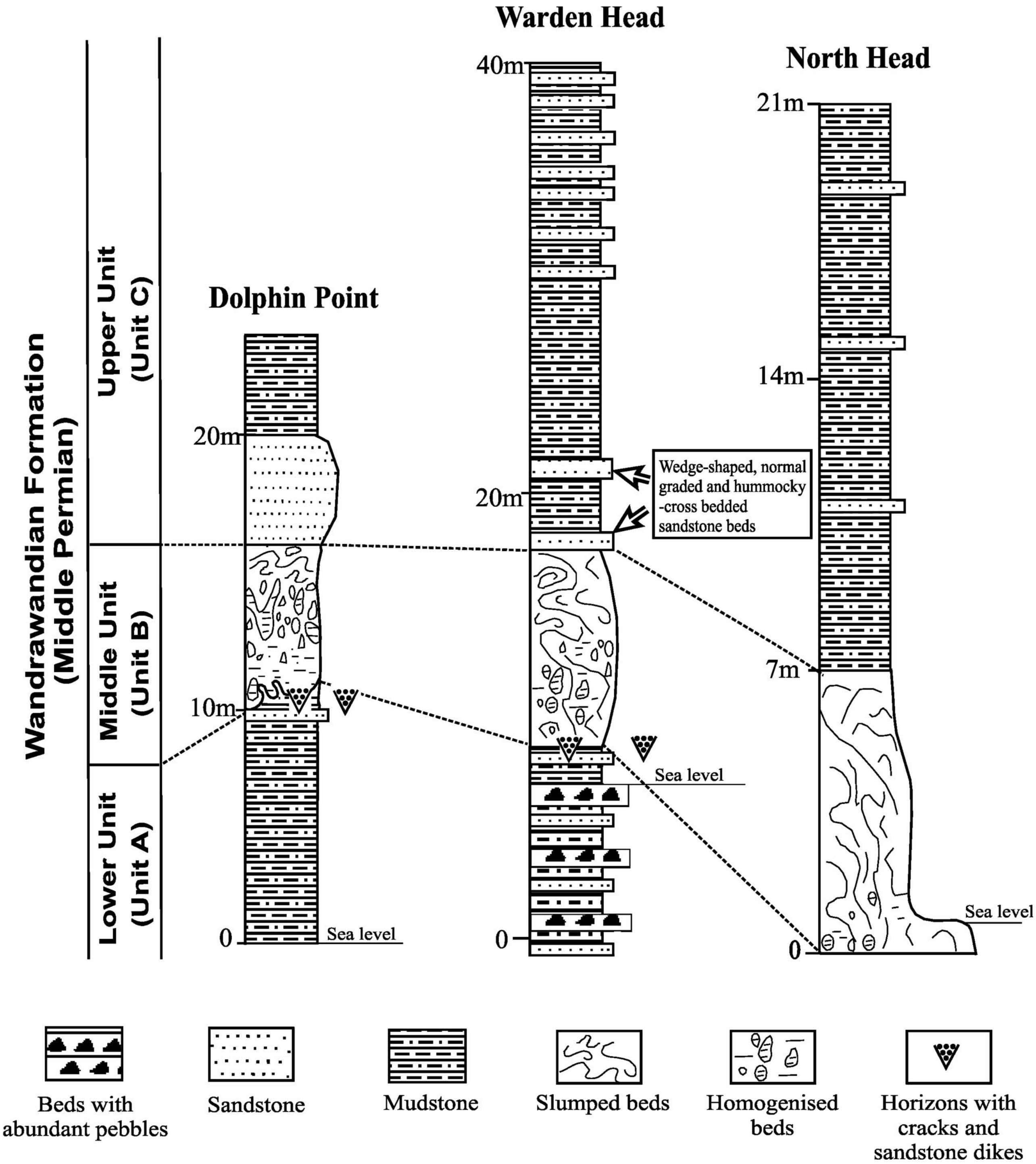

Figure 2 Stratigraphic columns of the studied sections showing the vertical successions of the Wandrawandian Siltstone as exposed at Dolphin Point, Warden Head and North Head.

sandstone bed with abundant brachiopod and bivalve fossils (Figure 2).

The upper unit (Unit C in Figures 2, 3a, 4a) is dominated by very fossiliferous, monotonously laminated, locally bioturbated siltstone and mudstone. At Warden Head, two closely spaced, thick-bedded, normal-graded sandstone wedges occur in the lower part of this unit (Figure 2). A similar but much thicker ($\sim$4 m) sandstone unit is also seen immediately overlying the middle chaotic unit at Dolphin Point (Figure 2). Here, Gostin (1968) also observed that this sandstone unit thickens southwards, reaching about 6 m at Lagoon Head, where it also incorporates a bed of conglomerate and a contorted bed of pebbly fine sandstone at the base. A striking difference between this unit and the underlying chaotic interval is its complete lack of slumping and other soft-sediment deformation structures that are common in the latter. In this regard, Unit C is very

