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Carbonate platform slopes of the Alpine Triassic and the Neogene - a comparison

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Abstract

Angle and curvature of terrestrial slopes depend on the grainsize of the slope-forming material and this principle, with slight modifications, also applies to the slopes of carbonate platforms. The Triassic platforms of the Dolomites area of the Southern Alps and occasionally in the Northern Calcareous Alps, are characterized by straight, steep (>30°) slopes that plunge to 400-800 m water depth. In agreement with the above principle, the Triassic slopes consist of sand, rubble and lenses of micritic carbonate precipitated in situ under the influence of microbes. Neogene platforms of the Bahamas and the Maldives, as well as smaller platforms in the Caribbean and off eastern Australia show vertical cliffs and steep talus cones only in the upper 150-200 m, i.e. in the approximate range of sea-level fluctuations. The main parts of the slopes are gentle (<5°) and abound with evidence of creep and slumping. The sediment of these lower slopes is predominantly mud, in particular clay-size aragonite shed from the platforms. The contrast between Triassic and Neogene platform slopes is surprising at first, because the basic depositional environments on the platforms show very similar zonation of tidal flats, lagoons and wave-resistant organic framework at the platform margin. We propose that the difference lies in the way the fine-grained (= micritic) carbonate is formed. In the Neogene, fine-grained carbonate is either precipitated in the water column or stored as loose accumulation on the platform, easily re-suspended during storms. Both processes generate frequent suspensions of carbonate fines on the platform that may be carried off into the basin. In the Triassic, strong circumstantial evidence indicates that most precipitation occurred on the sea floor as crusts and pellets in microbial mats. This material was carried off the platform as debris of hard pellets and intraclasts. The platform slopes reveal the difference between the mud-shedding Neogene and debris-shedding Triassic platforms.

Neigung und Krümmung terrestrischer Hänge werden bestimmt durch die Korngrösse des den Hang aufbauenden Materials. Mit gewissen Anpassungen gilt dieses Prinzip auch für die Hänge mariner Kalkplattformen. Die Triasplattformen der südalpinen Dolomiten und manche nordalpinen Plattformen zeigen gerade, steile (>30°) Hangschichtung, die bis 400-800 m Wassertiefe hinabreicht. Die Hangsedimente bestehen, in Übereinstimmung mit obigem Prinzip, aus Sand, Grobschutt und Linsen von mikritischem, mikrobiell gefälltem Karbonat. Neogene Plattformen der Bahamas, der Malediven, der Karibik und östlich von Australien zeigen steile Schutthänge und vertikale Kliffs nur in den obersten 150m, d.h. im Bereich der pleistozänen Schwankungen des Meeresspiegels. Der Hauptteil der Hänge ist flach (<5°) und zeigt häufig Spuren von Sackungen und Kriechbewegungen. Das Sediment dieser tieferen Hänge ist vorwiegend Schlamm, vor allem von den Plattformen eingetragener Aragonit mit Korngrösse im Tonbereich. Der Gegensatz zwischen triassischen und neogenen Plattformen ist überraschend, weil die Ablagerungsmilieus auf den Plattformen sehr ähnlich sind – Watten, Lagunen und wellenresistente organische Strukturen am Plattformrand. Unsere Arbeitshypothese ist, dass der Unterschied bestimmt wird durch den Bildungsprozess des mikritischen Karbonats. Im Neogen wird der feinkörnige Aragonit vorwiegend in der Wassersäule gefällt, wahrscheinlich vor allem mit Hilfe planktonischer Algen, und als Schwebfracht beckenwärts abgeführt. In der Trias weist alles darauf, dass das mikritische Karbonat als Krusten und Pellets in mikrobiellen Matten gefällt wurde und als Sand und intraklastischer Feinschutt von der Plattform abgeführt wurde. Die Plattformhänge verraten den Unterschied zwischen Schlamm- und Schutt-exportierenden Plattformen.

1. Introduction

It is well established in terrestrial geomorphology that the declivity of regolith-covered slopes depends on the proportions of clay, sand/silt and gravel in the regolith (Kirkby, 1987). Kenter (1990) showed that similar trends govern the declivity of submarine carbonate slopes. Quantitative analysis of the angle and curvature of submarine slopes (Adams et al., 1998; Adams and Schlager, 2000) support the findings of Kenter (1990) and refine the quantitative aspects. Regolith-covered terrestrial and depositional subaquatic slopes differ in one important aspect: The relief of subaquatic slopes frequently results from the sediment accumulation itself whereas on terrestrial slopes the relief is inherited from the bedrock and the regolith only modifies the morphology of the slope, including its declivity. Subaquatic slopes may assume a wide range of angles as the sediment accumulation gradually builds relief. The critical property for the following discussion is the equilibrium profile of the sediment pile, i.e. the maximum slope angle the sediment can maintain. This maximum angle, here loosely referred to as “angle of repose”, is a good indicator of the proportions of mud and coarse debris in the slope sediment (Fig. 1).

The concept of Kirkby (1987) offers a continuous, quantitative representation of slope angles for the entire range of grain sizes. Kenter (1990) emphasized that two end members of the spectrum are particularly useful in field studies and seismic interpretations of carbonate platforms. Figure 2 summarizes the characteristic equilibrium profiles of these two end members: muddy, cohesive sediments on the one hand and piles of non-cohesive sand and rubble on the other. We will refer to the systems that generate these slope types as mud-shedding and debris-shedding platforms respectively.

This report shows that the Neogene platforms around the world are of the mud-shedding type while the platforms of the Alpine Triassic are debris-shedders. The difference in sediment export from the platform is probably caused by differences in the mode of fine-grained carbonate production at the platform top. The concept of "automicrite" is important in this context. We use the term in the sense of Wolf (1965) and Reitner et al. (1995) for micritic (= fine-grained) carbonate formed in place (as opposed to material deposited by moving water). Precipitation of most automicrite seems to have been induced by microbes but the processes are variable and, for ancient examples, still rather speculative. Thus we prefer the neutral term "automicrite" to the genetically more specific term "microbialite".

