Chapter 49
Inclusion of Substrate Blocks Within a Mass Transport Deposit: A Case Study from Cerro Bola, Argentina

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Abstract The preservation of large, relatively undeformed blocks is a characteristic feature of mass transport deposits (MTD). We examine a well-exposed succession at Cerro Bola in La Rioja Province, western Argentina, which comprises mid to late Carboniferous fluvio-deltaic sediments, turbidites and MTD's. The main MTD, which is up to 180 m thick and crops out over 8 km, is characterized by allochthonous sandstone blocks that range in size from metres to 100s of metres in length, and are up to tens of metres in thickness. Blocks are preserved throughout the entire MTD, but are typically larger and much more abundant towards its base where they comprise up to ~30 % of the unit, and become progressively smaller and less frequent upward. Blocks were eroded from the underlying unlithified deltaic sands, and incorporated into the MTD during its transport and emplacement, resulting in local gouges and grooves in the substrate along the basal contact of the MTD. Sandstone blocks are interpreted to have undergone progressive abrasion and fragmentation as they rose through the MTD, thereby creating smaller blocks in the upper parts of the unit. We suggest that buoyancy-driven rise combined with the synchronous fragmentation of sandstone blocks that are entrained within a finer matrix, provides a mechanism for the observed distribution of blocks during overall downslope transport of the MTD.

49.1 Introduction

Submarine gravity-driven failures are widely described from modern and ancient deep water sedimentary basin, with their deposits commonly representing 50 % or more of the deep-water stratigraphic succession (e.g. Moscardelli and Wood 2008). They are considered to be created by a highly complex process comprising creep, slide, slump, debris flow and multiphase granular flow, and the resulting deposits are termed MTD's

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(mass transport deposits) or MTC's (mass transport complexes). Such processes may be initiated in shallow water and transport sediments long distances downslope into the deep water environment, with their size ranging from a few hundred square metres to tens of thousands square kilometres (e.g. Hampton et al. 1996).

During translation, the mass movement can incorporate sediment through erosion, or bypass via a process of hydroplaning. Based on scaled laboratory experiments, several authors have advocated extensive hydroplaning as a means to explain the exceptional mobility and long-run-out of some subaerial mass movements, (e.g. Mohrig et al. 1998). Conversely, erosional features at the base of MTDs are commonly described both from seismic data (e.g. Moscardelli and Wood 2008) and from outcrop (e.g. Dykstra et al. 2011). The whole erosional process is not well understood due to the lack of data on the mechanical and physical properties, which can only be deduced by theory, limited physical experiments or by circumstantial evidence, and therefore involves substantial uncertainty.

49.2 Geological Setting

The study area is located in the southwestern part of La Rioja Province in northwestern Argentina, and consists of a large N-S trending west-vergent doubly-plunging anticline located in the hanging wall to a thrust that dips eastward at about 24° related to the Late Tertiary to Quaternary Pampean Range orogenic deformation (Fig. 49.1) (Zapata and Allmendinger 1996). The sedimentary succession of Cerro Bola exposes a thickness of c.1 km of Carboniferous rocks of the Guandacol Fm. (Gulbranson et al. 2010) that are organized into three individual 200–400 m thick shallowing-upwards packages (Milana et al. 2010) (Fig. 49.1).

The first of these packages has an overall thickness of 200 m and comprises an MTD (MTDI) overlain by a 90 m thick sequence of fluviodeltaic sediments. The second package has an overall thickness of 375 m and is composed of an MTD (MTDII) with sandstone blocks (the focus of this study), overlain by ponded turbiditic sandstones, a black siltstone (maximum flooding surface), a turbidite sandstone unit, and ending in a fluviodeltaic unit. The third package has an overall thickness of 400 m and is quite similar to the second but it is capped by Permian red Beds (Milana et al. 2010). The succession is controlled by high-amplitude glacio-eustatic sea level changes; the upper surfaces of the fluviodeltaic units were thus flooded to substantial depths before the emplacement of overlying MTDs (Dykstra et al. 2011).

