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Analytical Structure of Soft Sediment Deformation

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Abstract - The Chaibasa Formation in Eastern India, which was deposited between 2100 and 1600 million years ago, shows deformations that must have formed when the sediments were not yet consolidated. Some of these deformation structures have never been described before. Here they are described, depicted and their origin is analysed. We show that they must be the result of shocks, which can only be explained satisfactorily as triggered by earthquakes. The layers containing these deformation structures are termed bseismitesQ. They are among the earliest records of earthquakes known in the Earth's history. Penecontemporaneous decimetre-scale soft-sediment deformation structures are reported from the basal part of the Upper Jurassic–Lower Cretaceous Vaca Muerta Formation, in the Malargüe–Las Leñas area of the back-arc Neuquén Basin (Mendoza Province, Central Andes). The deformed interval (Amarillas bed) is only 0.3 to 0.9 m thick but occurs in a wide area, larger than 1500 km2. Its age, determined by ammonite biostratigraphy, is Early Tithonian.

The soft-sediment deformation structures were generated in finely laminated, partially consolidated, organicrich, carbonate microbialites that were deposited in open-marine, poorly oxygenated settings, apparently devoid of any significant slope. Those structures include boudins of different sizes and complexity, a variety of folds, normal (listric) dm-scale faults, sub-horizontal detachment surfaces and other features, which are part of several larger-scale, complex slump structures. Deformation was dominantly plastic but near to the ductile–brittle field transition.

Several types of syndepositional deformation structures contain strain localization structures known as disaggregation bands. Abundant field examples from Utah show that such bands can be related to vertical movements linked to loading and fluid expulsion, forming a pre-tectonic set of strain localization structures in deformed sandstones that can easily be overlooked or misinterpreted as tectonic structures in petroleum reservoirs.

Plug measurements and thin-section investigations show that they have little or no influence on fluid flow. In contrast, disaggregation bands formed as a response to tectonic stress at higher confining pressures (depths) in the same lithology show up to 3–4 orders of magnitude reduction in permeability. This makes it important to distinguish between synsedimentary and tectonic deformation bands. They should also be separated because only bands formed in relation to tectonic stress can be used to predict nearness to important faults and to assess the extent of faulting in a reservoir.

The standard explanation for soft sediment deformation is associated with overturn of inverted density gradients. However, in many cases, observations do not support this interpretation. Here we suggest an alternative in which stably stratified layers undergo a shear instability during relative sliding via the Kelvin–Helmholtz Instability (KHI) mechanism, triggered by earthquake shaking. Dead Sea sediments have long stood out as a classical and photogenic example for recumbent folding of soft sediment. These billow-like folds are strikingly similar to KHI structures and have been convincingly tied to earthquakes. Our analysis suggests a threshold for ground acceleration increasing with the thickness of the folded layers.

The maximum thickness of folded layers (order of decimeters) corresponds to ground accelerations of up to 1 g. Such an acceleration occurs during large earthquakes, recurring in the Dead Sea.

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INTRODUCTION

The Chaibasa Formation in Eastern India, which is entirely siliciclastic, is 6–8 km thick. It is underlain by a granitic basement and siliciclastic sediments, and overlain by the Dhalbhum Formation (Saha, 1994; Bose et al., 1997). The formation cannot be dated directly, but the underlying volcanics are 2100 million years old (Roy et al., 2002a) and the minimum age of overlying lavas is 1600 million years (Roy et al., 2002b). The rocks suffered several post-depositional deformation phases, as well as greenschist to amphibolite facies metamorphism around 1600 Ma ago (Naha, 1965; Mazumder, 2005). Although the rocks described here are metamorphosed, we will refer to them as sandstones and mud/siltstones, to emphasize their character, as it was when the sediment layers described here were deformed.

The Chaibasa Formation consists of alternations of sandstones, heterolithic units (very fine sandstone/siltstone/mudstone) and shales. Layers with soft sediment deformation structures are abundant in its upper part. These structures show a wide variety of shapes and occur in units that are separated by un deformed intervals. Trigger mechanisms for the deformations have been analyzed following the approach suggested by Owen (1987), including distinction between synde positional and meta depositional deformation (Nagtegaal, 1963; Allen, 1982; Owen, 1995), and reconstruction of the deformational mechanisms.