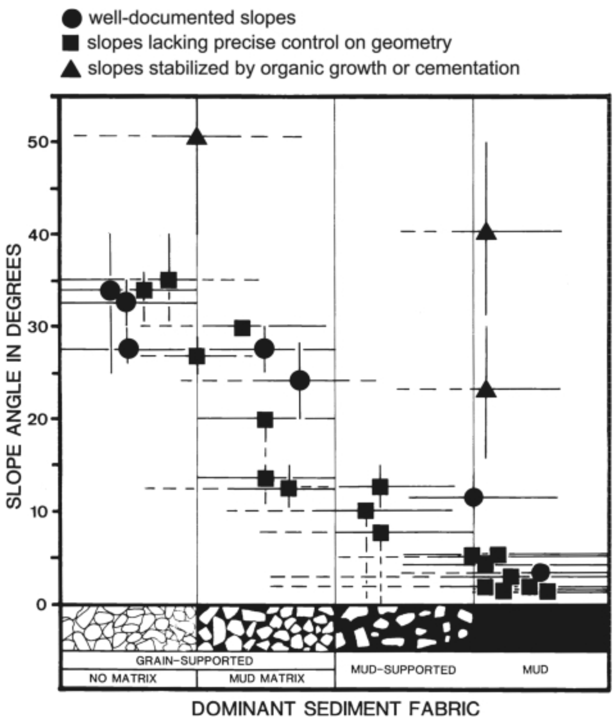


Figure 1: Slope angles of carbonate platform flanks as a function of sediment fabric. Slope angle decreases with increasing mud content from ~35° for mud-free submarine talus to 2-5° for mud with insignificant amounts of sand or rubble. Slopes stabilized by organic growth, e.g. reef structures or automicrite, may be significantly steeper. Modified after Kenter (1990).

2. Neogene Platform slopes

2.1 Bahamas

The Bahama Banks represent the archetype of a tropical carbonate factory. The flat platform tops including the rims of reefs and sand shoals produce vast amounts of carbonate particles ranging in size from few microns (e.g. aragonite needles) to reef boulders of several meters. The present sediment cover of the platforms is dominated by sand with minor amounts of mud and the most common sediment fabric is packstone (Purdy, 1963; Enos, 1974; Reijmer et al., 2008). Mud dominates only in the most protected parts of the platforms, particularly on the leeward side of islands (Enos, 1974; Schlager and Ginsburg, 1981). However, there is much more fine-grained carbonate produced than deposited on the platforms. Most of these fines, particularly clay-size aragonite, are carried off the platform top and accumulate on the slopes (Wilber et al., 1990; Rendle et al., 2000; Roth and Reijmer, 2005) and in the adjacent basins where they mix with fine-grained planktonic carbonate to form "periplatform ooze" (Kier and Pilkey, 1971; Schlager and James, 1978). Another portion of the fine-grained production dissolves in the deep water, significantly increasing the carbonate saturation in the interplatform basins (Droxler et al., 1988).

The large export of fines from the platforms is reflected in the morphology of the platform slopes (Figs. 3, 4). The upper 100 m consist of a near-vertical wall, followed by a talus slope of 35-45° that is onlapped at about 150-200 m by mud. This muddy slope is concave in profile and rapidly decreases to <5° with increasing depth. Slumps and creep phenomena indicate that the lower slopes are built up to the angle of repose of muddy sediment (Fig. 4). The platform-derived body of mud extends many kilometers into the interplatform basins (Eberli et al., 1997; Rendle et al., 2000); in addition, large amounts of excess sediment leave the Bahamas via an extensive canyon system (Schlager and Ginsburg, 1981). Figures 3 and 4 clearly show that the present slopes of the Bahama platforms are strongly influenced by Quaternary sea-level fluctuations in their uppermost part and by mud accumulations in their lower part.

2.2 Caribbean

In the Caribbean, the Belize carbonate province shows slope profiles very similar to the Bahamas: Steep, often vertical slopes dominate the upper 100-150 m, below 150 m slope angles rapidly decrease to few degrees. Despite the low slope angle, evidence for slumping and debris flows is common on the muddy lower slopes, again suggesting deposition at or near the angle of repose (Enos et al., 1979). Similarly, the platforms on the Nicaragua Rise in the Caribbean have near-vertical slopes above 150 m and concave, rapidly flattening slopes below. Extensive debris flows that raft boulders across 1°-slopes have been observed in numerous seismic profiles (Hine et al., 1992) and attest to the high content of fine material on the slopes. Sediment cores show that a very significant portion of the fine carbonate is platform-derived aragonite and magnesian calcite (Glaser and Droxler, 1993; Reijmer and

Andresen, 2007).

2.3 Pacific

In the Pacific region, the Neogene platforms of the Queensland Plateau show strongly concave slopes with steep parts in the range of sea-level fluctuations and broad, gentle lower parts that gradually merge with the basin floor (Davies et al., 1991). ODP boreholes indicate that the platforms exported large amounts of fine-grained aragonite and magnesian calcite that form a dominant component of the slope sediment (Haddad et al., 1993). The Queensland Shelf with the Great Barrier Reef just W of the Queensland Plateau also exports large amounts of fine-grained carbonate but slope sedimentation and slope morphology are strongly influenced by the large influx of terrigenous material (Davies et al., 1991; McKenzie et al. 1991).

2.4 Maldives

The Maldives archipelago constitutes another large extant platform-basin system, albeit less well explored than the Bahamas. Nonetheless, several sets of good seismic data in combination with boreholes and soft-sediment cores suffice to show the similarities to the Bahamas with regard to the platform-basin transitions. The platforms consist of reef rims and lagoons covered by sand and muddy sand (Ciarapica and Passeri, 1993; Gischler, 2006).

