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Depositional Processes and Sequence Stratigraphic Interpretation of Cretaceous Carbonate Slope Deposits, South-central Pyrenees, Spain

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INTRODUCTION

Recent exploration strategies have prompted more than a decade of research on the stratigraphy and depositional processes of siliciclastic slope systems. Unfortunately, carbonate slope systems have not benefited from such an economic stimulus, and the processes responsible for the construction of carbonate slopes are more poorly understood. The same depositional processes operate on both siliciclastic and carbonate slopes, including gravitational settling and a variety of sediment gravity flow processes. However, there are some fundamental differences that must be addressed when studying carbonate systems, including higher depositional slope angles, potentially higher sedimentation rates, sediment type, early cementation, linear sediment sources, local sediment production, and highstand shedding of sediment onto the slope. In addition, extrinsic forces operate on carbonate slopes, including changes in sea level, tectonics, paleoceanographic events, climate, and siliciclastic influx.

Cenomanian to Santonian carbonate slope strata from the south-central Pyrenees in northern Spain were deposited on a bypass slope, where coarse, platform-derived debris was transported across the upper slope and is deposited on the middle and lower slope. The upper slope is built by hemipelagic and periplatform sediment that fines from coarse carbonate sand near the margin to carbonate wackestone near the middle slope. The middle slope is characterized by hemipelagic carbonate wackestone, mudstone, and submarine slumps interbedded with channelized megabreccias that contain margin-derived clasts. The lower slope is an amalgamation of hemipelagic sediments, submarine slumps and slides, and a variety of megabreccias and megaconglomerates. It has a measured depositional gradient of at least 12°, and this slope was presumably even higher on the upper slope.

The Pyrenean platforms were initiated on the southern margin of an active wrench basin in the Cenomanian, and the location of the margin was controlled by a syndepositional fault with a significant normal component. Movement along this fault was not only responsible for maintaining high accommodation in the basin, but it may also have acted as a triggering mechanism for the abundant sediment gravity flow deposits (mainly debrites) preserved on the middle and lower slope. The strata have been subdivided into five depositional sequences, including UK-1 (Middle Cenomanian), UK-2 (Late Cenomanian), UK-3 (Turonian), UK-4 (Late Turonian to Early Coniacian), and UK-5 (Middle Coniacian to Early Santonian). The slopes of sequences UK-1 and UK-2 are progradational in nature. Sequence UK-3 is a pelagic unit that drapes the underlying strata. Sequences UK-4 and UK-5 were deposited during an episode of major platform backstepping in response to a change from extensional to compressional tectonics.

SEDIMENT GRAVITY FLOW DEPOSITS

Sediment gravity flow deposits that are preserved in the slope strata of the Upper Cretaceous carbonate platforms of the south-central Pyrenees include submarine slumps and slides, and carbonate megaconglomerates/megabreccias that are interpreted as debris flow and rock fall deposits. Three main types of megaconglomerates/megabreccias have been identified:

- *Slope-derived megaconglomerates* are composed of carbonate mudstone and wackestone clasts that are similar in composition to hemipelagic and periplatform slope facies. The matrix is also composed of slope-derived wackestone and mudstone. The clasts are often contorted, suggesting they were semilithified at the time of deposition. The internal fabric is chaotic, and there is no evidence of grading. These megaconglomerates typically amalgamate to form sheet-like deposits up to 30m thick and 1km wide that are restricted to the lower slope environment. They are interpreted to have been deposited by mud-rich debris flows that originated as submarine slumps and slides higher on the slope.
- *Matrix-rich, polymictic megabreccias* are composed of a range of rudstone, grainstone, packstone, wackestone, and mudstone clasts that represent a variety of slope and platform margin facies. The matrix is composed of wackestone and mudstone, as above, but occasionally contains biota that were derived from the platform shelf (miliolids, praealveolinids). The internal fabric of these deposits is chaotic, and there is no evidence of grading. These megabreccias are channelized (25m thick, 300m wide) on the middle slope, and sheet-like (25m thick, 1km wide) on the lower slope. They are interpreted to have been deposited by debris flows that originated by collapse of the platform margin, bypass and erosion of the upper slope, and deposition on the middle and lower slope.
- *Matrix-poor, polymictic megabreccias* are composed entirely of rudstone, grainstone, packstone, and wackestone clasts derived from the margin and upper slope environments. Matrix is rare, and appears to have filtered down between the clasts after deposition. This megabreccia lithology occurs as thick (up to 60m) deposits abutting the fault at the platform margin, and as thinner beds (up to 5m) that onlap the slope and

extend about 500m out into the basin. The beds that extend into the basin thin downdip until they are represented by a few outlier boulders. Both types of deposits are interpreted to be the result of rock falls and debris falls. They were typically confined to a position immediately adjacent to the fault scarp, but occasionally were transported further into the basin.

