Journal of
Sedimentary
Research

Journal of Sedimentary Research, 2007, v. 77, 256–262
Current Ripples
DOI: 10.2110/jsr.2007.032

TSUNAMIS IN A STORMY SEA: MIDDLE CAMBRIAN INNER-SHELF LIMESTONES OF WESTERN ARGENTINA

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ABSTRACT: **Coarse-grained strata deposited on continental shelves and epeiric seas in some tens of meters' water depth are conventionally ascribed simply to storms of varying intensity which interrupted the settling out of suspended mud. Surprisingly, the possibility of tsunamis is virtually never evaluated even though they might, indeed should, have been common in many regions. Portions of the Middle Cambrian La Laja Formation of the Argentine Precordillera formed in such a submerged epeiric platform or shelf. They comprise a suite of three limestone facies: variably argillaceous burrowed mudstone, bioclastic grainstone, and intraclastic conglomerate composed of pieces of mudstone including cemented haloes around burrows. Sporadically developed eocrinoid meadows and trilobite populations are recorded respectively by disarticulated ossicles and usually broken sclerites. The latter indicate that, generally, exoskeletons became fragmented by repeated bottom turbulence. Hence, the mudstones and grainstones show that, before stabilization by calcite cementation which began beneath the sediment–water interface and away from burrow margins, physical reworking of the surface sediment by storms was so frequent that it did not leave a specific signature of individual events. By contrast, scattered lenticular beds of intraclastic conglomerate were due to anomalous, brief episodes of deep scour and strong oscillatory flow from powerful wave action. These conglomerates then escaped subsequent reworking. Because they are abruptly interbedded and encased within uniform mudstone, and there are no stratigraphic patterns, allochthonous material, or unconformities to indicate sea-level fluctuation, the events that created the conglomerates were more likely tsunamis, not storms. They could have been unleashed by faulting elsewhere on the shelf or rifting beyond the shelf margin to the (present-day) west to southwest. Those originating in the rift basin may have been diffracted by marginal shoals and attenuated by the shallowness of the platform which caused the waves to break some distance offshore. In any case, the study area was not affected by backwash. Recognition of tsunami-laid beds urges a reexamination of the standard tempestite paradigm with its use of coarse-grained strata as a simple measure of storm frequency and intensity.**

INTRODUCTION

A tsunami is a long-period wave train triggered by submarine faulting, landslide, volcanism, or bolide impact which displace a large mass of water and thereby generate an energy pulse. In a typical event the coast is swept by a series of incoming waves minutes to tens of minutes apart. Nearshore wave heights of several tens of meters and run-up heights of over 100 m have been experienced in historical times (Bryant 2001). (For comparison, the 26 December 2004 tsunami involved a maximum run-up height of $\sim$ 30 m on parts of northwestern Sumatra [e.g., http://walrus.wr.usgs.gov/tsunami/sumatra05/index].) Successive waves suspend nearshore sediment and carry some of it inland. Through backwash, or off-surge, the sea bottom suffers more scour and large volumes of material are carried seaward.

Tsunami-laid sediments have been identified with reasonable certainty in a number of Holocene coastal areas around the Pacific Ocean because they have structures indicative of anomalously high energy and can be correlated to historical or well-dated events (e.g., Kelsey et al. 2005; Bourgeois et al. 2006). Tsunami deposits on beaches and in shallow bays in Japan have erosional bases, consist of bundles of poorly sorted layers, contain both reworked and transported shells, and are laterally variable due to the combined effects of incoming waves and backwash, coastal geomorphology, and local bathymetry (Fujiwara et al. 2000; Nanayama et al. 2000; van den Bergh et al. 2003). Associated beds laid down by typhoons are internally simpler and better sorted (Nanayama et al. 2000). Both storm and tsunami effects get obscured or erased by quotidian processes, especially later storms and bioturbation. Unsurprisingly, then, only a small number of nearshore sandstones and conglomerates have ever been ascribed with confidence to tsunamis (Massari and D'Alessandro 2000; Rossetti et al. 2000; Dypvik and Jansa 2003; Schnyder et al. 2005; Fujino et al. 2006).

By contrast, in one of the most commonly preserved sedimentary environments in the rock record—that of offshore shelves or platforms of minimal slope below fair-weather wave base and above storm wave base—distinguishing between storm deposits ("tempestites") and tsunami deposits ("tsunamites") presents a particular challenge because this setting is held to be conducive to preserving individual high-energy sedimentation events. From both continental margins and epeiric seas they are typically a succession of mudstones (siliciclastic or calcareous) punctuated by coarser-grained beds of sandstones, ooidal or bioclastic grainstones, shell accumulations, or intraclastic (often "flat-pebble") conglomerates (rudstones). The standard explanation for these kinds of