The platform flanks facing the Inner Sea are about 300-500 m high. Near-vertical cliffs and steep slopes of about 20° form the upper 100-200 m; the deeper slopes rapidly flatten to declivities of few degrees (Purdy and Bertram, 1993; Belopolsky and Droxler, 2004). Much like the Bahamas, the Maldives platforms export significant amounts of fine-grained carbonate that accumulates on the lower slopes and the flat basin floors of the Inner Sea (Droxler et al., 1990). It remains unclear exactly how this fine-grained carbonate is produced on the platforms. The platform flanks facing the open ocean are much steeper and constitute bare and erosional escarpments, comparable to the escarpment on the eastern, ocean-facing side of the Bahama Banks.

2.5 Origin of aragonite-rich mud on Neogene platform slopes

The aragonite-rich mud in the Bahamas has been studied for more than 50 years and the data far exceed those of other areas in the world. We therefore rely on the Bahamas again as an example and standard in the discussion on the origin of this fine-grained platform sediment.

The muds on Great Bahama Bank contain more than 80% clay-size aragonite, the remainder being magnesian calcite and calcite (Milliman, 1974, p. 186-189). The origin of this fine-grained carbonate is controversial. There is debate between advocates of inorganic and organic precipitation (e.g. Broecker and Takahashi, 1966; Shinn et al., 1989; Yates and Robbins, 1999; Morse et al., 2003). Much of this debate revolved around the “whitings”, clouds of fine carbonate in the water covering the inner banks, e.g. near Andros Island. Whitings have been interpreted as bottom sediment stirred up by fish (Broecker et al., 2000) or precipitates from the water column whose formation was induced by the metabolism of planktonic micro-algae (Yates and Robbins, 2001). In addition, it is unclear how much of the carbonate mud in the protected platform environments stems from abrasion of coarser skeletal material, such as green algae, in the agitated environments of the platform (e.g. Bathurst, 1971, p.102-120; compare also Gischler and Zingeler, 2002 for Belize). Regardless of the origin of the Bahamian mud, it is clear that there is abundant clay-size carbonate on the platforms that may stay in suspension for weeks or months and thus can be carried off the platforms by storms and tides. Plumes of fine sediment moving off the platforms after storms have been well documented (e.g. Neumann and Land, 1975; Rankey et al., 2004). The accumulation of this material on the platform slopes has been found to vary in response to changes in sea level and climate (Droxler et al. 1983; Roth and Reijmer, 2004).

Precipitation in microbial mats is another important pathway to fine-grained carbonate. This process can be very efficient but the important difference to the “whitings” process is that the fine-grained carbonate rarely ever becomes suspended in the water column. The carbonate grains are held in place by

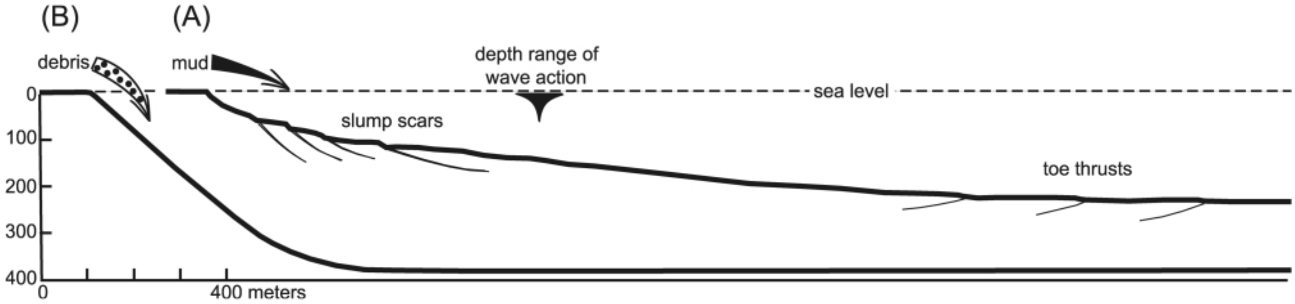


Figure 2: Characteristic features of equilibrium slope profiles of mud-rich, cohesive sediments and non-cohesive piles of sand and rubble. It is assumed that there were no sea-level fluctuations and the slope reached equilibrium with sediment supply and wave action. Basin depth is variable. (A) Mud-shedding platform. Steep slopes occur only in the zone of winnowing by waves. Main part of slope is dominated by cohesive sediment. Slope angle is <5°; slump scars and downslope toe thrusts indicate that sediment rests close to angle of repose. (B) Debris-shedding platform. Straight clinoform bedding at angles of >25° extends far below zone of wave action. This indicates that non-cohesive sediment dominates and is piled up to the angle of repose. Concave lower slope (usually with exponential curvature) forms the transition zone to the flat basin floor.

organic filaments or slime and frequently lithify to lumps and crusts at the place of precipitation. Precipitation in microbial mats is crucial for the formation of Recent stromatolites (Visscher et al., 1998; Reid et al., 2000) and for a variety of other carbonate accumulations (Riding, 2000). Microbial mats are common on modern carbonate tidal flats where they are also associated with carbonate precipitation (Hardie and Ginsburg, 1977; Andres et al., 2006). Observations by Rankey et al. (2004) on the platform lagoon and the tidal flats of Great Bahama Bank before and after a recent hurricane illustrate the difference in mobility of fine-grained carbonate on the subtidal platform dominated by bare sediment and on the tidal flats with extensive microbial mats and crusts. Large plumes of suspended sediment left the subtidal platform but on the tidal flats even the micromorphology showed very little evidence of sediment re-mobilization (Rankey et al., 2004, Fig. 2 versus Figs. 3-5). It should be noted that microbial mats on Great Bahama Bank are not restricted to tidal flats and areas with rigid, columnar stromatolites. Mats are wide-spread on the shallow-lagoon floors but these structures are weak and do not seem to lead to carbonate cementation. The mats disappear when buried by new sediment (Bathurst, 1971, p. 122-126).