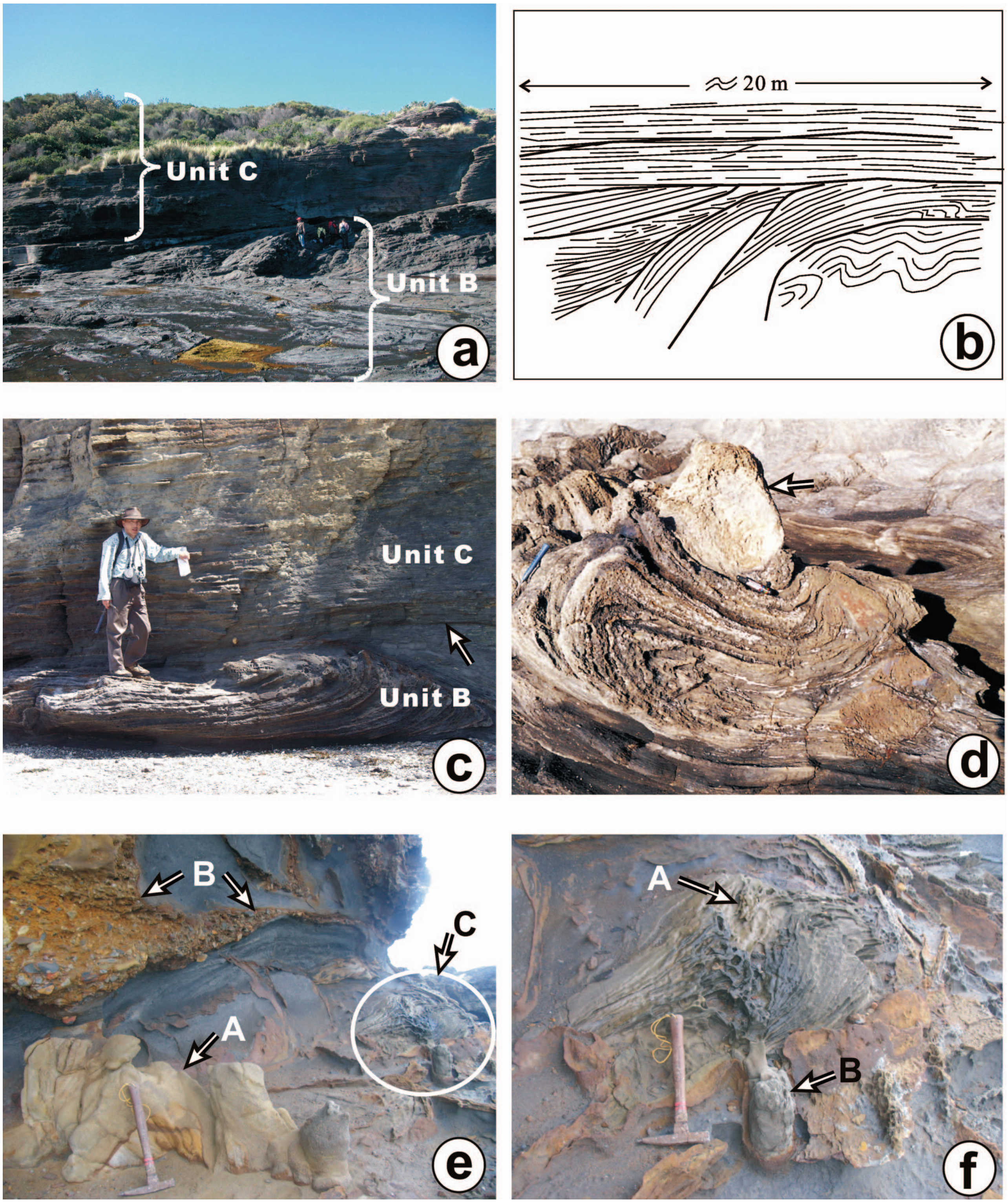

Figure 3 (a, b) Photograph and sketch of various slump structures in Unit B and the overlying undisturbed Unit C, separated by a low-angle lateral thrust fault, Warden Head (AMG 8927, 720802). Figures for scale. (c) Recumbent slump fold in Unit B with sharp contact (arrowed) with overlying undisturbed beds of Unit C, North Head (AMG 8927, 713847). Figure for scale. (d) Flow-roll structure enveloping a harder and sandier rotated block (arrowed) as the core of the upper recumbent fold, Warden Head (AMG 8927, 719836). Hammer for scale is 32.5 cm long. (e) Tabular sandstone dyke (arrowed A), irregular-shaped syndepositional slump folds (arrowed B) and a mushroom-shaped structure interpreted as a possible sand volcano [arrowed C, enlarged in (f)], Lagoon Head (AMG 8927, 678783). Hammer for scale is 34.5 cm long. (f) Mushroom-shaped structure interpreted as a possible sand volcano, also showing the internal convoluted bedding, the crater (arrowed A) and the vertical sandstone pipe (conduit) (arrowed B), Lagoon Head (AMG 8927, 678783). Hammer for scale is 34.5 cm long. All locality reference numbers are from the Australian National Topographic Map Series, scale 1:100 000, Sheet 8927 (Ulladulla).