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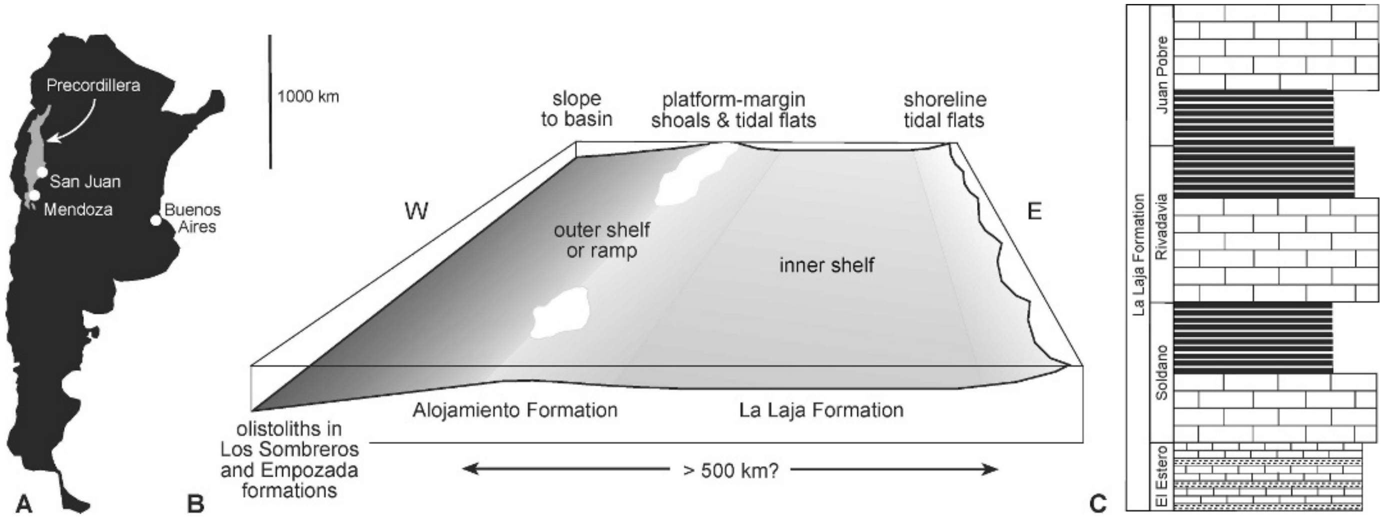

FIG. 1.—**A)** Map of Argentina showing location of Precordillera terrane. Studied outcrops of La Laja Formation are close by city of San Juan, on Cerro Tres Marias and in Quebrada de Zonda, Sierra Chica de Zonda. More detailed geological maps are in Baldis and Bordonaro (1981), Keller (1999), and Bordonaro (2003a, 2003b). **B)** Paleogeographic reconstruction of west- to southwest-facing carbonate platform or shelf, perhaps > 500 km wide, as recorded by Middle Cambrian strata. The shelf was part of a passive margin that probably faced a small rift basin adjacent to southeastern Laurentia (e.g., Thomas and Astini 2003). Upper slope/ramp/outer shelf facies and discontinuous marginal shoals and tidal flats are represented by Alojamiento Formation; scattered olistoliths in Upper Ordovician shales are also composed of deeper-water facies. La Laja Formation was deposited in protected inner shelf; shore-fringing tidal flats are inferred. (Modified from Keller 1999, his fig. 9; Bordonaro 2003b, his fig. 4). **C)** Stratigraphy and schematic weathering profile of La Laja Formation and its four members in San Juan area. Thin brick pattern with dashed lines denotes heterolithic El Estero Member, with minor sandstone interbeds. Large brick pattern denotes medium- to thick-bedded limestones, representing shallow-water carbonate banks locally exhibiting high-energy ooidal shoals. Horizontally striped portions are mostly rubbly weathering, thin-bedded lime mudstone deposited in somewhat deeper water; the upper Soldano and lower Juan Pobre members are slightly argillaceous and therefore the most recessive.

beds is that they represent storm deposits in which material is either allochthonous (transported from shallower areas) or autochthonous (derived from *in situ* erosion and winnowing) (e.g., Aigner 1985; Liang et al. 1993; Meng et al. 1997; Saltzman 1999; Myrow et al. 2004; DiBenedetto and Grotzinger 2005). Remarkably, only a handful of studies have attempted to identify tsunamites (Pratt 1998a, 1998b, 2001, 2002), even though tsunami waves could have been common in many regions and potentially could have reached a much greater magnitude than those from available storms. This neglect plus a dearth of information about tsunami deposits off modern coasts and uncertainties about tsunami wave mechanics in broad shallow shelves mean that criteria to recognize them in ancient offshore settings have yet to be elaborated (e.g., Dawson and Stewart in press).

Here we report a new and instructive example in which trilobite paleoecology and taphonomy illuminate the role of storms and thus enable us to recognize with confidence individual tsunami events.

FACIES ASSOCIATION

The Lower Cambrian to Lower Ordovician of the Precordillera of west-central Argentina (Fig. 1A) formed a (now west- to southwest-facing) epeiric carbonate platform or shelf perhaps exceeding 500 km in width (Fig. 1B; Keller 1999; Bordonaro 2003b). The Precordilleran terrane is allied to lower Paleozoic North America (Laurentia) by virtue of its biogeographic attributes, and it is commonly reconstructed as a piece of the craton rifted from southeastern Laurentia before being sutured much later onto Gondwana (e.g., Thomas and Astini 2003). La Laja Formation forms the lowest part of the succession and is late Early to late Middle Cambrian (Bordonaro 2003a, 2003b; Bordonaro and Pratt, in preparation). It is subdivided into four members (Fig. 1C). Compared to the other portions, which represent shallow-water, locally ooidal carbonate banks (Keller 1999; Gómez and Astini 2005), the upper Soldano and upper Rivadavia through lower Juan Pobre members are considered to have accumulated in the inner-shelf area under somewhat deeper water: below fair-weather wave base but above ambient storm wave base, and landward of a probably discontinuous barrier of shoals and tidal flats (Keller 1999). The sea bottom would have been flat and practically featureless, and water depth would probably have been in the range of 10–20 m. These intervals contain the putative tsunamites over a combined stratigraphic thickness of ~ 150 m, which we examined in bed-by-bed detail in two sections located 10 km apart. The Cerro Tres Marias section was slightly more landward because it contains a cross-laminated sandstone unit 5 m thick in the upper Soldano Member, which is represented in the Quebrada de Zonda area by thin-bedded, glauconitic sandy limestone. Likewise, the upper Rivadavia Member is barren of trilobites at Cerro Tres Marias but carries a fauna in Quebrada de Zonda. Severe folding in El Estero and lower Soldano members in both places precludes accurate palinspastic restoration, but an original separation of at most some tens of kilometers is envisaged.