49.3 MTDII

MTDII is exposed in a seismic-scale outcrop (Dykstra et al. 2011); the "protolith" is ice-rafted debris (IRD) consisting of fine-grained (silt-size) matrix, with granitoid and metamorphic clasts interpreted as drop-stones. Laminated siltstone rafts are

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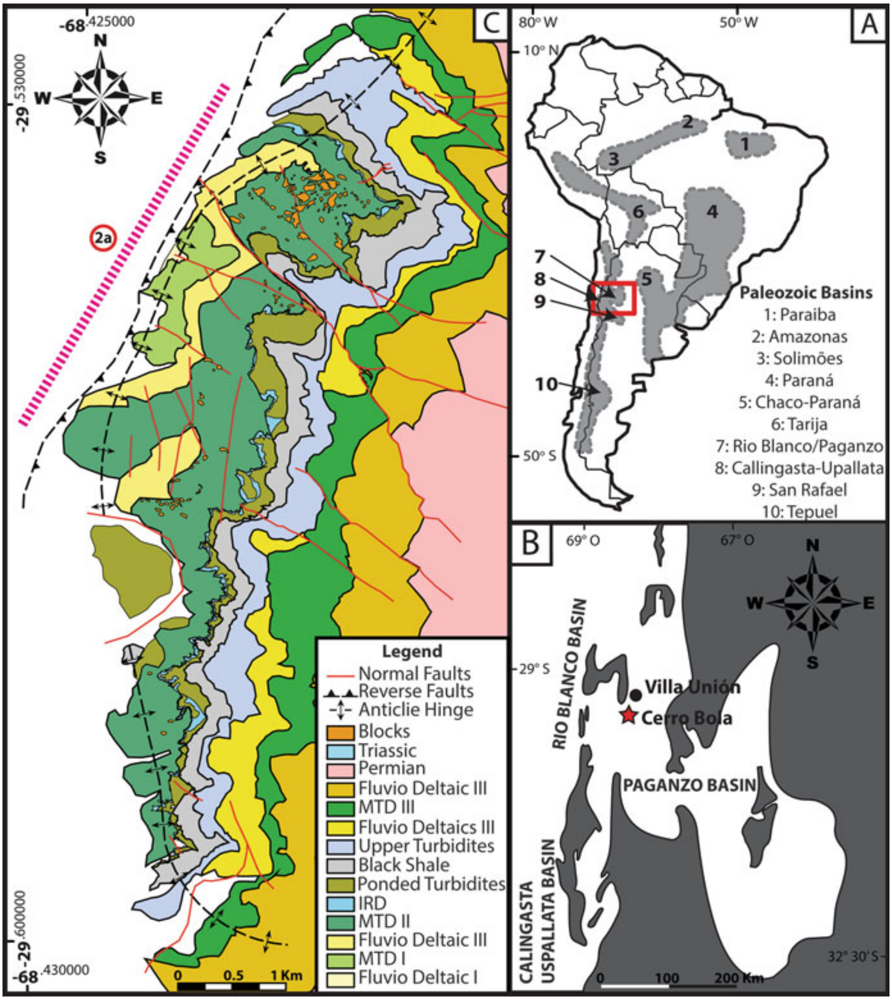

Fig. 49.1 (**a**) Outline map of South America showing the late Paleozoic sedimentary basins. The study area is marked by the *red rectangle* (Modified from Gulbranson et al. 2010). (**b**) Paleogeographic map of the late Paleozoic sedimentary basins of western Argentina (Modified from Gulbranson et al. 2010). (**c**) Geological map of Cerro Bola showing the location of Fig. 49.2a (Modified from Dykstra et al. 2011)

interpreted to be the least-deformed remnants of the "protolith", and are up to several metres thick and 200 m in length. MTDII possesses an erosive contact with the underlying fluviodeltaic rocks (Dykstra et al. 2011). MTDII at Cerro Bola has been stratigraphically divided into three distinct zones (lower, middle and upper) according to its internal variations in textures and structures (Dykstra et al. 2011). The lower part is characterized by numerous blocks of sandstone, that petrographically resembles the underlying fluviodeltaic sandstone deposits (Garyfalou 2015).