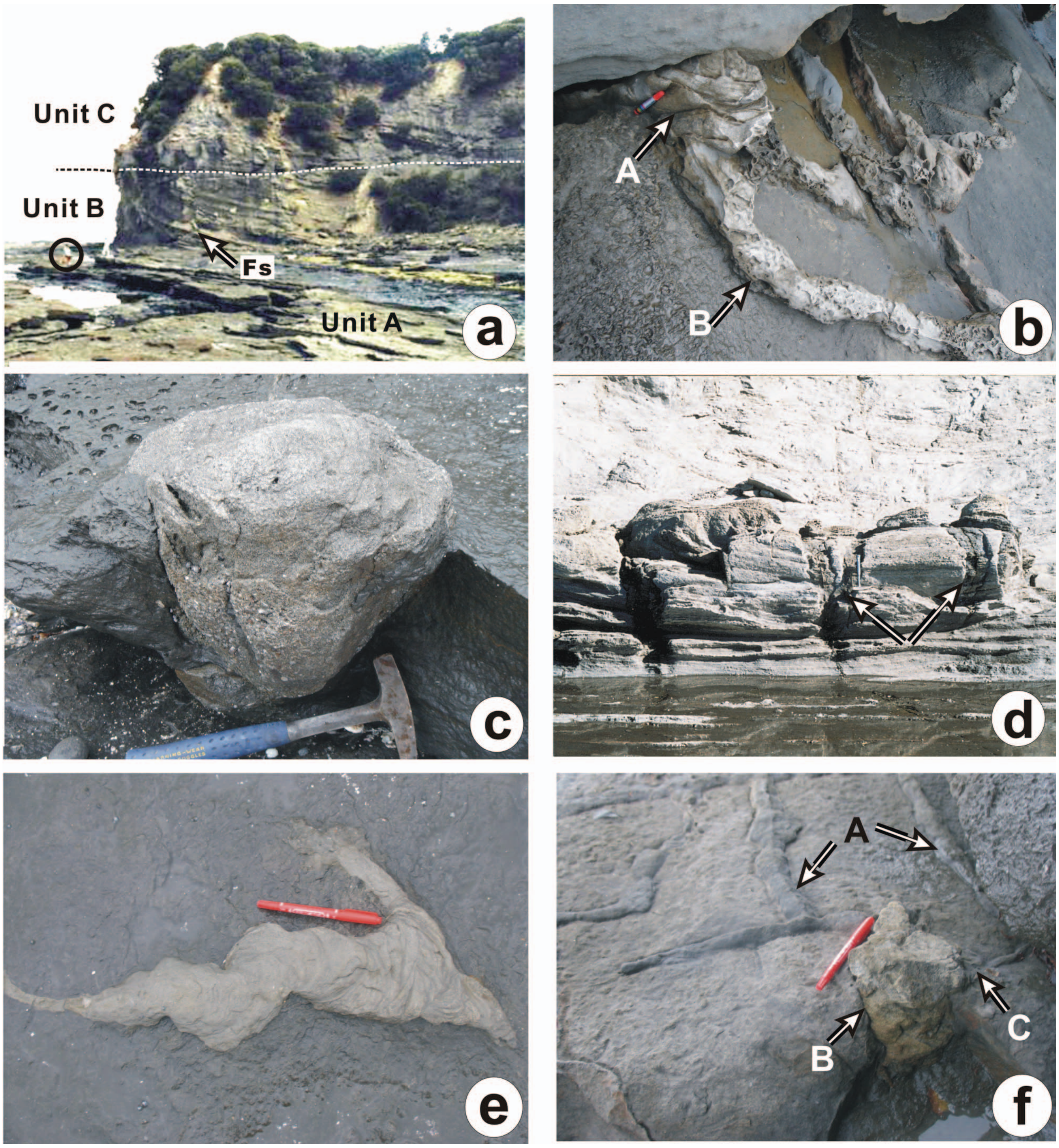

Figure 4 (a) Flexural stratification (Fs) with a gradational basal contact with Unit A below but a sharp thrust contact with the overlying undisturbed Unit C (AMG 8927, 718837). Figure for scale. (b) Network of sandstone dykes (arrowed B) and conical sandstone intrusions (arrowed A), Lagoon Head (AMG 8927, 679784). Marker pen for scale is 10 cm long. (c) Conical sandstone intrusion structure, south Dolphin Point (AMG 8927, 679785). Hammer for scale is 32.5 cm long. (d) Large vertical V-shaped cracks and dykes occurring at the base of Unit B, Warden Head (AMG 8927, 719835). Hammer for scale is 32.5 cm long. (e) Ptygmatically folded sandstone dyke, Dolphin Point (AMG 8927, 679784). Pen for scale is 13 cm long. (f) Networks of small fissure-like cracks and in-filled sandy mudstone dykes (arrowed A) and a conical sandstone intrusion structure (arrowed B), which also appears to be connected to sandy mudstone dyke (arrowed C), Dolphin Point (AMG 8927, 678785). Pen for scale is 13 cm long. All locality reference numbers are from the Australian National Topographic Map Series, scale 1:100 000, Sheet 8927 (Ulladulla).

similar to Unit A in overall lithology and sedimentary structures, but they differ in that the former contains fewer pebbles and more abundant and evenly distributed shelly fossils. Brachiopods are particularly rich in Unit C, but they do not form concentrated shell pockets, as they do in Unit A. At Warden Head, a *Terrakea*-dominated brachiopod assemblage is abundant in the middle part of Unit C, while a rich association of large bivalves (including *Vacunella, Myonia* and *Deltopecten*) and spiriferid brachiopods (notably *Tomiopsis* and *Sulciplica*) is concentrated near the top of this unit at Warden Head. Most of the spiriferid brachiopod and bivalve shells are preserved with valves conjoined, while the spiny *Terrakea* and *Strophalosia* productids retain their delicate spines intact on the shell surfaces.

Trace fossils occur throughout the entire cliff sections of the Wandrawandian Siltstone in the study area, and are particularly common at Warden Head. Our preliminary field examination of these trace fossils suggests the following genera: *Bergaueria*, *Cruziana, Helminthopsis, Keckia, Palaeophycus, Taenidium, Thalassinopsis*, and *Zoophycos*. Except for the first form, which is relatively rare and appears to be restricted to silty – sandy facies, the rest are commonly found in the more silty and muddy sediment. These trace fossils together appear to indicate a *Cruziana – Zoophycos* ichnofacies.

To date, the Wandrawandian Siltstone has generally been interpreted as the deposit of a moderately deep-marine shelf environment (i.e. below storm wave-base), in which the influence of wave action was restricted probably by the presence of seasonal rafting ice and also probably an offshore volcanic arc to the present east (Gostin & Herbert 1973; Ramli & Crook 1978; Shi & McLoughlin 1997). This conclusion is supported by the high-quality preservation status of most of the shelly fossils, the presence of the *Cruziana – Zoophycos* ichnofacies characteristic of most of the bioturbated layers of the formation, and the common occurrence of dropstones of varying sizes and types throughout the unit (Eyles *et al.* 1998). A cool-water temperature condition has been generally accepted as the climate regime responsible for the presence of a low-diversity, high-abundance benthic biota, abundant poorly sorted angular to subangular pebbles, and glendonites in the unit (Gostin & Herbert 1973; Carr *et al.* 1989; Eyles *et al.* 1998).