Deformation can take place after a bed has been covered by younger layers (postdepositional deforma-tion); during the depositional process (syndepositional deformation); and after deposition but before the sediment is covered by a younger layer (metadepositional deformation). Determining whether deformation was syndepositional or metadepositional is of great importance for genetic interpretation. Seismic influences, for instance, may easily affect subaqueous sediments that are still being deposited and have had no time for consolidation, however slight; whereas metadepositional deformation affects surficial sediments that already have achieved some degree of consolidation.

Relatively few mechanisms can cause metadepositional deformation, and a shock (whether or not induced by earthquakes) is one of those mechanisms. Soft-sediment deformation structures related to earthquakes (i.e., seismites) are often preserved in deposits with contrasting granulometry, such as the alternating sands and argillaceous beds that characterize many alluvial plains, lacustrine environments, coastal and deltaic systems, and turbidite settings (e.g., Ringrose, 1989; Obermeier et al., 1989, 1993; Seth et al., 1990; Alfaro et al., 1997; Enzel et al., 2000; Alfaro et al., 2002; Rossetti and Santos, 2003; Jewell and Ettensohn, 2004; Singh and Jain, 2007; Fortuin and Dabrio, 2008; Perucca et al., 2009). More rarely, they have been described from more homogeneous sediments, such as fine aeolian sands (e.g., Moretti, 2000), sabkha evaporites (Bachmann and Aref, 2005), peritidal carbonates (Kahle, 2002), or lacustrine laminated deposits (e.g., Calvo et al., 1998). However, very little published documentation exists for soft-sediment deformation generated by seismic shocks that affect homogeneous, fine-grained sediments generated in open marine settings. Characterization of such levels, however, can have a noticeable importance in determining regional seismicity and synsedimentary tectonic activity in depositional settings that are commonly characterized by tectonic quiescence.

In this work we describe examples of soft-sediment deformation structures recognized in open-marine, finely laminated, organic-rich, micritic carbonates of Late Jurassic age, generated in the Neuquén Basin (Central Andes, Argentina). The aims of this paper are 1) to characterize these deformed deposits and their structures, and 2) to document their seismogenic origin and discuss their significance in the geodynamic evolution of the basin.

The ubiquitous stratification in low-energy deposits, where density typically increases with depth, inhibits gravitational instabilities of the Rayleigh–Taylor type. Yet such deposits commonly show structural evidence of mechanical instabilities experienced in the unconsolidated state. Layer-parallel displacements, not uncommon in soft sediments, force shear between layers and possibly drives instabilities of the Kelvin–Helmholtz (KH) type. Layer-parallel shear in post-depositional situations can be driven by a number of mechanisms such as sloping substrates or water flow above the sediments. Yet, soft sediment deformations are observed also on vanishing slopes and at calm water environments. Sediments in the Dead Sea basin provide long environmental records comprising finely laminated layers, radiometrically dated to a precision of tens to hundreds years. Laminated lake deposits, such as in the Quaternary Dead Sea, provide spectacular examples for such deformation structures. These structures have been tied to strong earthquakes, providing a source for shear energy. Earthquakes may leave several types of marks on soft laminated beds, including faulting, folding and fragmentation. Counting laminas (thought to represent seasonal deposition) provides a resolution approaching annual that recently enabled matching of particular deformed laminas to historically documented earthquakes.

The folding of soft sediments appears at various intensities, seemingly indicating various stages of the deformation. Folding can evolve from a wavy shape which can be distorted further to a billow-like or recumbent form. The layer may deform further and become fully turbulent, creating a thoroughly mixed breccia layer featuring fragments from the original laminas .

TYPES OF SOFT-SEDIMENT DEFORMATION STRUCTURES

1. Convolute bedding - forms when complex folding and crumpling of beds or laminations occur. This type of deformation is found in fine or silty sands, and is usually confined to one rock layer. Convolute laminations are found in flood plain, delta, point-bar, and intertidal-flat deposits. They generally range in size from 3 to 25 cm, but there have been larger formations recorded as several meters thick.

2. Flame structures - consist of mud and are wavy or "flame" shaped. These flames usually extend into an overlying sandstone layer. This deformation is caused from sand being deposited onto mud, which is less dense.

3. Slump structures - are mainly found in sandy shales and mudstones, but may also be in limestones, sandstones, and evaporites. They are a result of the displacement and movement of unconsolidated sediments, and are found in areas with steep slopes and fast sedimentation rates. These structures often are faulted.