The Bahamian examples lead to the following conclusions with regard to the theme of this report: Carbonate precipitates in microbial mats and precipitates in the water column behave very differently during transport and sedimentation. The clouds of clay-size carbonate in the water column are easily carried off the platforms and into the surrounding basins (Fig. 5A). The fine-grained carbonate in the microbial mats is bound to the sea floor; it is either fossilized in place or eroded by waves and currents and carried away as sand- or pebble-size particles (Fig. 5B). This difference in hydrodynamic behavior of the carbonate material leads to a significant difference in sediment export from the platform to the basin. Platforms of the Bahama type with extensive formation of loose, clay-size carbonate at the bank-top, export much of the excess material as suspension – they are “mud-shedding platforms”. In stark contrast, platforms with extensive precipitation in microbial mats are likely to export mainly sand and rubble; they are “debris-shedding platforms”.

2.6 Role of coccolithophorid carbonate on Neogene slope sedimentation

Not all fine-grained carbonate on the platform slopes stems from the neritic factory at the platform top. Coccolithophorid nannoplankton of the open ocean also produces clay-size carbonate that mixes on the slopes and basin floors with the material shed from the platforms. The two sources have different mineralogy and thus can be separated: coccolithophorids produce low-magnesium calcite that can be easily distinguished from the platform-derived aragonite and magnesian calcite. Using X-ray diffraction Kier and Pilkey (1971), Droxler et al. (1983), and Rendle et al. (2000) showed that during the interglacials, when the Bahamian banks were fully flooded, the ratio of aragonite to calcite in the slope mud was 3:1 to

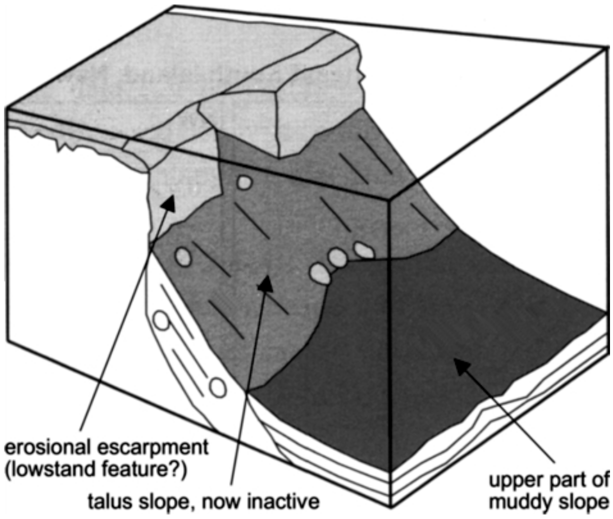


Figure 3: Uppermost slopes of Great Bahama Bank in late Quaternary, based on bathymetric surveys and submersible observations of Grammer et al. (1993). Near-vertical wall at the top and steep slope below are interpreted as erosional cliff and talus formed during Quaternary sea-level fluctuations. The onlapping mud wedge represents the currently accumulating slope mud that gradually buries the now largely inactive talus slope.

6:1. Thus, the contribution of coccolithophorids to the Bahamian slope sediment is small. If the coccolith fraction were to be removed, the vast majority of sediments on the slopes and in the periplatform basins would still be mud. The overwhelming role of platform input on slope sedimentation in the Bahamas is also illustrated by the seismic architecture of the slopes. The leeward platform slopes receive the bulk of platform sediment and therefore prograde rapidly, the windward slopes - cut off from platform supply -, retreat or aggrade vertically (Eberli and Ginsburg, 1989). However, the contribution of coccolithophorids to slope sedimentation may have been significantly greater during certain periods in the past.

3. Platform Slopes of the Alpine Triassic

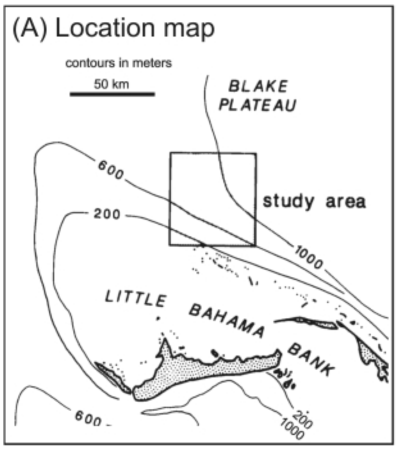
Knowledge of Triassic carbonate platforms is much more fragmentary than that of the Neogene platforms. However, the Triassic of the Southern Alps and certain parts of the Northern Calcareous Alps offer large outcrops of well-preserved platform-basin transitions that we use for comparison with their Neogene counterparts.

3.1 Sella

The Sella mountain in the Dolomites area of the Southern Alps is an exceptionally preserved Triassic atoll (Fig. 6). It is late Ladinian to early Carnian in age and shows well exposed, prograding slopes on all sides (Bosellini, 1991). The diameter of the platform top was about 5 km at the end of progradation. The main part of the clinoforms is straight in cross section with angles of 25-35°, only the lowermost part is concave with exponential curvature (Kenter, 1990). Slope angles decreased during the final stages of growth as the basin filled up and slope height decreased.

Keim and Schlager (1999; 2001) describe the sediment composition and offer a model of the functioning of the carbonate factory of the Sella. Two thirds of the upper slope deposits consists of an intricate mixture of automicrite and marine cement, one fifth is debris (mainly peloids and clasts of automicrite facies), one eighth cannot be diagnosed because of recrystallization. Skeletal grains contribute only 5% of the total volume. The steep angles and straight bedding of the upper slopes indicate deposition close to the angle of repose of non-cohesive material. This condition could only be achieved and maintained if (1) there was sufficient supply of non-cohesive material from the platform top; and (2) if the automicrite factory on the slope was smothered intermittently by debris avalanches from the top and therefore could not build mound structures that are typical of microbially-induced carbonate on gentle slopes below the zone of wave action.