Three limestone facies are distinguished: the fine-grained host and two interbedded coarser-grained facies (Fig. 2). Given outcrop geomorphology and the lenticular nature of the coarser beds, their true stratigraphic distribution cannot be determined with certainty. However, while their relative abundance does vary we perceive no evidence for any stratigraphic pattern such as cyclicity or relative sea-level fluctuation and no obvious unconformities or major erosion surfaces within the mudstone units.

Mudstone and Grainstones

Mudstones exhibit tabular to lenticular thin bedding (Fig. 3A), are locally peloidal and rippled (Fig. 3B), and are riddled with calcite-spar-filled, horizontal tubular burrows ~ 2–7 mm wide, referable to *Palaeophycus* and *Thalassinoides* (Fig. 3C), which were made mainly by deposit-feeding worms. Bed contacts are more or less planar or bioturbated, and lack distinctly downcut scour surfaces. Body fossils are practically absent, limited to very rare, dispersed trilobite sclerites from molted exoskeletons and disarticulated carcasses, or scattered ossicles from disaggregated eocrinoid echinoderms.

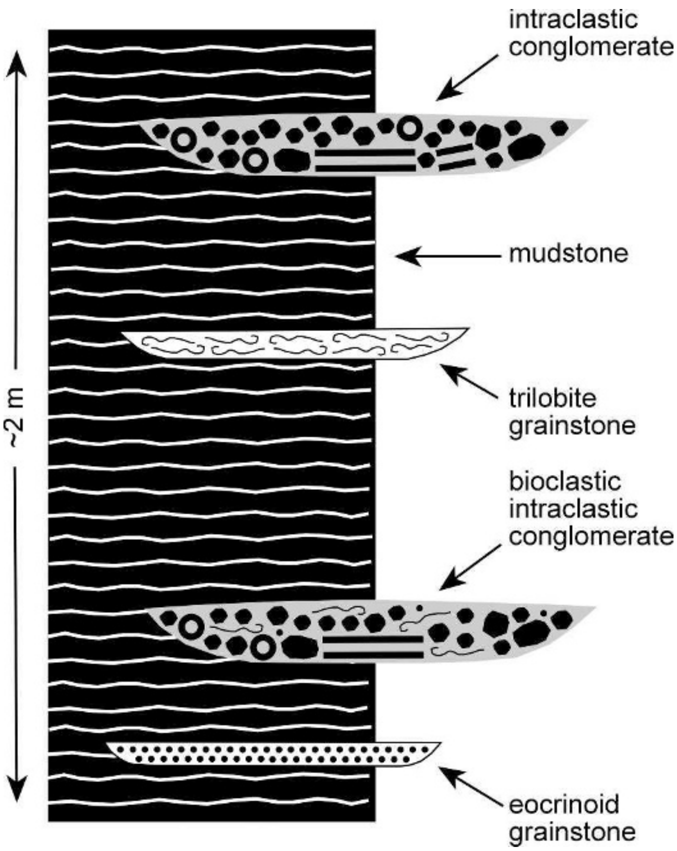

FIG. 2.— Stratigraphic motif of hypothetical ~ 2-m-thick interval broadly representative of portions of La Laja Formation consisting of thin-bedded lime mudstone with scattered thick laminae and thin beds of trilobite and eocrinoid grainstones (patterned with diagrammatic sclerites and stipples, respectively), and thin- to medium-bedded intraclastic conglomerate (gray with diagrammatic intraclasts and bioclasts). (Relative abundance of these facies does vary: bioclastic grainstones are rare in the upper Rivadavia Member, and intraclastic conglomerates are rare in the uppermost Soldano Member.) Column depicts seemingly random and abrupt interbedding of lenticular coarse-grained limestones, implying occasional patchy development of benthic invertebrate fauna, countless storms, and infrequent tsunamis.

Instead, fossils are concentrated into bioclastic grainstone laminae and, rarely, thin beds which are intercalated here and there with the mudstones. These grainstones are lenticular at the meter scale (Fig. 4A). Trilobite sclerites occur as rare thin pavements and coquinas with sharp planar bases. The fauna in any one bed is of low diversity, typically comprising only one or two species of mainly adults (holaspides) that were ~ 0.5–3 cm in length. In some laminae cranidia and pygidia are complete and mostly oriented convex upward (Fig. 4B), but otherwise the sclerites are variably fragmented (Fig. 4C), in places down to flakes less than ~ 1–2 mm across (Fig. 4D); the degree of fragmentation is broadly uniform within individual layers. Other grainstones are eocrinoid encrinites. Both kinds of grainstone may contain some admixed sclerites and ossicles, respectively, but mudstone intraclasts are notably absent.