SOFT-SEDIMENT DEFORMATIONAL STRUCTURES

Cracks

Steeply inclined to vertical cracks have been observed from the base of Unit B at Warden Head (Figure 4d). The cracks are mainly tensile, irregular in shape and profile, and confined within natural sedimentary layers When viewed from the depositional surface, they are oriented in a disorderly fashion. All the cracks are filled with mud mixed with minor sand, resulting in the formation of sandy mudstone dykes, or neptunean dykes (defined as passive fillings of a fracture or karst feature that is open to the surface, or the sea bed: Jolly & Lonergan 2002). These Neptunean dykes are wedge-shaped (Figure 4d), ranging in width from 1.5 cm at the bottom to 30 cm at the top, and up to 70 cm in depth. Internally, the lithology of the sandy mudstone dykes is dominated by mud, mixed with minor amount of poorly sorted, angular to subangular quartz sand and occasional fragments of shelly fossils. The sandy mudstone dykes are clearly demarcated in both lithology (composition and texture) and colour from the surrounding primary deposits of dark-grey, richly fossiliferous mudstone. These cracks and infilled material may superficially look like post-depositional structures such as conjugated tensile-shear or compression-shear structures, but they do not display any orderly orientation and lack planar fractures filled with quartz veins that would be characteristic of tectonically formed shear zones or quartz-vein systems. We, therefore, consider the cracks and their infilled sandy mudstone dykes as early post-depositional features formed by a secondary process as a result of soft-sediment liquefaction and fluidisation and subsequent deformation (cracking/ fracturing), followed by mud and sand infilling (see below for discussion).

Networks of sandstone dykes and fissure-like structures

In addition to the V-shaped cracks, we have also observed large networks of sandstone dykes and smaller-scale fissure-like structures. At Warden Head, Dolphin Point and Lagoon Head, sandstone dykes were frequently observed on shore platforms and from large cobbles at the base of the shore cliffs (Figures 3e, 4b, 4e). Typically, these sandstone dykes are composed of medium- to coarse-grained sand, mixed with minor small pebbles. Unlike the infilled V-shaped sandy mudstone dykes mentioned above, these sandstone dykes are more planar in vertical profile. Laterally, the sandstone dykes may extend for several metres, are ptygmatically folded (Figure 4e) and branch off at random. The branches may pinch out laterally over a short distance from the main dyke (Figure 4e; see also Conybeare & Crook 1982 plate 53B) or join again laterally to form a complex anastomosing network of dykes (Figure 4b). The plan view of the sandstone dykes and their branches indicates a highly irregular and random spatial distribution without any particularly preferred spatial orientation.

In addition to the medium- to coarse-grained sandstone dykes, there are also networks of closely connected smaller fissure-like structures on the shore platforms of Warden Head and Dolphin Point. These fissure-like structures are between 3 and 8 cm wide, and are usually composed of silty mud, forming low ridges slightly above the surrounding more muddy and less weathering-resistant matrix sediment (Figure 4f). On bedding planes, the networks formed by these small fissure-like structures look like desiccation marks, but they are clearly different from the latter as they are highly irregular in network geometry and connectivity (i.e. they do not form regular polygons and some of the branches are discontinuous laterally); they also cannot be confused with tectonic joints because they display a high level of spatial connectivity and lack any consistent spatial orientation. At least at one location on the shore platform at Dolphin Point, networks of these fissure-like structures are closely associated with a conical sandstone intrusion structure (see below) (Figure 4f).

Conical and mushroom-shaped sandstone intrusions

On the shore platforms at both Dolphin Point and Lagoon Head, we have observed several occurrences of conical sandstone intrusion structures (Figures 4c, f, 5). One typical such structure (Figure 4c) measured 35 cm in maximum diameter on the bedding plane and 31.5 cm long, and displays a typical tapering-down conical geometry with an apical angle of 40°. Invariably, these cone-shaped sandstone structures are composed of moderately to poorly sorted coarse sand and, as such, they are clearly demarcated from the surrounding muddy siltstone matrix rocks. Viewed on the bedding plane, these structures are nearly perfectly circular in outline (Figure 4c), but asymmetrical or irregular shapes are also present. Internally, the structures often display vague concentric or convoluted internal bedding (Figure 4c). The visible depth of these conical sandstone structures ranges from 10 to 70 cm, and in one case we have observed that the root of one such structure has penetrated through the immediately underlying muddy siltstone bed, through which it is then connected to a sandstone bed (Figure 5). However, in most other cases, the roots of these conical structures are either not exposed or tend to be buried in the surrounding muddy siltstone.

Most of the conical sandstone structures have been observed in isolated occurrences, but at two locations, they are found either directly connected to a cluster of sandstone dykes (Figure 4b) or closely associated with a network of fissure structures described above (Figure 4f). In the former, the conical sandstone structures tend to form nodes from which the sandstone dykes radiate out and reconnect with other similar sandstone dykes from another conical sandstone node in the same network (Figures 4b, 5). In the latter, at least one fissure appears to be also connected to the conical sandstone structure (Figure 4f).

At Lagoon Head, we have observed another type of sandstone intrusion structure with striking resemblance to a sand volcano (Figure 3f). This structure, measuring 65 cm in diameter and 36 cm in height, is clearly demarcated from the surrounding muddy siltstone matrix rocks by its sandy composition and internal structure characterised by somewhat convoluted bedding (Figure 4c). The upper periphery is dome-shaped with flanks sloping laterally at about 35°. Close to the apex of the dome is a small raised ridge (about 5 cm across), which, due to differential weathering, is well exposed and differentiated from the surrounding material (Figure 3f, arrow A). Downwards, the sandstone dome is connected to a vertical cylindrical sandstone pipe of the same lithology (Figure 3f). The sandstone pipe, 10 cm in diameter, is rooted in and penetrates through a muddy siltstone. Further down, across the muddy siltstone layer, the basal part of the sandstone pipe is not exposed; however, about 1.5 m away from this sandstone pipe, another similar-sized cylindrical sandstone pipe connects to an underlying sandstone bed (Figure 5).