4. Dish structures - are thin, dish-shaped formations that normally occur in siltstones and sandstones. The size of each "dish" often ranges from 1 cm to 50 cm in size, and forms as a result of dewatering. Pillar structures often appear along with dish structures and also form by dewatering. They have a vertical orientation, which cuts across laminated or massive sands. These formations can range from a few millimeters in diameter to larger than a meter.

5. Sole markings - are found on the underside of sedimentary rocks that overlie shale beds, usually sandstones. They are used for determining the flow direction of old currents because of their directional features. Sole markings form from the erosion of a bed, which creates a groove that is later filled in by sediment.

6. Seismites - are sedimentary beds disturbed by seismic waves from earthquakes. They are commonly used to interpret the seismic history of an area. The term has also been applied to soft sediment deformation structures, including sand volcanos, sand blows, and certain clastic dikes.

SOFT-SEDIMENT DEFORMATION INTERVAL

In the lower part of the Vaca Muerta Formation, the soft-sediment deformation is confined almost exclusively to one level, which is only a few decimeters thick, but shows a regional lateral continuity. Six zones covering an area of ~500 km2 (Amarillas Creek, Lagunilla, Cañada Ancha, Felipe Creek, Loncoche Creek and Bardas Blancas) have been investigated in the Malargüe–Las Leñas area in order to characterize this deformed interval.

All the six zones and the corresponding sections were analyzed for soft-sediment deformation structures and sampled for laboratory analyses and ammonite biostratigraphy. Among them, the Amarillas creek section, located a few kilometers west of the little town of Los Molles, exposes an 88 m thick stratigraphic interval; this offered the best possibilities for a detailed study, with well-developed structures along more than 500 m of excellent and continuous lateral exposure.

In this section, detailed sampling for biochronostratigraphic analysis allowed the sedimentary succession to be placed in the Tithonian. Ammonite biozones include from the Virgatosphinctes mendozanus. Zone (Lower Tithonian) up to the Corongoceras alternans Zone (Upper Tithonian) (Riccardi, pers. commun.). It should be noted that the good exposure of Vaca Muerta Fm. sediments in the area allows us to infer that this interval of softsediment deformation is a unique event. Other soft-sediment deformation structures appear through the stratigraphic sections (mostly affecting sandy layers towards the top of the unit), but their lateral continuity points towards a local origin.

SETTLING AND SEDIMENTATION

In high water content sedimentation tests, three different regimes or conditions can be identified Figure the “suspension” condition where particles do not form a skeleton capable of transmitting a shear perturbation ~effective skeletal stress s8=0 and shear stiffness G=0!; ~2! the “soft sediment” condition, which is a transition stage between the suspension phase and the soil phase, where the properties of the percolating granular skeleton are determined by long-range inter particle electrical forces ~s8=0 and G.0!; and ~3! the “Terzaghian soil” condition where behavior is determined by inter particle skeletal forces that result from applied effective stresses 8.0 and G.0. Been and Sills 1981 hypothesize that the transition stage is where the flocs in suspension come into contact with each other and start breaking up. Then, as more particles settle, the weight of the overlying particles decreases the inter particle distances and a soil forms Sridharan and Prakash 1998. Soil formation occurs due to particle movement and possibly due to a reorganization of the water structure, both of which are time dependent processes Zreik et al. 1997!. Thus, the accumulation rate of sedimenting particles is faster than the construction rate of the soil structure, resulting in creep Toorman 1999. The concept of inter particle contact becomes fuzzy in the case of fine particles and high water contents. In a very general sense, two particles are “in contact” when there is an interaction between them. Two particles in very close proximity interact through Born repulsion and hydration forces separation distance less than 10^{-9} m!. Long-range electrical forces can extend to about 10^{-8} m. Furthermore, particles can interact through hydrodynamic effects to a distance on the order of the particle diameter.