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The blocks range in size from a few to tens (occasionally hundreds) of metres wide, and up to ~10 m thick, and decrease in abundance upward. Such textures have been described by Mutti et al. (2006) (cited in Ogata et al. 2012a) as blocky flows.

These blocks are interpreted as being ripped up from the underlying fluviodeltaic sediments during mass movement and incorporated into the moving mass (cf. Ogata 2010). The blocks would have been unlithified upon incorporation into the MTD hence it is possible to observe original bedding in some blocks where it has not being destroyed by shearing during transport. The boundary between the MTD and the underlying deposits is markedly irregular (Fig. 49.2a). Individual blocks exhibit fragmentation by stretching and boudinage (Fig. 49.2b) in the inferred transport direction. Material sheared from the blocks forms sand streaks or blebs within the matrix (Fig. 49.2c) that decrease in abundance away from the blocks. In areas of the lower part that are poorer in sandstone blocks there is also a lack of sand in the matrix.

Stratigraphically, the middle part of the deposit consists largely of an apparently structureless siltstone, containing granule- to boulder- size crystalline clasts of IRD, sandstone blocks and rafts of laminated siltstone. Blocks of sandstone are also present, but show evidence of less shearing at their margins, with consequently less sand in the matrix. The upper part of the deposit consists of folded and sheared siltstones, that are imbricated along discrete thrust-sense shear planes, dipping approximately 20° east (Dykstra et al. 2011).

The textural differences between the sand-rich matrix of the lower zone and the rest of the deposit may be explained in part by the dominance of simple shear in the lower part of the flow. This would result in the rotation and fragmentation of the blocks, and the shear-stripping of their outer surfaces to introduce sand into the matrix. Conversely, the upper part of the deposit may have less simple shear and therefore have been more dominated by pure shear, or acted as a plug for some of its movement.

The structures within the MTD are very complex, with compressional and extensional features occurring alone or overprinting one another (Alsop and Marco 2014). They are more evident in the lower zone due to sand streaks in the matrix which act as markers. Structural analysis reported in Dykstra et al. (2011) indicates movement towards the WNW.

49.4 Blocks

The distribution of sandstone blocks is shown in Fig. 49.4, in which the block's midpoint height is measured upwards from the base of the MTD (normalized to the local thickness of the MTD), and is plotted against block size (taken as the square root of the block's outcrop area). The outcrop essentially represents a strike section of the deposit, so this plot represents the vertical distribution of blocks at one point along the transport pathway. It is evident that: (a) blocks, though present throughout the MTD, diminish in frequency upwards (in contrast, for example, to the deposits