Intraclastic Conglomerate

Lenticular beds of intraclastic conglomerate occur sporadically and are abruptly interbedded (Fig. 5A), the most frequent being three in one meter in the lowermost Juan Pobre Member and a couple of examples where two layers appear amalgamated. Beds range from less than one meter to several meters wide (Fig. 5B), although shape in plan view cannot be determined at either locality; however, linear features like channels and gutters are effectively absent. Bed contacts are sharp, and bases are commonly scoured, up to ~ 10 cm, while tops are sometimes gently convex upward. In thickness, most beds are 3–5 cm, some reaching 10 cm and rarely 20 cm.

Mudstone intraclasts are granule- to pebble-sized and angular to subangular, although subrounded in a few beds. They are commonly blocky to shard-like in shape, but many are whole and broken tubes ~ 5–10 mm in width and up to ~ 5 cm in length, with walls ~ 1–5 mm thick (Fig. 5C, D)—these are pieces of cemented haloes around burrows (see also Gómez and Astini 2004). (The intraclasts do not have a flat-pebble shape because they were not eroded from thin layers sandwiched between soft muds.) In some beds where intraclasts are elongate they show crude, variably directed imbrication (Fig. 5D). Mud usually forms geopetal fillings in shelter pores under intraclasts and inside tubes; a few trilobite sclerites and eocrinoid ossicles are admixed in some beds.

DEPOSITIONAL SETTING

Background Processes

Fallout of suspended lime mud, its bioturbation and pelletization, and reworking by innumerable storms which caused only rather weak turbulence and produced sedimentary structures no greater than small ripples, represent the background depositional processes (Fig. 6). Storm effects were probably not especially severe, given the likelihood that the shelf faced a relatively narrow rift basin and the interior was probably somewhat protected by discontinuous marginal shoals, as well as the broad latitudinal belts characteristic of the greenhouse Cambrian.

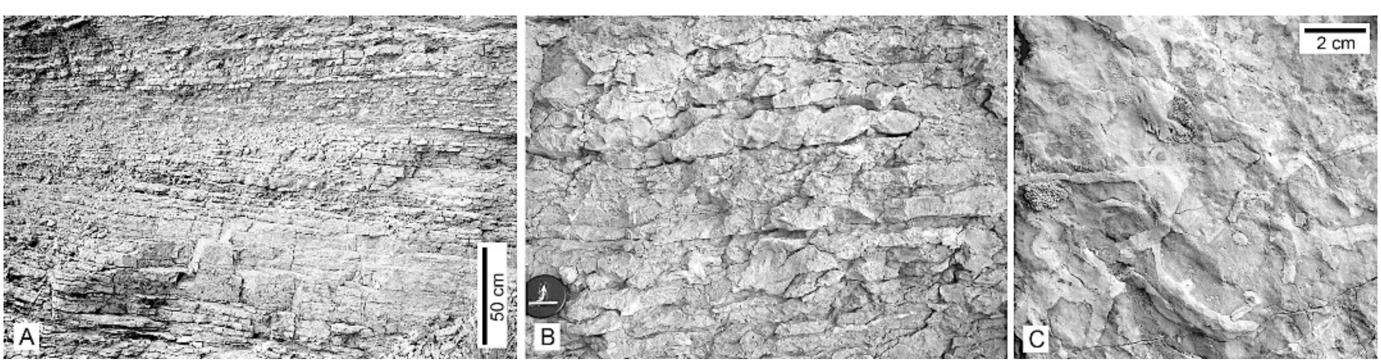

FIG. 3.—Mudstone facies. **A)** Thin and wavy bedding; variable argillaceous content is reflected by recessiveness. Upper Soldano Member, Quebrada de Zonda (south side). **B)** Thin and wavy beds, locally with rippled tops. Lower Soldano Member, Cerro Tres Marias; lens cap is 5 cm wide. **C)** Bed surface showing dolomite-replaced *Thalassinoides* burrows. Lower Juan Pobre Member, Cerro Tres Marias.