Slump structures

Early post-depositional slump deformations of varying morphology are common in the study area. These are usually observed at metre scale and are confined to Unit B of the Wandrawandian Siltstone. Associated with these slump structures are large-scale complex-type folds, convoluted bedding, flexural stratification, and concave-up structures (depressions).

The large-scale complex-type folds are the most common deformation structures observed in the unit; they extend laterally over the entire strike-parallel cliff

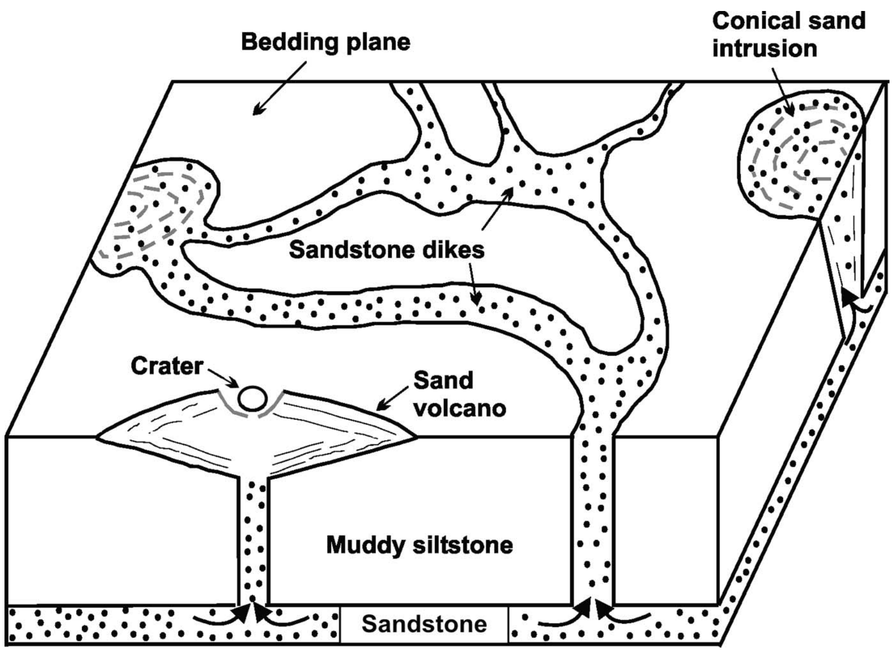

Figure 5 Diagram showing the spatial configurations and geometric shapes of the various intrusive sandstone structures observed in the study area. Thick black arrows indicate direction of sand movement during liquefaction.

sections in the study area (Figure 2). In vertical succession, the folds are frequently represented by inverse or recumbent folds (or flow rolls) with complex and irregular shapes (Figure 3c, d). In almost every case, the overturned upper flank lies horizontally and merges into an overlying horizontal layer or an adjacent slump fold. Laterally, the folds emerge abruptly from an undistorted underlying layer and then may grade into discontinuous, subhorizontal beds. Close examination of these folds usually demonstrates distinct internal convoluted bedding (Figure 3c). Most of the folds extend laterally for 2 – 8 m. Up-section, the complexity of the fold shapes seems graded, with isoclinal cylindrical folds appearing in the lower part of the folded strata and more open, less complex folds in the upper part. The axes of most of the slump folds are subhorizontal, roughly parallel to each other and gently plunge southwards. The strike of the folds is south-southwest – north-northeast, with the axial plane generally gently inclined 260 – 285°W at 20 – 30°, suggesting an easterly direction of slumping.

At Warden Head, the complex-type recumbent folds are associated with flexural stratification and broad concave-up structures (depressions). Flexural stratification usually develops in Unit B, especially at the northernmost part of Warden Head, where one such structure is 12 m long, dips at 20 – 25° and is unconformably overlain by undeformed layers of Unit C (Figure 4a). Concave-up depressional structures are also common in the middle slumped unit and are usually locally confined within the folded strata and exhibit broad concave layers; they are commonly observed on shore platforms at both Warden Head and North Head where individual concave-up structures are up to 500 cm long and 50 cm deep.

Fractures, shears and faults

There are also small-scale, localised fractures in the folded middle Unit B in the study area. These fractures consist of shears as well as normal, and some thrust, faults. The shears have concave or undulating shear planes with distinct discordant or abrupt contacts with underlying layers. Field measurements indicate that the shear planes are mostly north – south-oriented and dip to the west or southwest (Figure 3a). Most of the observed normal faults have small displacements of < 50 cm offset and are roughly north – south-oriented, parallel to each other, and gently inclined eastwards.

At Warden Head, there are some distinctive fracture features, comprising breccias and rotated blocks. Brecciation is indicated by the accumulation of fragmented original sedimentary layers along the folded/fractured horizons. These fragments of varying sizes (50 – 110 cm across) are typically angular to subangular, unsorted and irregularly distributed. Internally, some fragments have distinct bedding structures, but they are usually convoluted or distorted and, as such, are clearly discordant with bedding structures in the surrounding matrix rocks. In some cases, large fragments are totally displaced and floating/rotated within the otherwise fine laminated siltstone-dominated matrix, which also shows evidence of wrapping or enveloping around the breccias (Figure 3d).

In addition to the localised small-scale normal faults and shears described above, the study area also contains larger-scale (tens of metres or more along strike), low-angle thrust faults. For example, at North Head, the boundary between Unit B and Unit C is clearly marked by a lateral thrust fault that separates the slump folds below from relatively undisturbed flat-lying to subhorizontal beds above (Figure 3c). At the southern end of Warden Head, a thrust fault cuts across the normal-graded sandstone bed at the top of Unit B (Figure 3a). Gostin (1968 figure 1 – 9) also depicted a set of roughly parallel east-dipping, low-angle (13 – 25°) thrust faults that cut through the Wandrawandian Siltstone succession at the Warden Head cliff section.