The topset beds of the Sella contain 40% micrite. However, there is little evidence for sedimentation in the form of soft mud. The clotted or pelleted texture of the micrite and the abundance of large shrinkage pores filled with marine cement suggest formation *in situ* as stiff material. Thus, we propose that the micrite at the platform top formed mainly *in situ* as hard pellets and crusts in microbial mats. Consequently, very little of what now appears as micrite in thin-section could have been carried off the platform as fine-grained carbonate in suspension. Most micrite must have been shed down the slope as pelletal sand and intraclastic sand and rubble generated by erosion of the automicrite facies at the platform top. Bedding architecture and sediment composition indicate that



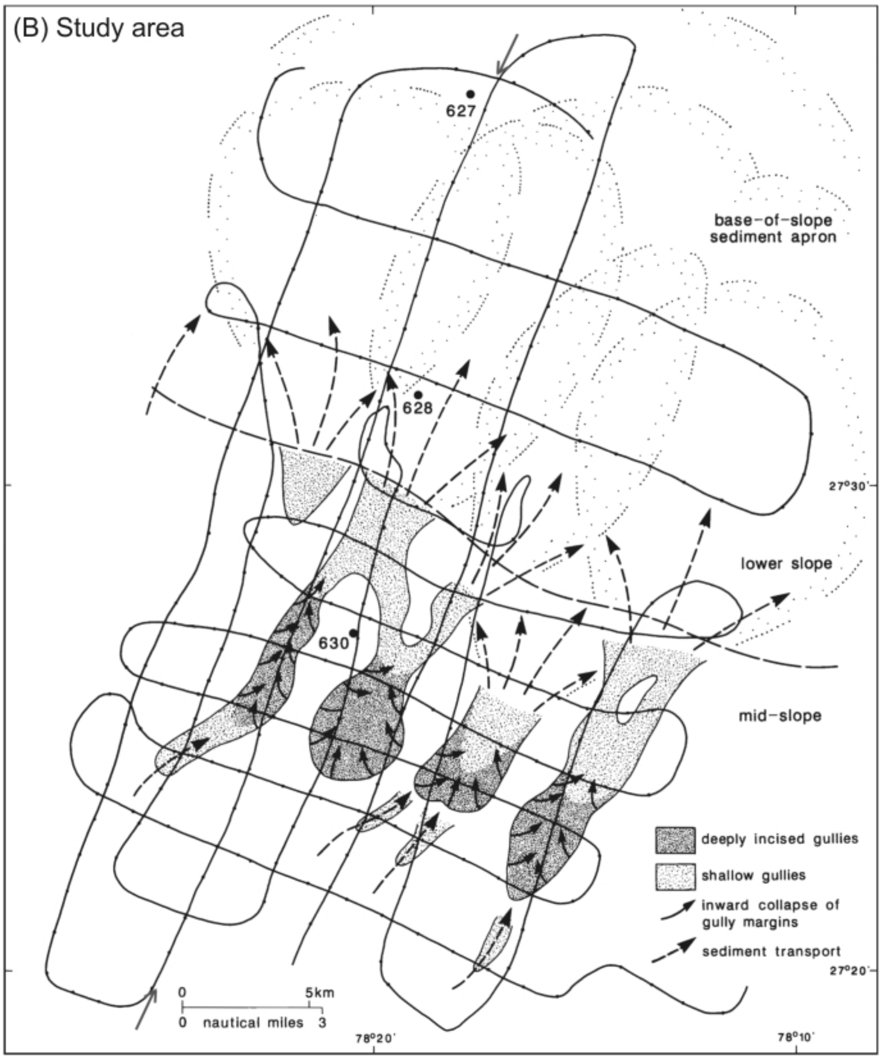
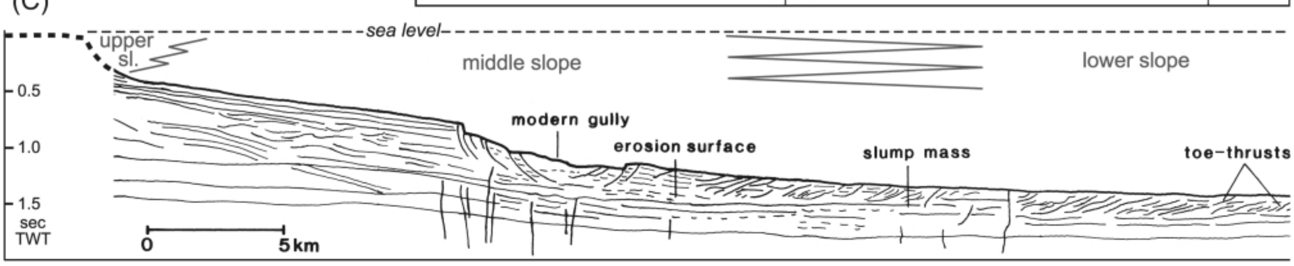


Figure 4: Northern slopes of Little Bahama Bank - a Neogene mud-shedding platform (after Harwood and Towers, 1988). (A) Location map. (B) Map view of gullies with slumped margins and downslope sediment apron dominated by turbidites. Grid of seismic lines and numbered boreholes are also indicated. Arrows – approximate position of C. (C) Interpretation of seismic line based on boreholes of Ocean Drilling Program; dotted profile extension on the left based on bathymetry of Mullins et al. (1984) and observations summarized in Fig. 3. Note subdivision of slope in steep upper part within the range of wave action and Quaternary sea-level fluctuations, middle part with gullies and slump scars and a lower part with toe thrusts due to downward creep of the muddy sediment.



the Sella slopes were very similar to the slopes of Late-Paleozoic mud-mounds, such as the well-documented example of Blendinger et al. (1997). The carefully mapped Carboniferous Cuera platform slopes in Spain also provide an analogue, albeit one with a distinct platform rim of automicrite facies as the main source of slope debris (Della Porta et al., 2003).