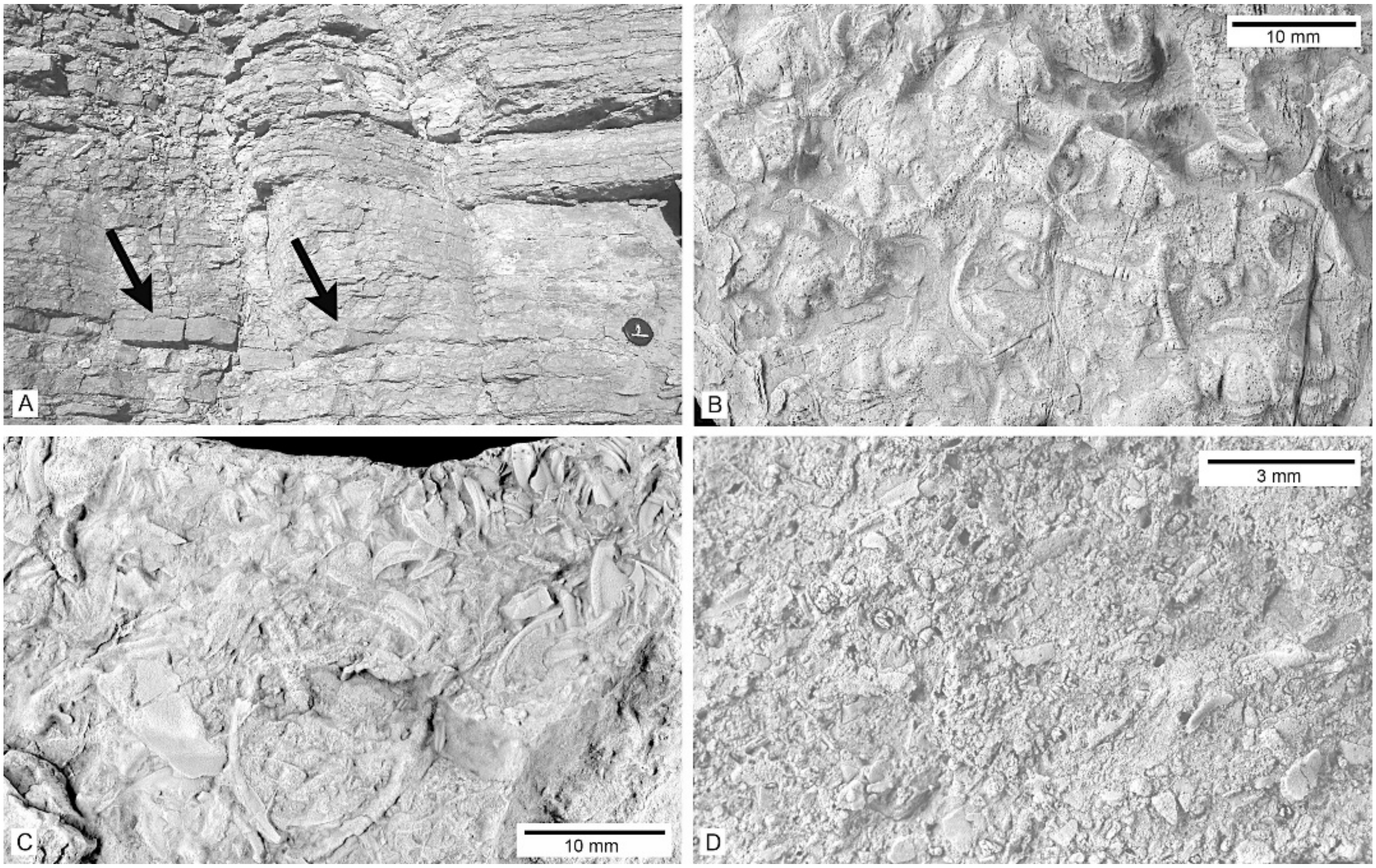

FIG. 4.— Grainstone facies. **A)** Thin- and locally wavy-bedded mudstone with lenticular thin bed of bioclastic grainstone (arrowed; bed appears offset due to perspective on corner of the exposure). Upper Soldano Member, Cerro Tres Marias; lens cap (lower right) is 5 cm wide. **B)** Bed surface of disarticulated but unbroken trilobite sclerites. Lower Juan Pobre Member, Cerro Tres Marias. **C)** Bed surface of broken but still fairly large trilobite sclerites. Upper Rivadavia Member, Quebrada de Zonda (south side). **D)** Bed surface of tiny trilobite fragments and eocrinoid ossicles. Middle Soldano Member, Cerro Tres Marias.

The mud started to become solidified by microcrystalline calcite cementation which began a few centimeters beneath the sediment–water interface and away from the walls of empty burrows. (This and other examples of similar intraclasts [e.g., Saltzman 1999] show that preferential early cementation around burrows is not uncommon in Cambrian limestones, arguing against the notion [Sepkoski 1982] that intraclastic conglomerates simply reflect a lack of substrate modification by infaunal animals.) It is probable that substrate cementation proceeded relatively uniformly in this part of the shelf because the mudstone exhibits no distinct scour surfaces that would suggest lateral inhomogeneity, and grainstones lack even small intraclasts. This cementation eventually rendered the shallowly buried sea bottom impervious to the typical levels of storm-induced scour experienced in this setting.

Bioclastic grainstones record short-lived populations of trilobites and eocrinoids which became established due to temporarily favorable ecological conditions such as availability of appropriate food resources. The laterally impersistent nature of the grainstones was due to the patchy distribution of these benthic animals. (The suggestion that such grainstones might have formed by repeated winnowing and concentration of bioclasts that were perennially present and widely dispersed in the mud [Westrop 1986] is rejected for these units because of the rarity of fossils in the mudstone and the overall scarcity of grainstones.) Unless they were buried and cemented quickly, trilobite sclerites lying on the sea bottom were progressively comminuted by repeated events of the same low levels of storm-induced turbulence that reworked the muds. While these sclerites were rigid, the thinness of the exoskeletons of the specific taxa and their microstructure of elongate, surface-normal calcite crystals gave them comparatively little mechanical strength. Evidence of breakage by predators (see Pratt 1998c; Zhu et al. 2004) is lacking. There is no way to judge the frequency of storms because each grainstone bed represents an ecological phenomenon typically followed by many episodes of reworking. Thus, neither the grainstones nor the mudstones retain a signal of individual events.

Impact of Tsunamis

By contrast, intraclastic conglomerates punctuating this comparatively low-energy succession record erosive wave events of exceptional magnitude, because these tore into the lithifying mud, especially via burrow systems, elevated pore pressure until localized rupture occurred, swept the resulting intraclasts into lenticular beds, and at times left them imbricated. The exact rheology of these cementing muds is unknown, but they were sufficiently stiff, especially around burrows, to have suffered brittle failure and survived transport by oscillatory currents. The angularity of the intraclasts in most beds implies that, by and large, they were not exposed to subsequent reworking (although in a few cases they probably were).