In addition to the megabreccia and megaconglomerate lithologies described above, the slope contains hemipelagic sediments (deposited by gravitational settling across the slope). Periplatform grain flow deposits occur on the upper slope. Submarine slide deposits (internal bedding is undeformed) and submarine slump deposits (internal bedding is contorted) are common on the middle and lower slope.

DEPOSITIONAL CONTROLS

Many factors influence the depositional processes that build carbonate slopes, including slope gradient, sedimentation rates, sediment type, early cementation, highstand shedding of sediment, relative changes in sea level, tectonics, paleoceanographic events, climate, and siliciclastic influx. The major controls on slope deposition for sequences UK-1 to UK-5 include:

- *Sediment type* is a major control on slope stability and depositional processes. Mud-rich middle and lower slope sediments like those in the Pyrenean Basin are unstable at depositional gradients greater than 5° (Kenter, 1990), and would certainly be unstable at the 12° slopes measured for sequences UK-1 and UK-2. These lower and middle slope sediments have been extensively resedimented by submarine slides, slumps, and debris flows (slope-derived megaconglomerates). Coarser, more mud-lean debris flows resulted in the matrix-rich polymictic megabreccias. Rock falls and debris falls resulted when mud was absent (matrix-poor polymictic megabreccias). When coarse debris was not available (for example, in sequence UK-3) only submarine slumps, slides, and slope-derived megaconglomerates were deposited.
- *Slope gradient* provides a fundamental control on the initiation and deposition of sediment gravity flow deposits (Figure 1). Mud-rich submarine slides, slumps, and slope-derived megaconglomerates are common on the lower slope, and are rare on the middle and upper slopes. The coarser matrix-rich polymictic megabreccias were deposited at slightly higher depositional angles in the middle and lower slopes, and matrix-poor polymictic megabreccias were deposited on the upper and middle slopes, where the depositional gradient was most likely greatest. The apparent lack of carbonate turbidites can be explained by the slope gradient as well. Turbidites are unlikely to be deposited on the steep slopes observed in these sequences (Figure 1).
- *Regional and local tectonics* are interpreted to have played a major role in controlling slope sedimentation in sequences UK-1 through UK-5. High rates of increase of accommodation associated with wrench tectonics

during deposition of sequences UK-1 and UK-2 were the primary cause of steep depositional gradients on the slope. In addition, seismic activity along local faults is a likely triggering mechanism for the margin-derived debrites. Slope gradients and the abundance of debrites decreased in sequences UK-4 and UK-5, as the carbonate platforms backstepped in response to the initiation foreland basin tectonics.

- *Relative falls in sea level* are commonly interpreted as major controls on carbonate slope sedimentation, either through exposure and erosion of the shelf margin, or by promoting slope failure by decreasing pore fluid pressures in slope sediments. Although there are a number of debrites with margin-derived clasts that have evidence of subaerial exposure, it is unclear whether a fall in sea-level alone is responsible for these deposits. Similar lithologies occur in both lowstand and highstand systems tracts.
- *A paleoceanographic event* at the Cenomanian-Turonian boundary resulted in the drowning of the Cenomanian platform and cessation of shallow carbonate production during sequence UK-3. Consequently, no coarse carbonate material was available for transport into the basin, and only submarine slumps, slides, and slope-derived megaconglomerates were deposited. At this time, the basin was beginning to fill up through stratal onlap, and the slope gradient probably decreased with time.