3.2 Gosaukamm

A Late-Triassic platform slope is exposed in the Gosaukamm range of the Northern Calcareous Alps. The overall geometry is not as exquisitely preserved as that of the Sella but a large part of the clinoforms and the adjacent basin-floor deposits are well exposed and the topsets of the platform, the "bedded Dachsteinkalk", are also preserved albeit separated from the Gosaukamm by young strike-slip faults (Mandl, 1984; Kenter and Schlager, 2009). Nearly all rocks are limestone and the preservation of microfabrics is much better than at the Sella.

The morphologic reconstruction leads to a platform-basin profile very similar to the Sella (Kenter and Schlager, 2009). According to Wurm (1982), the clinoforms consist mainly of reef-derived sand and rubble. No beds of automicrite have been found but automicrite is abundant in the form of clasts and rims on skeletal fragments. Based on point-counts of photographs in Wurm (1982), the proportions of skeletal fragments, automicrite and marine cement in the slope debris are estimated as 40%, 40%, and 20% respectively (Schlager, 2003, Fig.13). This implies that the clinoforms of the Gosaukamm are richer in skeletal debris and lower in automicrite than the clinoforms of the Sella.

The basinal limestones (Gosauseekalk) have been described by Wurm (1982), Reijmer and Everaars (1991), and Reijmer et al. (1991). The formation consists of decimeter-thick limestone beds separated by millimeter-thick laminae of greenish marls. Most common are graded beds of packstones and grainstones with shallow-water debris. Detrital micrite, as opposed to automicrite, is common in intervals rich in radiolaria, thin-shelled bivalves ("filaments"), and ammonites. These intervals are commonly reddish or very light gray and resemble Hallstatt limestone.

The sedimentation model we propose for the Gosaukamm resembles the one of the Sella. Straight clinoforms at ~30°, maintained over a depth range of >500 m indicate that non-cohesive sand and rubble had been piled up to the angle of repose. This is only possible if there was sufficient supply of this material from the top, i.e. the platform proper. Slope geometry also implies that, unlike the modern Bahama Banks, the platform exported little mud.

The assumption that the Dachsteinkalk platform exported mainly sand and rubble and little mud is, at first sight, in conflict with the composition of the platform deposits. The "Lofer cyclothems" of the bedded Dachsteinkalk consist of three elements (Fischer, 1964; Enos and Samankassou, 1998): Member A is a discontinuous soil horizon formed at times of platform exposure. Member B consists of micritic lithologies with abundant evidence for microbial activity. Member C represents about 90% of the total volume and is dominated by fine-grained carbonate. Enos and Samankassou (1998) found member C to consist of 41% wackestone (grains floating in mud) and 51% packstone (grains resting on grains but interstices filled with mud). Thus, fine-grained carbonate was the dominant material on the Dachsteinkalk platform, yet the slopes indicate that the platform, like Sella and other the Ladinian platforms of the Dolomites, shed almost exclusively sand and rubble down the slope. This conflict can be solved if one assumes that what appears as micritic carbonate in thin section did not form as loose accumulation of silt- and clay-size particles but rather as automicrite in microbial mats. One indication for in-situ origin is the pervasive occurrence of shrinkage pores (fenestrae or "birds-eyes") in the micrite. Fenestrae are the dominant feature in member B and occur in over a third of all thin sections in member C (Enos and Samankassou, 1998, p.210). (See "Comparison of Neogene and Triassic platforms" for further discussion).

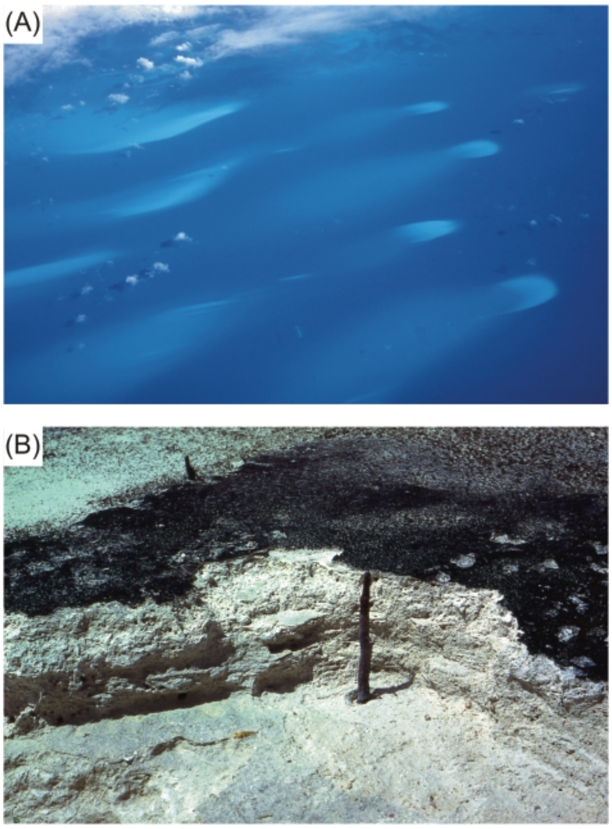


Figure 5: Two different ways to produce fine-grained carbonate. (A) Aerial photograph of suspensions of fine-grained carbonate ("whitings") on Great Bahama Bank W of Andros; largest clouds are few kilometers long and several hundred meters across. Whitings are caused by carbonate precipitation induced by unicellular planktonic algae or by fish that re-suspend bottom sediment. (B) Microbial mats of the inter-supratidal boundary zone of western Andros Island on Great Bahama Bank. Note dark living mat above and mud with mm-thick lithified laminae below. Mangrove root at center is about 10 cm high. Firm or rigid microbial mats also occur locally in the subtidal zone, for instance in stromatolites.