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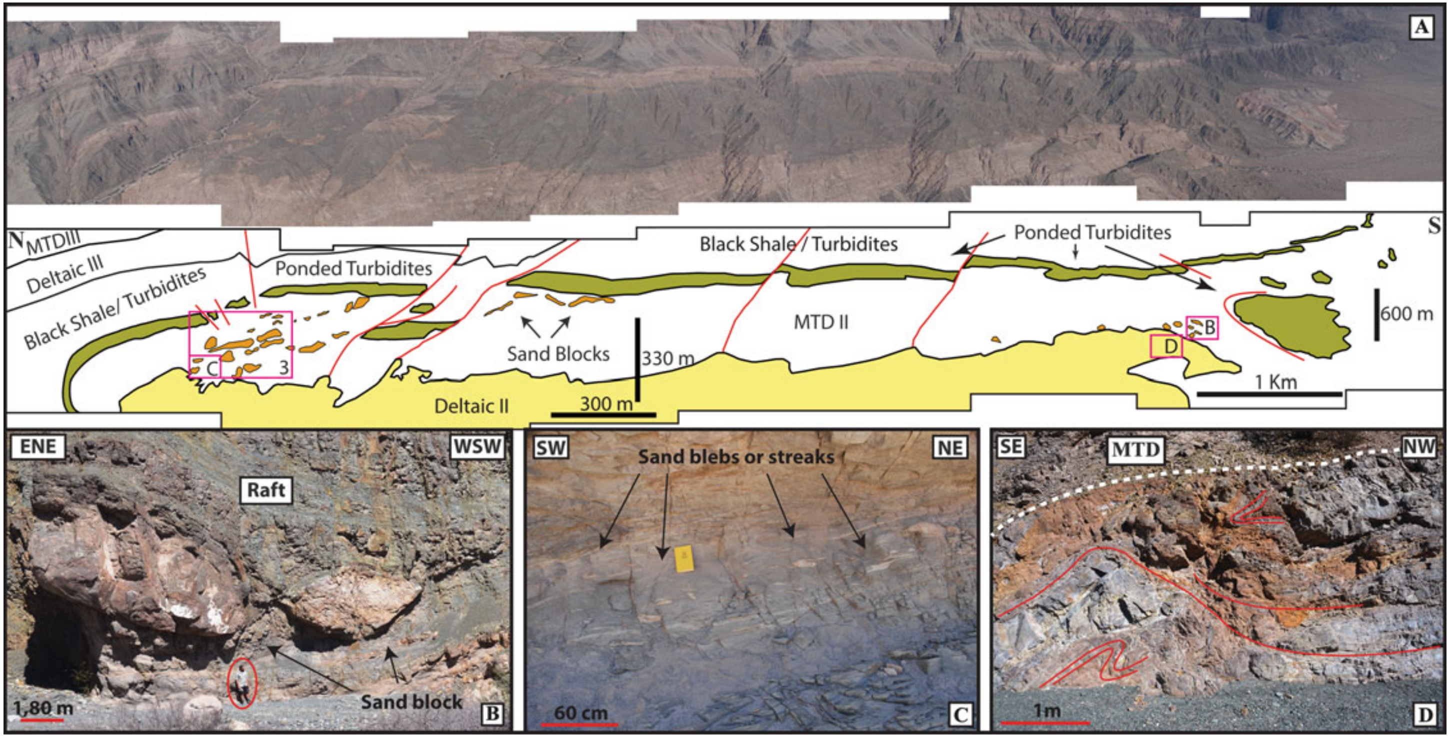

Fig. 49.2 (**a**) Oblique photo-mosaic looking east at Cerro Bola and showing the erosive boundary between the deltaic rocks and the MTD, as well as the distribution of sandstone in the MTD. Note the variation in thickness of the ponded turbidites overlying the MTD. Location shown in Fig. 49.1, while the units legend is the same as Fig. 49.1, showing the location of (**b–d**) and 49.3. (**b**) Two large scale sandstone boudins overlain by a siltstone raft. (**c**) Sand streaks sheared from sand blocks. (**d**) Deformation in the upper most zone of the fluvio-deltaic unit immediately underlying the MTD

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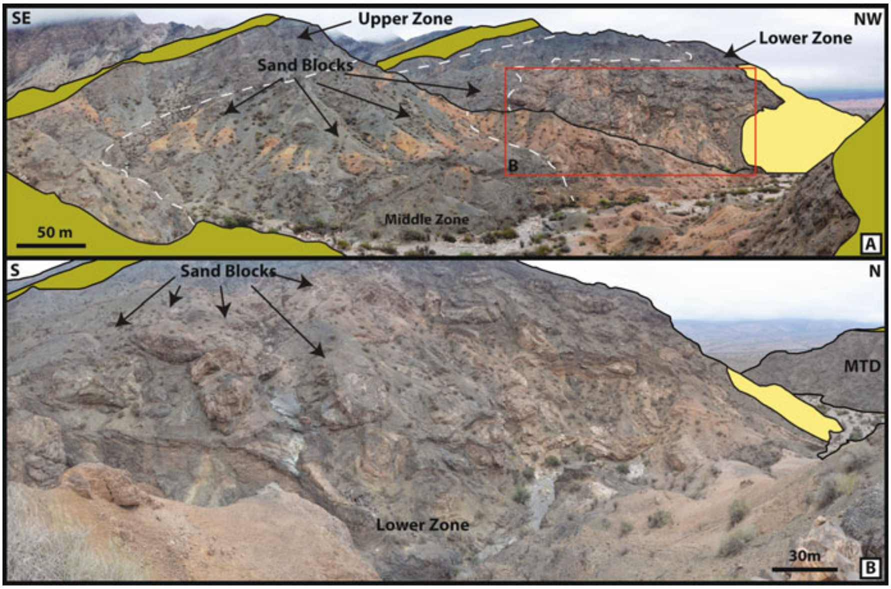