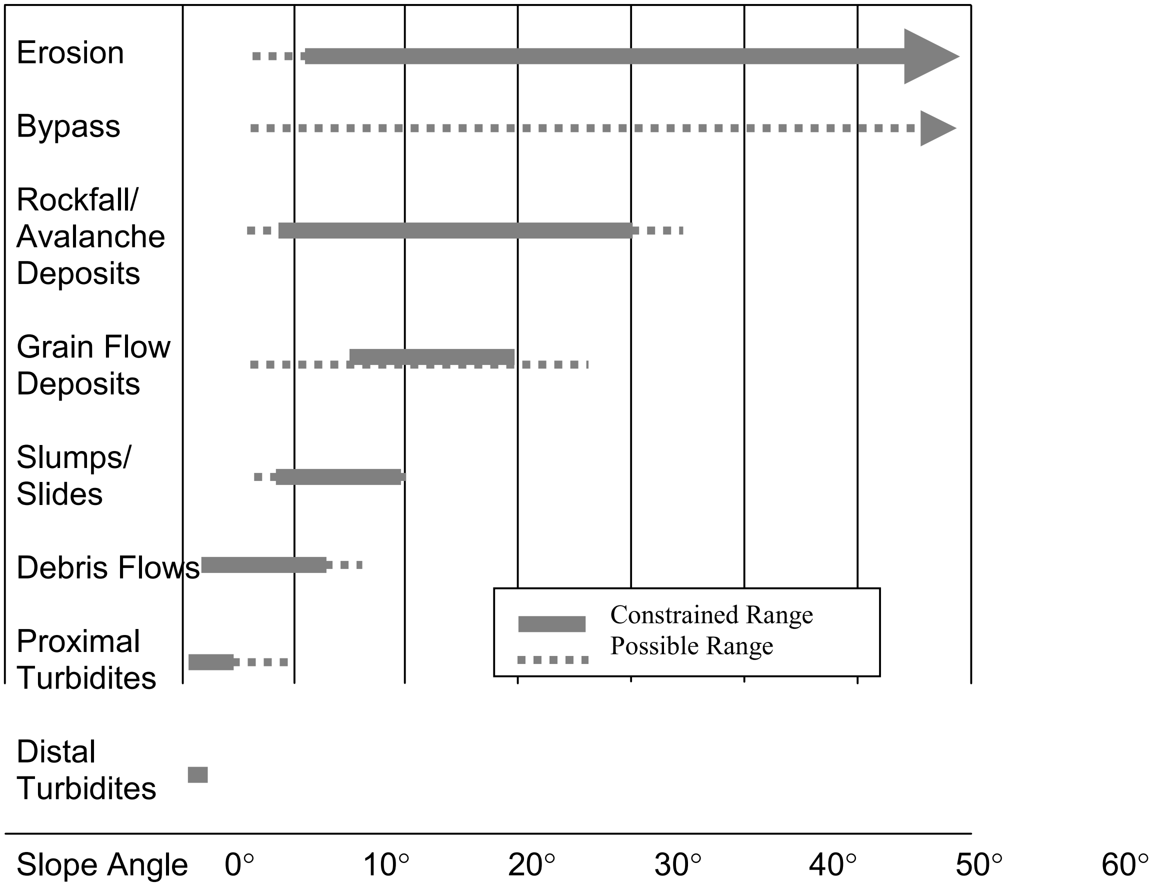

Figure 1. Relationship between depositional products and slope angles for carbonate slopes from the Bahamas and several ancient examples. Data was compiled from Drzewiecki and Simo (2001), Eberli (1987), Enos and Stephens (1993), Harris (1994), Hiscott an James (1985), Kenter and Campbell (1991), Lehrmann et al. (1998), Mullins and Neuman (1979), Mullins et al. (1984), Playford (1980), Playford et al. (1989), Schlager and Ginsburg (1981), and Srivastava et al. (1972).

SEQUENCE STRATIGRAPHIC MODELS

The lateral and vertical slope facies associations varied as the depositional controls discussed above evolved through time. Typical vertical facies stacking patterns for prograding, draping, and backstepping slopes in the Pyrenean Basin are outlined below and shown in Figure 2.

Prograding slopes (UK-1 and UK-2, Figure 2) have a lowstand systems tract that is underlain by an erosional surface. The lowstand systems tract (LST) in sequence UK-1 does not contain any resedimented deposits, and is interpreted to have been a low angle ramp. The LST of sequence UK-2 is composed of debrites containing margin-derived clasts that have evidence of subaerial exposure. The transgressive systems tract (TST) records condensed sedimentation, but may be resedimented if the slope gradient is steep enough. The highstand systems tract (HST) of UK-1 is a shallowing-upward succession of periplatform and pelagic sediments that records progradation. The latest HST deposits contain submarine slumps, slides, and slope-derived megconglomerates, suggesting that the slope steepened with time. Sequence UK-2 appears to have had a steep depositional slope throughout the HST, and is composed of submarine slumps, slides, slope-derived megaconglomerates, and matrix-rich polymictic megabreccias, with little material left in its original depositional state. A high frequency cyclicity exists composed of matrix-rich polymictic megabreccias at the base, submarine slumps, slides, and slope-derived megaconglomerates in the middle, and periplatform grain flow deposits at the top. These vertical facies assemblages reflect progradational stacking of the lateral facies assemblages that make up the slope during deposition of sequence UK-2.

Sequence UK-3 drapes the underlying sequences and is composed entirely of fine pelagic mudstone to packstone (Figure 2). The slope of UK-3 is composed of pelagic sediment, submarine slumps, slides, and slope-derived megconglomerates in the TST (no LST observed). Resedimented deposits decrease in abundance in the HST, as the slope gradient was reduced by sediment onlap.