3.3 Other platform slopes of the Alpine Triassic

A brief review of published case studies reveals that Sella and Gosaukamm are but two members of a much larger group of similar platforms in the Alpine Triassic. In the Anisian-Carnian of the Dolomites, straight clinoforms of 25-35° represent the most common slope architecture and are well exposed in dozens of large outcrops (Bosellini, 1984). Platform growth in the Dolomites was severely curtailed during an interlude of intense volcanism in the Ladinian but the pre- and post-volcanic platform slopes are very similar both in composition and geometry. Compositional analyses by Blendinger (1994) on pre-volcanic, un-dolomitized clinoforms in the Marmolada Massif match the estimates from the Sella (Keim and Schlager, 2001) to within a few percent. In contrast to Blendinger (1994), we believe that the straight clinoforms of the Marmolada, like those at the Sella, were built to the angle of repose of non-cohesive sediment; maintaining the straight bedding and steep angle during progradation requires significant input of sand and rubble from the platform top.

In the Northern Calcareous Alps, only few slopes have escaped tectonic deformation. The well-preserved Rhaetian Steinplatte platform shows maximum slope angles of about 25° (Piller, 1981; Stanton and Flügel, 1989). However, the slope bedding is distinctly sigmoidal and it remains unclear if the slope ever evolved to the angle of repose by supply of non-cohesive material from the platform top.

Hochkönig Massif, 15 km W of the Gosaukamm, shows a complete platform-to-basin transition, well documented by Satterley (1994). The facies succession is continuously exposed but reconstruction of the slope profile is difficult because of the strong tectonic tilt (35-50°) and patchy metamorphic overprint of the area. Satterley (1994, p.143-145) arrives at a primary slope of 3-10°. We doubt this estimate for the following reasons: (a) the entire massif was treated as one rigid block during Alpine tectonism, (b) the removal of the average tectonic tilt of the block leads to landward dip of ~ 9° in the bedded lagoon facies and (c) the photograph of a sample

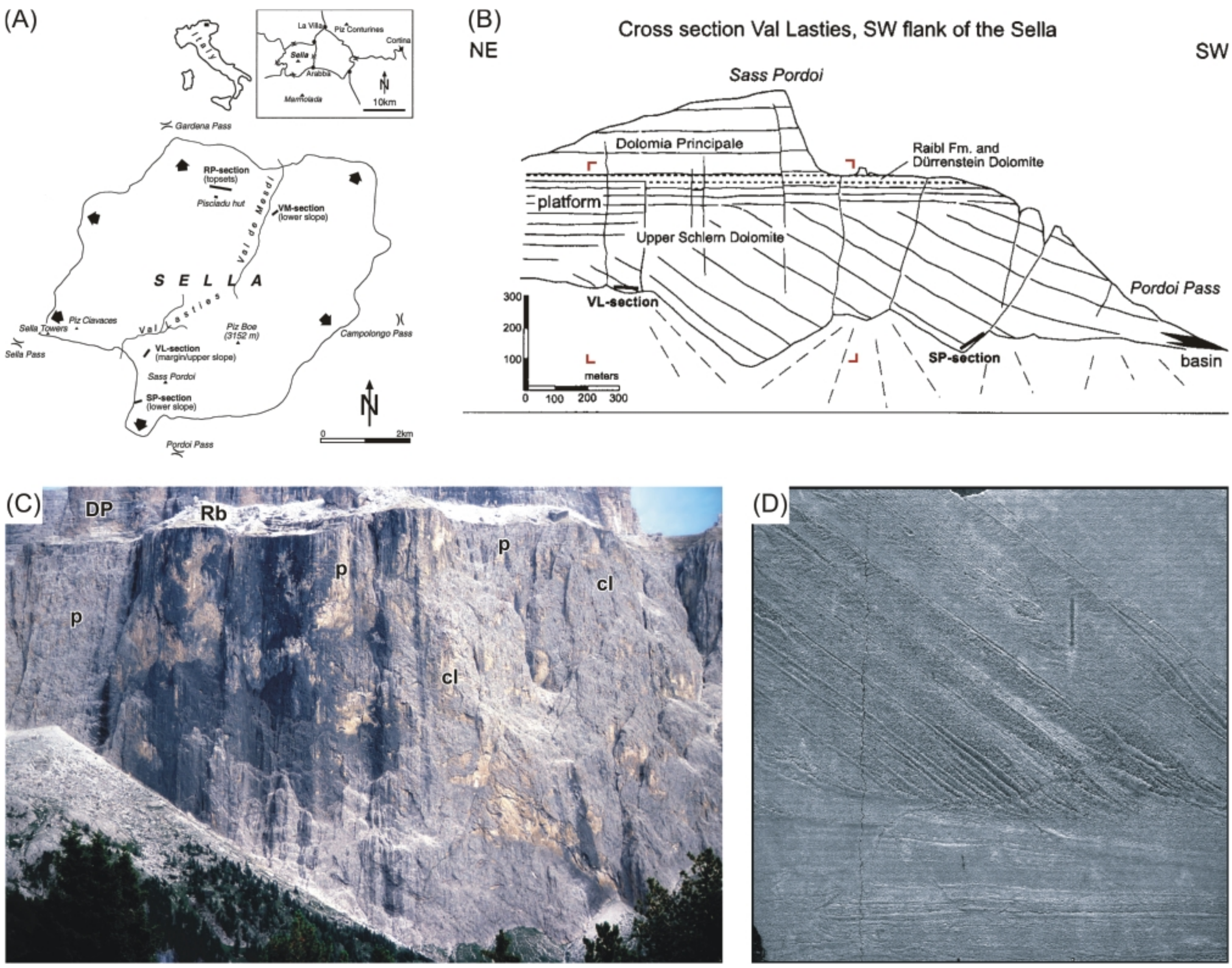


Figure 6: Sella atoll in the Southern Alps – a Triassic debris-shedding platform. (A) Location map. (B) NE-SW section of southern part of Sella, location of C marked in red. (C) 450 m high rock face exposing southward prograding slope; p = horizontally bedded platform interior facies; cl = straight clinoforms plunging from platform top to ~400 m paleo-depth; note similarity in dip between clinoforms and modern scree. Rb = Raibl Fm., DP = Dolomia Principale Fm. (D) 40 cm high foresets of an eolian sand dune – the prototype of slopes of non-cohesive material at the angle of repose (Holocene, Netherlands). A-C after Keim and Schlager (2001), D after Adams and Schlager (2000).

with both geopetal fabrics and slope bedding (Satterley, 1994, Pl. 24/4) shows a difference of 17-20° between the two structures; if the geopetals are close to the paleo-horizontal, the primary slope angle would have to be at least 17-20° for this particular sample.