Fig. 49.3 (**a**) Photo-mosaic taken parallel to the inferred transport direction and showing the distribution of the sand blocks throughout the stratigraphy of the MTD. Note how the block size diminishes towards the left-hand side. *Dotted lines* mark the zones boundaries (**b**) Photo-mosaic taken normal to the transport direction and showing the accumulation of blocks in the lower zone of the MTD. The location is shown on (**a**) and unit legends are the same as Fig. 49.1

described by Ogata et al. 2012b, 2014), especially in the upper half of the MTD; and (b) maximum block size diminishes upwards, though blocks near the base have a wide range of sizes.

Two questions arise concerning the distribution of the blocks:

– Given that they were apparently derived by erosion at the lower boundary, how were they transported to the upper part of the MTD? and
– What process explains the block size distribution within the deposit?

Addressing the first of these issues; since the MTD is stratigraphically zoned, it seems unlikely that wholesale imbrication could be invoked to transport sandstone blocks from the base towards the top. An alternative mechanism is buoyancy, requiring that the blocks have a lower density than the matrix. The mineral density of the arkosic sand that makes up the blocks is likely to be in the range of 2620–2640 kg m^{-3}. The porosity of poorly compacted, well sorted sand may be as much as 42–45 % (Rogers and Head 1961), leading to a possible bulk density in the range of 1905–1964 kg m^{-3} for the sandstone blocks.

The matrix of the MTD consists of quartz-rich siltstone with varying proportions of crystalline lithic fragments (IRD), largely of granodioritic or schistose composition. Estimation of the original density of the matrix is subject to substantial uncertainties concerning the initial porosity and the proportion of crystalline lithic

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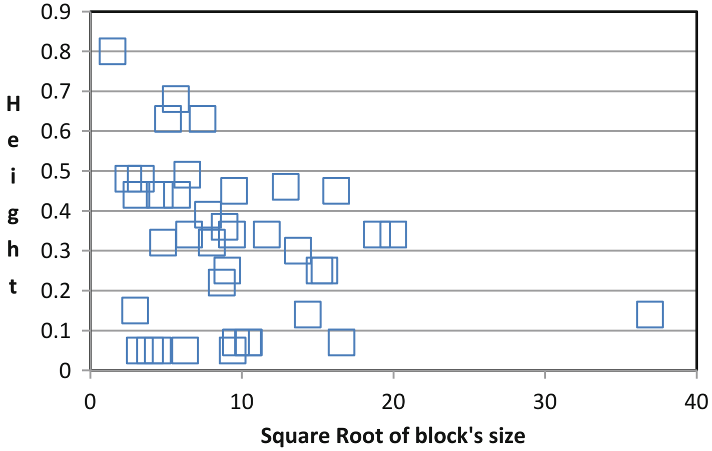