The observations that there is no stratigraphic pattern to the conglomerates and that, rather, sedimentation returned abruptly to its prior muddy style indicate that these beds did not involve shifting bathymetry due to allogenic causes such as changing sea level. There is no perceptible intergradation between grainstones and conglomerates to

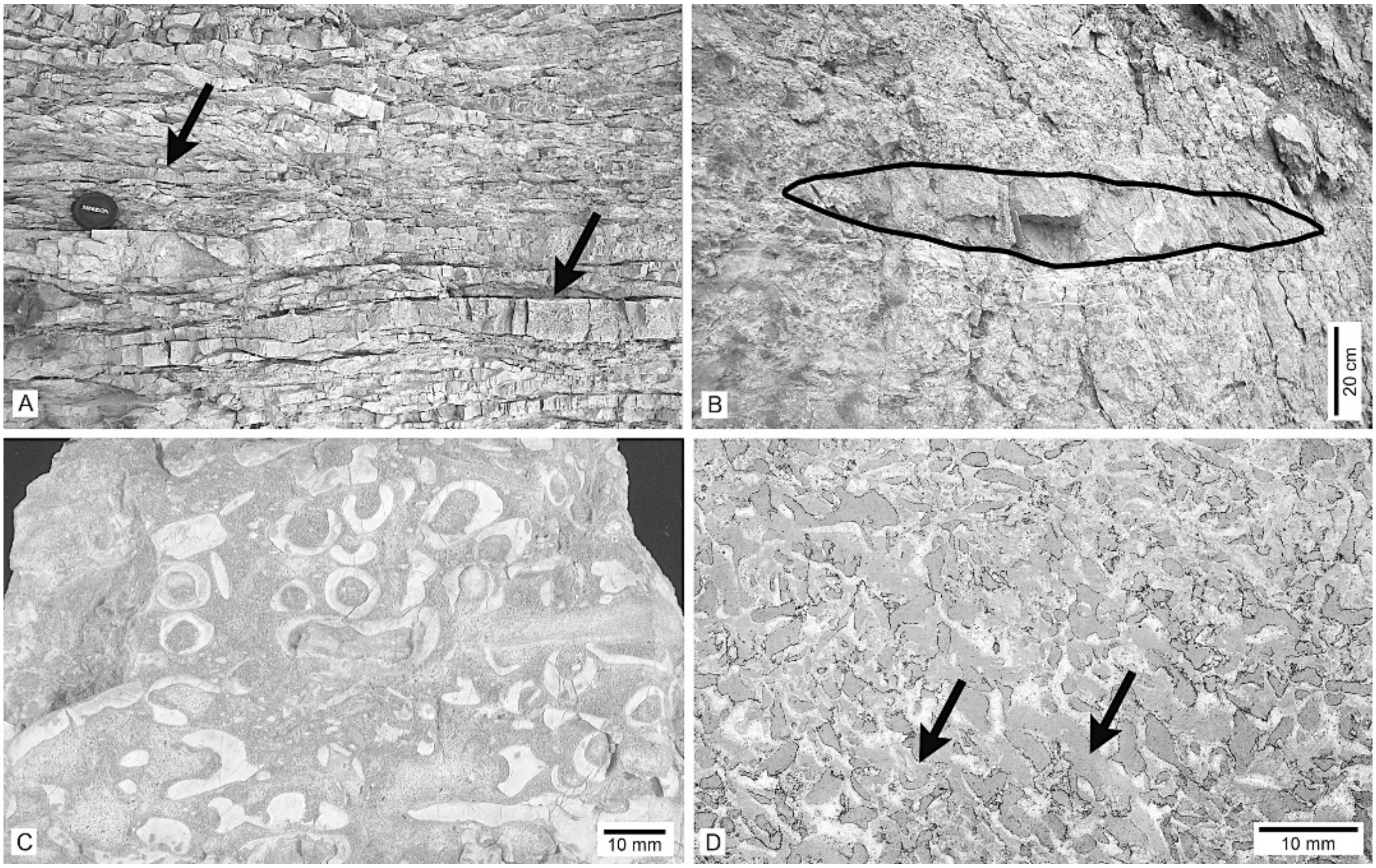

FIG. 5.—Conglomerate (rudstone) facies. **A)** Thin- and wavy-bedded mudstone with thin lenses of intraclastic conglomerate (arrowed). Lower Juan Pobre Member, Quebrada de Zonda (north side); lens cap is 5 cm wide. **B)** Thin-bedded mudstone enclosing medium-bedded lens of intraclastic conglomerate (outlined); upper surface of lenticular bed is gently convex. Upper Rivadavia Member, Quebrada de Zonda (south side). **C)** Coarse sand- to pebble-sized mudstone intraclasts. Most larger intraclasts are recognizable fragments of cemented, tubular burrow walls. Lower Juan Pobre Member, Cerro Tres Marias. **D)** Acetate peel showing crudely imbricated, angular and subangular mudstone intraclasts of various sizes, with interparticle pores locally floored by micrite. Some intraclasts are recognizable burrow wall fragments (arrowed); also admixed are scattered eocrinoid ossicles and rare trilobite sclerites. Lower Juan Pobre Member, Cerro Tres Marias.

suggest a continuum between weak and exceptionally powerful storms that would account for the range in effects. In addition, it is difficult to envisage that the distinct hydraulic jump needed to erode a local area of cementing mudstone could have been achieved by such a continuum.