The Wettersteinkalk platforms of the NCA are approximately coeval with the Sella and other high-rising platforms in the Dolomites. Unfortunately, most platform-basin transitions have been severely deformed by tectonics. Brandner and Resch (1981) document part of a platform-slope transition from the western NCA that suggests angles around 5° for the uppermost slope. No detailed studies have been published from the less deformed (and less well exposed) eastern NCA. However, field relationships at the Schneealpe reported by Mello (2001, Fig. 3) indicate clinoforms with slope angles of approximately 30°, very similar to the Gosaukamm.

4. Comparison of Neogene and Triassic Platforms

All examples discussed here in detail show fairly complete platform-to-basin transitions. If all components of this transition are examined, it becomes clear that the observed differences in slope geometry are related to the sediment produced on the platforms and exported to the slopes. The extant platforms of the Bahamas, the Maldives and the Queensland Plateau have been shown to produce and export mainly fine-grained material, in particular significant quantities of clay-size aragonite. In line with this export pattern, only the upper slopes in the zone of wave action and sea-level fluctuations are steep and built to the angle of repose of non-cohesive materials. Below 150-200 m, sedimentation is dominated by mud and slope angle decreases rapidly to less than 5°. Deformation structures related to creep and slumping indicate that the mud-rich sediment is piled up to its intrinsic angle of repose.

Sediment export of the Triassic platforms must be reconstructed from the stratigraphic record. The slopes consist of layers of automicrite-plus-cement and layers of debris. Straight bedding of 25°-35° indicates that slope geometry was mainly determined by the angle of repose of the debris layers. A significant fraction of this debris may have been produced on the slope by disintergration of automicrite layers. However, in several outcrops the straight bedding can be shown to extend upward to the platform top. This geometry could only develop if there was significant supply of debris from the platform top. The slope angle also indicates that the amount of fine material shed from the top (plus any contribution from plankton) was insufficient to let the slope sediment behave cohesively. All these observations lead to the conclusion that the Triassic platforms exported mainly non-cohesive debris and small amounts of fines.

The facies of the topsets of the Neogene and Triassic platforms are seemingly at variance with the postulated export patterns. Bahamas, Maldives and most other Neogene platforms are dominated by sand; mud is a minor component that prevails only in very protected areas at the platform top (e.g. Enos, 1974; Reijmer et al., 2008). The Triassic platforms, on the other hand, show predominantly fine-grained lithologies. For the Late-Triassic Dachsteinkalk this has been established by serveral detailed studies (e.g. Fischer, 1964; Enos and Samankassou, 1998); for the Ladinian-Carnian platforms of the Southern Alps the pattern is similar, albeit somewhat less certain because of widespread dolomitization.

Our working hypothesis is that the solution to this “export paradox” lies in the different modes of fine-grained carbonate production and storage on the platforms. On the mud-shedding platforms of the Neogene, fine-grained carbonate was either precipitated in the water column or produced by abrasion or disintegration of skeletal grains. The material was either formed in suspension or stored as bare accumulations that could be easily re-suspended by storms and tides. Both processes fueled efficient export of fine-grained carbonate into the basin. On the debris-shedding platforms of the Triassic, most fine-grained carbonate was precipitated as a by-product of organic and inorganic chemical reactions and fines created by abrasion were quickly stabilized by microbial mats. Consequently, most of the carbonate fines were held in place by organic tissue or slime long enough to become cemented and form hard pellets, crusts or thrombolitic layers. This material may appear as micrite in thin-sections but it did not behave as fine-grained, cohesive material during transport. Rather, it disintegrated into coarse silt, sand and rubble upon erosion and behaved accordingly during transport and deposition.

The Neogene platforms are mud-shedding systems because much carbonate is precipitated in the water column or deposited as loose accumulations that are easily re-suspended by storms and tides. The Triassic platforms shed mainly debris because most carbonate was precipitated in or stabilized by microbial mats.

5. Conclusions

Modern and Neogene carbonate platforms around the world and platforms of the Alpine Triassic display very similar basic facies belts, including wave-resistant bio-constructed rims and platform interior sediments rich in sand. Despite this similarity, their slope architecture is vastly different.

The slopes of Neogene platforms show cliffs and steeply inclined talus only between 0 – 200 m, approximately the depth range affected by Neogene sea-level fluctuations. Below 150-200m, slope angles decrease to <5° and platform-derived, muddy sediments dominate. Pervasive evidence for creep and slumping indicates deposition at the angle of repose. Triassic platform slopes consist of sand and rubble; clinoforms plunge from the platform margin directly to the basin floor at 300-500 m; straight bedding at angles of 25-35° indicates deposition at the angle of repose of non-cohesive material.

The contrasting slope architecture of Neogene and Triassic platforms may be caused by differences in the way fine-grained carbonate is produced at the platform top. Neogene platforms shed large amounts of fine-grained carbonate because much carbonate is precipitated in the water column on the platform or stored there as loose accumulations, easily re-suspended by storms. On the Triassic platforms, strong circumstantial evidence indicates that the micritic carbonate was produced mainly as pellets and crusts in microbial mats and carried off the platforms in the form of sand and rubble eroded from the platform top.

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