Fig. 49.4 Graph showing the height of sand blocks normalized from the base of the MTD (*vertical axis*), versus the square root area of blocks (*horizontal axis*). The plot illustrates how the blocks diminish in size and number upwards through the MTD (n = 32)

clasts, so must be based upon analogues. MTDs in the Amazon Fan within about 50 m of the sea floor have mean porosities of c.48 % (Busch and Brister 1997), and several authors (e.g. Elverhoi et al. 2000) suggest bulk densities of as little as 1500–1600 kg m^{-3} for subaqueous debris flows, yielding possible bulk densities lower than those of the sandstone blocks. Conversely Pratson et al. 2000 cite a range of 1200–2000 kg m^{-3} for subaqueous debris flows, and Iverson (1997) estimates saturated densities of subaerial debris flows to be in the range 2100–2400 kg m^{-3}. These figures suggest that if buoyancy is the mechanism by which the blocks ascended, the bulk density of the MTD matrix must have been at the upper end of the published range, with porosities perhaps as low as 40 %, though probably varying with depth within the flow. In reality, the majority of the sandstone blocks occur in the lower part of the MTD, perhaps suggesting close to neutral buoyancy for many of them, and only small positive buoyancy for those that did rise.

Positive buoyancy should exert a greater force on larger blocks, yet the blocks higher in the deposit tend to be smaller (Figs. 49.3 and 49.4). We suggest that this is due to progressive fragmentation of the blocks as they rose through the shearing flow. That block fragmentation did occur is indicated by the presence of numerous blocks frozen in the process of boudinage (Fig. 49.2b). The presence of smaller blocks within the lower zone of the MTD may either be due to fragmentation of more-or-less neutrally buoyant blocks that were not rising, or indicates that variably sized blocks were originally plucked from the substrate.

For the relatively low shear rates in natural debris flows, such materials behave as Bingham fluids (Govier and Aziz 1982) rather than as Herschel-Bulkley (shear-thinning) materials. Experimental data from O'Brien and Julien (1988) and Major and Pierson (1992) give some indications of the ranges of plastic viscosity and yield strength in muddy subaqueous debris flows, and their relationship with solids content. Even with small differences in density between the blocks and the matrix,

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the buoyancy force on the blocks would be great enough to overcome the yield strength of the matrix. The sheared margins of blocks clearly indicate that there was no stagnant fluid around them (cf Valentik and Whitmore 1965), suggesting rather low matrix yield strength. Given the linear relationship between shear stress and strain rate for Bingham fluids once their yield strength is exceeded, one can assume Stokes law for the rate of ascent of large blocks at low particle Reynolds numbers. Order of magnitude calculations, assuming viscosities of a few hundreds of Pa S (appropriate to solids concentrations of 0.5–0.6), block dimensions of the order of only 10 m and density difference of only a few kg m^{-3} suggest vertical velocities of the order of a metre per second, sufficient to allow some blocks to ascend through most of the flow even during a relatively short-lived event.

49.5 Basal Interaction

The presence of sandstone blocks, combined with the irregular gouged upper surface of the underlying fluvio-deltaic sediments, provides clear evidence that the MTD was interacting vigorously with the substrate. The incorporation of substrate as blocks requires the initiation of failure planes below the basal surface of the mass movement, within the underlying sand unit (unlithified at the time). This indicates that shear stress must have been transmitted through the interface into the upper part of the substrate. Evidence for this is demonstrated by strain within the uppermost few tens of metres of the fluvio-deltaic unit below the contact with the MTD, including abundant recumbent soft-sediment folds (Fig. 49.2c), and local large scale fragmentation and block rotation of the uppermost few tens of metres of the sandstone unit. It is interesting to note that a similar debate regarding the interaction and deformation of substrate below ice sheets and glaciers is currently taking place, and involves models of glacier-bed decoupling resulting in both recumbent soft-sediment folds and blocks (e.g. see discussion in Lesemann et al. 2010).

49.6 Conclusions

In common with many MTDs, this deposit shows clear evidence that the flow interacted with the substrate, removing material from the underlying unit and incorporating it into the mass movement. The strain front related to the mass movement therefore does not coincide with the base of the MTD, but occurs a considerable distance into the substrate. We propose a model whereby large sandstone blocks have risen through the MTD matrix via a density-driven mechanism. This is likely to have consequences for the interpretation of such deposits in more poorly exposed areas of outcrop, or in the subsurface. It also has considerable implications for the disruption of potential hydrocarbon reservoirs that occur below MTDs.

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