INTERPRETATIONS AND DISCUSSION

The various soft-sediment deformation structures described above may be compared with many similar features of either known or assumed seismic origin. First, the larger cracks from the study area look very similar to the seismic cracks reported by Mohindra and Bagati (1996) from the 19 January 1975 Kinnaur earthquake in India. Sets of smaller, closely connected fissure-like cracks in the study area resemble similar features described as fissures produced by seismic shocks from the recent (2300 a BP) muddy sediment in the Kawachi Lowland Plain in Oska, Japan (Matsuda 2000). Further, the sandy mudstone dykes also appear strikingly similar to the infillings of seismic cracks created by earthquake events in the Kinnaur earthquake (Mohindra & Bagati 1996), and they also resemble structures from some ancient seismites (Anand & Jain 1987; Gong 1993; Guiraud & Plaziat 1993; Mohindra & Bagati 1996; Bose *et al.* 1997; Rossetti 1999; Du *et al.* 2001).

All the slump or slump-related deformational structures in the study area are restricted to Unit B of the Wandrawandian Siltstone, separated from the undeformed beds of the lower (Unit A) and upper (Unit C) units, and can be correlated over more than 7 km along strike throughout the study area. The slump deformation structures (including convoluted bedding) observed in the study area exhibit forms similar to those reported by Mohindra and Bagati (1996), Bose *et al.* (1997), Rossetti (1999), Rossetti and Goes (2000) and Morriam and Förster (2002). In particular, the slump folds described above can be closely compared with similar slump folds from the Koldaha Shale of India (Bose *et al.* 1997), a submarine seismite deposit of the Tabernas Basin, Spain (Kleverlaan 1987) and the seismites of a synsedimentary strike-slip basin of Upper Benue, Nigeria (Guiraud & Plaziat 1993). They are also closely comparable to seismites from the Hinton Formation of USA (Stewart *et al.* 2002). These comparisons would imply that the slump folds in the study area are most likely products of hydroplastic deformation involving soft-sediment layers. This suggestion is also corroborated by the flexural stratification observed at Warden Head, which is very similar to flexures reported by Bose *et al.* (1997) from the slope-controlled seismic deformation of the Koldaha Shale, India. The latter has been interpreted to have formed by the uplifting of unconsolidated wet or plastic-state sedimentary layers following a seismic shock.

Breccias and evidence of block rotation in the study area are comparable with what has been described as either cycloidal structures (Hempton & Dewey 1983) or pseudo-nodules (Stewart *et al.* 2002), both having been linked to a seismic-shock origin. These fracture-related, broadly syndepositional features, as well as the Neptunean sandy mudstone dykes, may be collectively interpreted as evidence of sediment homogenisation caused by liquefaction. These structures are consistent with features that may be expected to result from liquefied soft, silty to sandy sediment layers under persistent vibration forces such as seismic shaking, as described and characterised by Lowe (1975), Owen (1987) and Morreti *et al.* (1999). Liquefaction caused by seismic vibration may also explain the origin of the broad, large-scale concave-up depressional structures observed in the study area whereby these depressions may be best described as a case of sediment sinking due to failure of the underlying layers by liquefaction and subsequent loss of load-bearing capacity after a seismic shock.

The presence of normal faults and shear planes more commonly found in the lower part of the studied sections is also of significant interest. These features resemble similar faults attributable to seismic origin as they are typically small in scale (usually <0.5 m in displacement), mostly isolated from each other (i.e. spatially they do not tend to form an orderly pattern) with no or very limited effect on the bedding structures of adjacent beds, often locally associated with fracture features, and usually abruptly overlain by normal sediment layers (Stewart *et al.* 2002). However, the interpretation of the larger scale thrust faults observed at Warden Head is less certain. The fact that these low-angle thrust faults (Figures 3a, c, 4a) cut through the slumped beds (including the sandstone bed immediately overlying Unit B at Warden Head) indicate that they must have been formed after the slumping event, although we cannot ascertain how much delay there was between the slumping and the reverse faulting event. In this context, it is interesting to note that these thrust faults appear to correspond to the D_2 faults recognised by Wiles (1995), who described them as west-directed backthrusts caused by an east–west compression of the southern Sydney Basin during the Late Permian. In this interpretation, clearly the thrust faults were considered as tectonic rather than early post-depositional features.

Among all the soft-sediment deformation structures observed in the field and described here, the discovery of the tabular sandstone dykes, conical and mushroom-shaped sandstone intrusions and associated cylindrical pipes is probably most significant. These structures have never been reported in the literature on the Permian rocks of the southern Sydney Basin, but their presence is not surprising given their close spatial and stratigraphic association with other soft-sediment deformation structures. The tabular sandstone dykes (Figures 3e, 4b, e) bear a striking resemblance to similar clastic dykes that have been observed from the relatively recent (<2 Ma) known earthquake-induced sedimentary deposits (Bourgeois & Johnson 2001; Gonzalez de Vallejo *et al.* 2003; Tuttle *et al.* 2005; Levi *et al.* 2006) or geological seismites (Shanmugam *et al.* 1994; Rodríguez-Pascua *et al.* 2000; Stewart *et al.* 2002; Upadhyay 2003). Likewise, the downward tapering conical sandstone structures (Figure 4c) can be closely compared with the cone-shaped sandstone intrusions recently reported by Shoulders and Cartwright (2004) from a Middle Eocene submarine fan deposit on the UK Atlantic margin, although the latter are much larger in size (kilometre scale). Shoulders and Cartwright (2004) attributed the cone-shaped sandstone intrusions to a liquefaction event of a pre-existing sandy layer probably triggered by a seismic shock.