Thus, we consider that large tsunamis are the only agent available to produce the anomalous degree of scour implied by the conglomerates (Fig. 6). Presumably the biggest waves of the wave train accomplished the scouring and set intraclasts into suspension, and they were moved to and fro before settling out as the event waned. Mud then drifted into the spaces between the intraclasts or during weak turbulence from later storms or minor tsunamis. Given the likelihood of a range of tsunami size, below a threshold when they could no longer erode the lithifying muds their effects would be indistinguishable from those of the stronger storms.

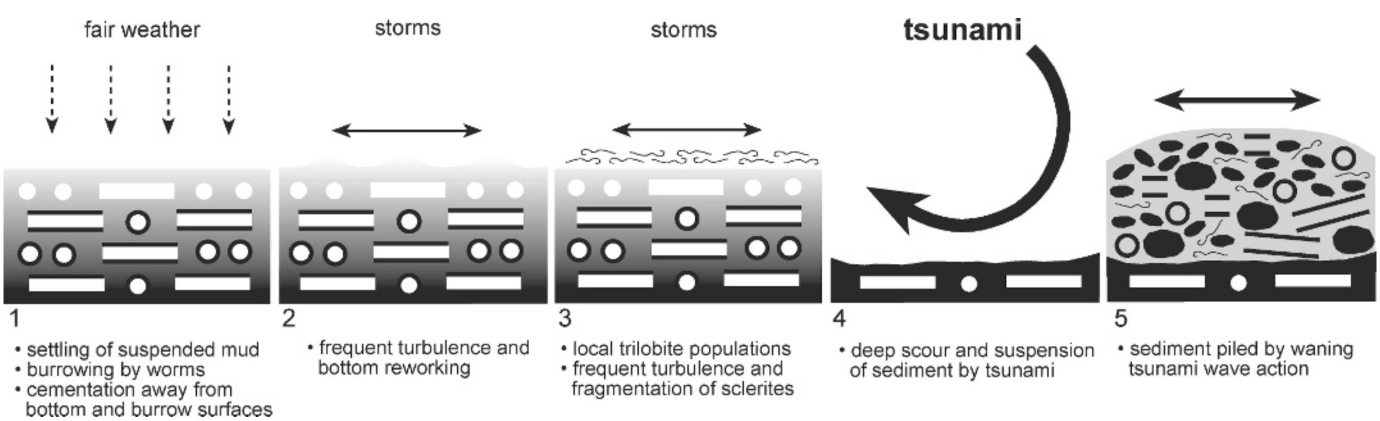

FIG. 6.—Model of sedimentation in Middle Cambrian inner carbonate shelf represented by La Laja Formation.

DISCUSSION

La Laja Tsunamis

Compared to wind-driven waves tsunamis have a much greater velocity (some 500–800 km h^{-1} over the ocean), a much longer wavelength (tens to hundreds of kilometers), and consequently periods of tens of minutes. Eyewitness accounts of incoming tsunamis describe the striking amount of suspended sediment, and deeper-water microfossil assemblages in tsunami-laid sediments on modern coasts attest to the ability of tsunami waves to scour and transport material from considerable depths (e.g., Dominey-Howes et al. 1999; Bahlburg and Weiss in press). Pickering et al. (1991) calculated that significant sediment movement should not occur on the sea bottom below 200 m deep. Nevertheless, the effects of recent tsunamis in offshore areas have yet to be studied, which hampers comparison with possible ancient counterparts.

Tsunami waves slow markedly and gain dramatically in height when approaching shallow water. Because the La Laja shelf was a broad, more or less featureless, low-gradient surface, large tsunamis could have shoaled far from shore, forming spilling breakers, losing some of their energy, and eventually becoming turbulent bores (see Noormets et al. 2004). For example, on a nearly horizontal sea bottom a wave with a height of ~ 5 m would start to break in water depths of ~ 10 m (Massel 1997). Nonetheless, the theoretical behavior of a tsunami wave train sweeping onto an epeiric shelf or generated within an epeiric sea is not clear, since analogs are nearly absent in modern seas and oceans, and to our knowledge no attempts at modeling these types of situations have been made.

Energy transferred to the sea bottom from a large tsunami naturally creates pore pressures in the sediment that are more immediately elevated than those from gradually building storm waves at comparable depths. Tsunami effects can be preserved if they escape reworking by the strongest storms which would be expected in general to occur much more frequently (see also Weiss and Bahlburg 2006). Tsunamites should therefore be distinguishable from tempestites in the inner La Laja shelf by the degree of erosion relative to the type of sediment present. Because both kinds of deposits are interpreted to occur together here, intraclast shape indicates that typical levels of ambient storm-induced turbulence, while strong enough to rework mud and bioclasts, must generally have been too weak to rework the conglomerates.

Where discontinuous banks and tidal flats were present along La Laja shelf margin, tsunami waves originating seaward of it would have broken over them, whereas those passing through could have been diffracted to some extent. Edge waves would have been created along and behind these obstacles. These factors plus the shallowness of the shelf causing waves to break offshore would have led to weaker and more irregular effects compared to what would be expected on an unobstructed coast with a more steeply inclined shelf. Combined, they may have been responsible for the localized scour surfaces characterizing the intraclastic conglomerate beds.