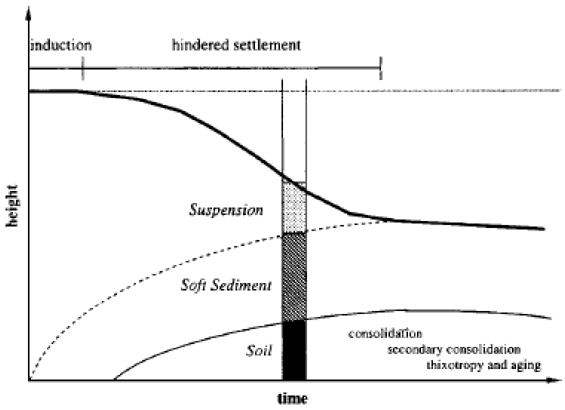

Figure: Sedimentation of high water content slurries. Three mixture conditions: suspension.

Discussion

Many of the soft-sediment deformation structures in the Chaibasa Fm. must be due to shocks. Considering the fact that most of these structures were formed synor metadepositionally in a deep-water environment, and also considering the fact that sedimentation took place in a tectonically active basin, a seismite origin of many of the deformed layers is by far more likely than any other origin. Strong evidence for such an origin is provided in particular by the collapse structures and the tabular depressions. In the case of the collapse structures, a shear plane developed between a bed with chaotic fabric and the overlying internally undeformed bed that collapsed. Earthquake waves cannot propagate across shear planes (Schwab and Lee, 1988), which explains the contrasting degrees of deformation in the two layers. In the case of the tabular depressions, a mechanism must have been active that enabled a large block of sediment, isolated from its adjacent material by more or less vertical cracks, to start moving upwards and to drift away, leaving a hole that gradually became filled up with laminated sediment. Considering that this process took place below storm wave base, hardly any other process than a fairly large shock can have triggered the movement of the block and its lifting. An earthquake seems by far the most plausible trigger mechanism.

Laminated fine-grained sediments, deposited on horizontal bottom under low-energy conditions, are expected to be stably stratified, so density increases with compaction and hence with depth. Since gravitational Rayleigh–Taylor instabilities are not likely under these conditions, alternative mechanisms should be at work. From an observational aspect, the striking similarity of structures in fine-grained laminated deposits to KHI billows, suggests that shear plays a central role in soft sediment deformation.

CONCLUSION

The extraordinary areal extent of soft-sediment deformation in the lower part of the Cotham Member suggests an exceptional cause. The most parsimonious interpretation is for a major seismic event triggering in situ foundering of poorly consolidated sediments, but its exact cause remains enigmatic. The seismite may represent separate earthquakes affecting individual basins, only appearing to represent a single event as a consequence of the limits of stratigraphic resolution and correlation between basins. However, its consistent position in the lower part of the Cotham Member, the lack of any evidence for more than one deformational event even at its thickest development, and the absence of similarly widespread phenomena in contiguous parts of the geological column, do not favour such a multipleevent scenario. Preferred orientations of slump-fold long axes from different sites are somewhat equivocal with regard to identifying a single epicentre. Although not showing the wide scatter that might be expected from independent earthquakes, the data also lack the tight focus that might arise from a single epicentre. The pattern observed may instead reflect the interaction of seismic shock waves with local geological and sedimentological anisotropies, or the triggering of more localized earthquakes by an impact generated shock wave.

The soft-sediment deformation structures are reported from the Amarillas bed, located in the basal part of Vaca Muerta Formation in all the studied outcrops of the Malargüe–Las Leñas area (Mendoza Province). The Amarillas bed is 0.3 to 0.9 m thick but extends over 1500 km2, and its age has been constrained in all the studied outcrops by ammonite chronobiostratigraphy (V. mendozanus Zone, Early Tithonian). The deformed interval as a whole is underlain and overlain by undeformed strata. Its isochronous nature is also supported by its invariable stratigraphic position in all studied sections.

The soft-sediment deformation structures were developed in finely laminated, partially consolidated, calcareous microbialites, deposited in open-marine, poorly oxygenated settings, apparently devoid of any significant slope. These deposits were deformed early after sedimentation.

At the time of soft-sediment deformation, the microbialite facies were characterized by high cohesion, high natural shear strength and high sensitivity to plastic or brittle deformation. The integration of fine material and microbial mats probably imparted high cohesion to these deposits from the moment of sedimentation.

On the contrary, they were not prone to extensive fluidization. On the basis of the observed soft-sediment deformation structures, their wide distribution, their lateral homogeneity, and the geodynamic framework of the basin in which they were generated, the Amarillas bed can be tentatively attributed to a large intermediate-depth earthquake that could have occurred within the plate that subducted beneath the Andean continental margin and the Neuquén back-arc basin.

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