The single mushroom-shaped sandstone structure observed at Lagoon Head (Figure 3f) strongly resembles what are commonly described as sand volcanoes or sand blows (Jolly & Lonergan 2002; Strachan 2002; Tuttle *et al.* 2005). In particular, this structure looks strikingly similar to the sand volcanoes described and illustrated by Strachan (2002 figure 9) from the Carboniferous Ross Formation of Ireland in size, geometric shape and internal bedding structure. In this comparison, the central raised ridge near the apex of this dome structure (Figure 3f) could be interpreted as a central crater now plugged with sandstone; and the cylindrical vertical sandstone pipe that supports the sandstone dome in our case would have acted as a feeding conduit to supply the sand upward into the sand volcano (Gallo & Woods 2004) (Figure 5).

Both experimental and field-based studies have shown that sand volcanoes can be formed by a variety of trigger mechanisms (Jolly & Lonergan 2002; Tuttle *et al.* 2002; Gallo & Woods 2004), although they are more commonly identified in tectonically active and mud-rich sedimentary environments where tectonic stresses facilitate the development of earthquakes. When an earthquake takes place, the hydraulic fluid pressure in the unconsolidated sedimentary system rapidly increases, especially in sandy sediment or sand-rich layers buried beneath the more cohesive mud-rich layers, causing liquefaction, fluidisation and upward injection of the sandy sediment through the mud-rich sediment layers. If the injected sand that ascends through a vertical feeding conduit (like the one observed at Lagoon Head: Figure 3f) is sustained by further hydraulic fluid overpressure and finally breaches the sediment–water interface on the seafloor, a rupture would occur to form a sand volcano. In the final stage of an earthquake event, the hydraulic fluid overpressure will drop back to its pre-shock state, hence terminating the force necessary to sustain further sand injection. As a result, the sediment supply to the sand volcano through the vertical conduit is depleted and finally shuts down, leading to the formation of a small crater at the center of the volcano, which subsequently could be plugged by passive backfill to form a raised central ridge (node) (Figure 5). There have been numerous reported examples of seismically induced sand volcanoes, from both modern and ancient sedimentary systems (Galli 2000; Rodríguez-Pascua *et al.* 2000; Tuttle *et al.* 2002; Gonzalez de Vallejo *et al.* 2003; Samaila *et al.* 2006). In almost all known case studies, the sand volcanoes are always found in close association with a wide range of other soft-sediment deformation structures, including cracks, sandstone dykes, fissures, slumps and faults. This combination of soft-sediment deformation structures is also consistent with what we have observed and described above from the southern Sydney Basin.

To summarise, nearly all the evidence suggests that the soft-sediment deformation structures of the Wandrawandian Siltstone in the study area are genetically related and represent penecontemporaneous early post-depositional deformation structures involving unconsolidated and/or semiconsolidated silty mud. Furthermore, it is apparent that the deformation events probably involved liquefaction, fluidisation, slumping and sliding as seen in the presence of sandstone dykes, conical and mushroom-shaped sandstone intrusions, faulted blocks and shear planes interpreted here as glide planes and faulted blocks.

In addition, we further infer that the early post-depositional deformation structures originated from seismic activity in the area during the Middle Permian. This conclusion is reached because all the evidence outlined above meets the criteria characteristic of a seismite. According to Sims (1975) and Wheeler (2002), the essential characteristics of a seismite would include the following: (i) sudden formation as indicated by sharp but non-erosive contacts of the seismite interval with undeformed rock units lying both above and below; (ii) synchroneity, which may be evidenced by the fact that all the observed soft-sediment deformation structures, albeit scattered in a study area, are confined within a relative short (narrow) and correlatable stratigraphic horizon; (iii) zoned distribution, as indicated by the deformed interval forming a laterally consistent and mappable stratigraphic horizon in the study area, with a trend of systematic decrease in any lateral direction in the complexity of deformation; (iv) size of soft-sediment deformation structures comparable with soft-sediment deformation structures of known seismic origin; (v) a suitable tectonic setting where earthquakes capable of generating large-scale and laterally persistent soft-sediment deformation structures could be expected; and (vi) a suitable depositional setting and sediment properties susceptible to seismic shaking and forming soft-sediment deformation structures, such as grainsize, lack of cementation and compaction.

All these criteria characterising a seismite deposit can be closely matched with our field observations and descriptions, with perhaps only one exception to the third criterion (zoned distribution). We have not observed an unequivocal trend of change in the complexity of deformation style nor in the magnitude of the deformations (measurable, for instance, by the tightness of folds and their frequency of occurrence) in any lateral direction. Presumably, this trend may only be recognisable if a larger area is studied (for instance, to also include the Jervis Bay area about 40 km to the north of the current study area where similar soft-sediment deformation structures in the Wandrawandian Siltstone have also been reported; G. Bann pers. comm. 2004). Another possibility for our possible failure in detecting such a systematic trend might be due to the fact that a significant portion of the southern Sydney Basin is now offshore, severely hindering our assessment of the eastward extent of the southern Sydney Basin beyond the present coastline.

Also arguably, some of the soft-sediment deformation structures described here could have been triggered by intense storm activities rather than seismic shocks. However, this may be ruled out because there are no signs of tempestites, hummocky cross-stratification, large-amplitude wave ripples—features that would be typical of storm-formed deposits (Molina *et al.* 1998). In addition, large storms are more common for low-latitude settings (5–20°) although they may also affect higher latitudes (Deng *et al.* 1997; Greb & Dever 2002).