The lack of linear scours, channels, and allochthonous sediment suggests that the inner shelf in the San Juan area did not experience shore-normal, unidirectional traction currents. The reason for this is unknown, but could include: (1) the coast was too far away such that backwash had dissipated; (2) backwash currents interfered with waning tsunami waves; (3) the tsunami waves had decayed to a large extent by the time they reached the coast; or (4) the coast was geomorphologically too complex to generate strong backwash.

In the many hundreds of meters of La Laja Formation examined, we have found but two beds, both in the lower Soldano Member, that possess deformation structures (one with convolute lamination and the other with syneresis cracks) that might be taken to record synsedimentary earthquakes. Thus, the putative tsunamis may have been generated by fault displacement somewhere else on the shelf. Or, they may have been triggered by faulting seaward of the shelf–slope break far to the (present-day) west to southwest, probably during rift-block motion. Because the shelf margin may have faced a companion rifting margin across a narrow ocean basin, tsunamis could have originated there as well. In addition, seiche-like effects could have arisen due to reflection. In any case, the tectonic setting was such that tsunamis should have impacted the carbonate shelf.

Other Offshore Shelf Tsunamites

In prior examples of putative tsunamites in offshore successions (Pratt 1998a, 1998b, 2001, 2002) the likely rarity of tsunamis versus an expected high meteorological frequency of storms helps make the interpretation compelling, even though the specific effects in each case are different than those in La Laja Formation. In the Deadwood Formation (Upper Cambrian) of central Montana, lenticular beds of intraclastic conglomerate (flat-pebble in this case) interrupt a succession of thin-bedded, fine-grained calcareous sandstone and shale. The sandstone beds were likewise rigid due to incipient synsedimentary microcrystalline calcite cementation, but there most possess crack arrays caused by the passage of earthquake waves through shallowly buried sediment. In addition to the dramatic contrast in levels of bottom turbulence between the finer-grained host facies versus the conglomerates, the polygonal outline of the intraclasts in most beds indicates that they were subjected to a single, brief event of erosion and deposition—likely from tsunamis that episodically swept across the shallow epeiric sea (Pratt 2002). However, as in La Laja shelf, backwash currents did not affect this area.

Low-energy siliciclastic and calcareous mudstones comprising, respectively, much of the lower and middle Belt Supergroup (Mesoproterozoic) of central-western North America are similar to the Deadwood Formation in that they contain features interpreted to have been generated by earthquake-induced shaking, but in this case abundant shrinkage–injection features (syneresis cracks and molar-tooth structure). Beds of coarse-grained, well-rounded sandstones containing mud rip-ups, or sandy ooidal grainstones containing fragments of molar-tooth vein fills, are sporadically and abruptly intercalated. These coarse beds overlie commonly linear scour surfaces and typically exhibit wave-ripple, combined-flow, or hummocky cross-stratification. The scoured bases of these sandstones and grainstones, their anomalous composition compared to the host mudstones, the strongly contrasting current strengths indicated by sedimentary structures, and their punctuational occurrence collectively point to an origin from strong backwash currents coupled with wave reworking by oscillatory currents (Pratt 1998a, 1998b, 2001).

CONCLUSIONS

Widespread early cementation of muddy and sandy calcareous sediment just beneath the sediment–water interface was a characteristic diagenetic process in relatively shallow, tropical shelves or platforms of Proterozoic through Early Ordovician age. The taphonomy of trilobite exoskeletons in an example of this offshore setting, as recorded by Middle Cambrian limestones of western Argentina, namely that sclerites were progressively fragmented by repeated physical impact, confirms unequivocally that countless occasions of storm-generated turbulence took place without eroding the lithifying mud. Therefore, those events that did lead to deeper scour and intraclast formation were exceptional, and due to outsized waves: we consider that these must have been major tsunamis. The lenticular geometry of the intraclastic conglomerate beds, which implies localized failure of the seafloor, may partly have been because the tsunami waves broke offshore. These tsunamis originated elsewhere in the shelf or, most commonly, in the rifting basin to the (present-day) west to southwest. However, the lack of allochthonous coarse material and linear scours means that this part of the shelf was not affected by strong backwash currents. Either they were attenuated by distance, or they did not develop because of the specific coastal geomorphology or the nature of the tsunami waves themselves. We have not recognized tsunamites in the thicker bedded intervals, probably because in the shallow-water carbonate banks they were vulnerable to reworking.

Our interpretation calls into question the assumption that coarse facies in offshore shelf successions simply represent storm deposits. Moreover, it casts doubt on the widely held inferences that storm frequency and intensity or relative sea-level change can be gauged reliably on the basis of the stratigraphic distribution of these facies. Thus, not only do further criteria need be developed for the recognition of tsunamites applicable to other examples, but also necessary is a reconsideration of the tempestite paradigm in general, in order to distinguish the two processes and thereby avoid misleading sedimentological, tectonic, and paleoclimatic reconstruction.

ACKNOWLEDGMENTS

We thank the Natural Sciences and Engineering Research Council (NSERC) and the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) for supporting our research on Cambrian trilobites of the Argentine Precordillera. We are grateful to H. Bahlburg and K.K. Poelzer for discussion, and A.G. Plint, G. Shanmugam, S. Reeder, and an anonymous referee for comments to previous manuscript versions.

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Received 23 June 2006; accepted 2 November 2006.