Given the high quality of the preserved soft-sediment deformation structures and their similarity to features of known seismic origin, it is possible to speculate how the early post-depositional deformation process took place. As suggested above, the Wandrawandian Siltstone is generally regarded as having been deposited in a moderately deep (below wave-base) marine shelf environment, and the deposition was accompanied by intermittent melting of probably seasonal coastal and river ice (as indicated by abundant dropstones and glendonites). At the time of deposition, this part of the basin was experiencing thermal subsidence and flexural loading (i.e. tectonic stage II of Tye *et al.* 1996). It is therefore plausible to suggest that the earthquake shocks may have preferentially affected the offshore areas that were experiencing overloading due to either rapid sediment influx or intensified tectonic compression or both, causing slope instability and hence sediment liquefaction, followed by mass movement and deformation of hydroplastic sediment layers.

The process may be inferred as follows (Figure 6). When an earthquake took place, seismic cracks formed first as a result of intense crustal vibration. Then, the soft, unconsolidated or semi-consolidated silty to sandy sedimentary layers became liquefied, fluidised and subsequently mobilised, resulting in a sudden increase of pore pressure in the less cohesive sandstone layers. This suddenly elevated hydraulic overpressure would then induce sand sediment to be injected upwards through the more cohesive overlying muddy siltstone layers, forming sandstone dykes and mushroom-shaped sandstone intrusions, including sand volcanoes where there was sufficient and sustained feeding of sand sediment through a vertical conduit to the sediment–water interface on the seafloor (Figure 5). Also at this stage, sliding and block faulting, regulated by small-scale (usually <0.5 m in offset) normal faults, may also have taken place, as indicated by the presence at Warden Head of some shear zones interpreted as glide planes.

As the vibration forces of an earthquake propagated across the basin, the effects on soft, semi-consolidated sedimentary layers started to intensify. In the study area, this is manifested by sediment infilling the early-formed seismic cracks and fissures resulting in the formation of Neptunean sandy mudstone dykes. At the same time, the remobilised layers of soft, semi-consolidated sediment started to move downslope, or even in discrete lobes, although all seem to have moved in a general easterly direction (Figure 6). It is at this stage that most of the observed slump folds, flow rolls,

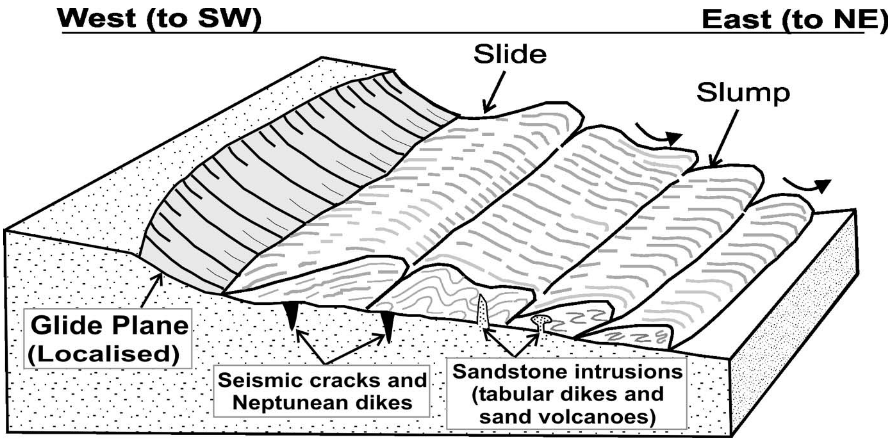

Figure 6 Schematic diagram (conceptual model) showing the formation of Neptunean sandy mudstone dykes (downward infillings into seismic cracks), sandstone intrusions (upward intrusive sandstone structures, including tabular dykes, conical sandstone intrusions and possible sand volcanoes), and the progressive downslope east to southeast transformation of slides through slump motions into sediment homogenisation during an earthquake event.

convoluted bedding, concave-up depressional structures were formed. During, or more probably towards the end of, this stage, localised homogenisation of the slumped layers appears to have taken place, resulting in the formation of breccias and rotated blocks. Also probably at this waning stage of the earthquake shock or shortly after it, sheets of coastal sand may have been transported into the slumped offshore area, resulting in the formation of localised thick- to massive-bedded, wedge-shaped and normal-graded sandstone units overlying the slumped siltstone beds, as seen at both Warden Head and Dolphin Point (Figure 2).

Finally, it is interesting to note that the timing of the above inferred earthquake event is broadly coeval with the onset of the Hunter–Bowen Orogeny (Harrington & Korsch 1985), although this cannot be concluded to imply a definite cause–effect relationship between them. The Hunter–Bowen Orogeny mainly affected the northeastern part of the Sydney Basin as the New England Fold Belt thrust westward over the Sydney Basin causing intense and extensive deformation and basin-wide subsidence (Veevers *et al.* 1994). It is therefore likely that the west-directed thrusting of the New England Fold Belt could also be responsible for the rapid subsidence of the southern Sydney Basin while the Wandrawandian Siltstone was being deposited, accompanied by submarine earthquakes causing liquefaction of soft-sediment layers and subsequent formation of sediment flow, sliding, and slump deformations. If this holds, it would be logical to suggest that the low-angle lateral thrust faults observed at Warden Head were formed during the later stage of this orogeny, probably in the Late Permian to Early Triassic, as a result of continued and perhaps intensified east–west compression of the southern Sydney Basin.

CONCLUSIONS

In conclusion, we consider that the cracks, sedimentary dykes (both elongate, tabular sandstone dykes and mushroom-shaped sandstone intrusions) and extensive soft-sediment deformation structures (slump folds, flow rolls, normal faults, slides, breccias, concave-up depressions, flexural stratifications) from the middle part of the Wandrawandian Siltstone at Warden Head and adjacent areas in the southern Sydney Basin represent an earthquake event deposit or seismite; they were formed in a moderately deep marine-shelf environment from mass movement of liquefied sediment and sedimentary layers. The timing of the inferred seismic shocks probably corresponded to the onset of the Hunter–Bowen Orogeny during the Middle Permian that caused basin-wide subsidence and instability.

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