The backstepping platforms (UK-4 and UK-5, Figure 2) contain matrix-rich and matrix-poor polymictic megabreccias in the LST and TST. In sequence UK-5, deposition of the matrix-poor polymictic megabreccias was deposited in response to development of a fault scarp over the platform margin of sequences UK-1 and UK-2. Coarse sediments were shed from this scarp as rock falls and debris falls. HST deposits for sequence UK-4 are trapped updip of the study area. HST deposits for sequence UK-5 are composed of a thick package of fine-grained pelagic and periplatform sediments that have limited evidence of submarine slumping. Coarse material was trapped in a landward location, as the shelf margin backstepped tens of kilometers.

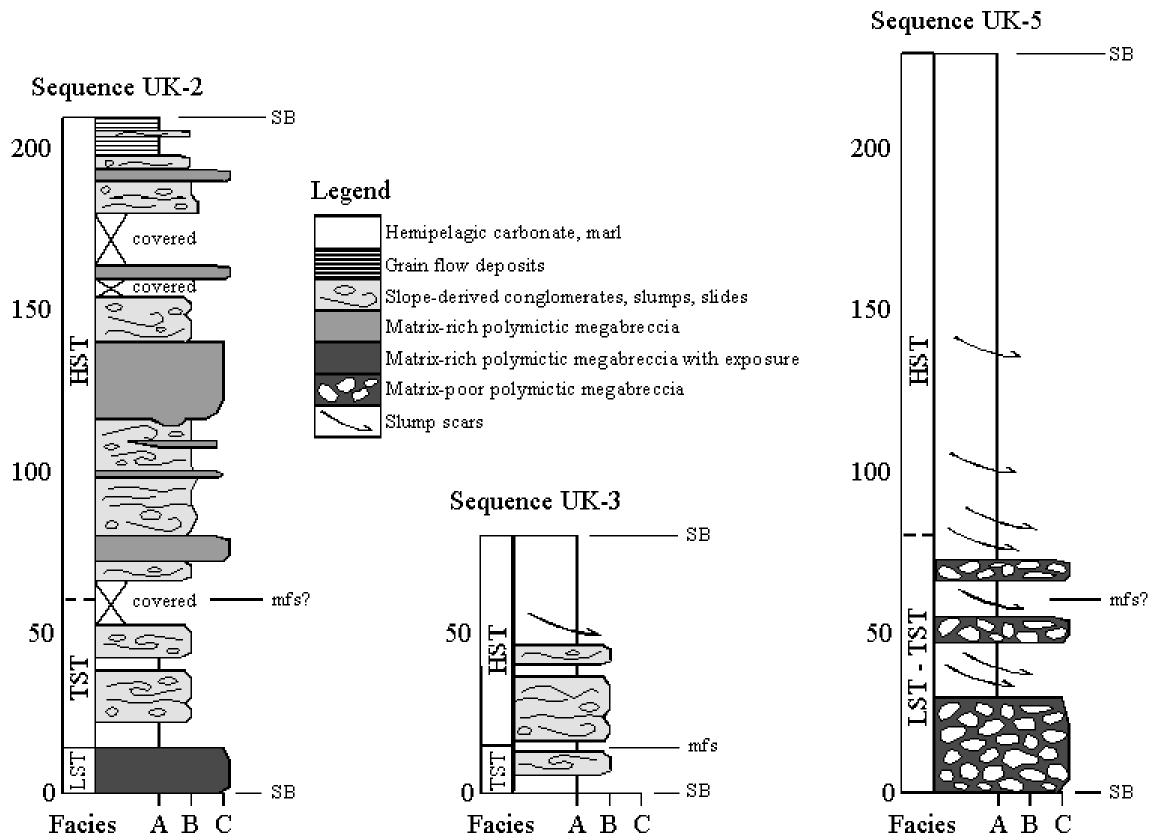

Figure 2. Vertical facies associations for prograding (Sequence UK-2), draping (Sequence UK-3), and backstepping (Sequence UK-5) slopes. Facies A contains hemipelagic carbonates, marls, and grain flow deposits that represent background slope sedimentation. Facies B contains resedimented slope deposits. Facies C contains resedimented slope and margin deposits. Thicknesses are given in meters. SB = sequence boundary, mfs = maximum flooding surface, LST = lowstand systems tract, TST = transgressive systems tract, and HST = highstand systems tract.

CONCLUSIONS

Upper Cretaceous slopes in the Pyrenean Basin contain a variety of gravity flow deposits that were laid down in response to a number of depositional controls, the most important of which were slope gradient, sediment type, relative changes in sea level, tectonics, and a paleoceanographic event. Mud-rich lithologies (submarine slumps, slides, and muddy debrites) were confined to the lower slope where the depositional gradient was the lowest. Mud-poor deposits (coarse-grained debrites, rock fall deposits, and debris fall deposits) can be deposited on higher depositional gradients, and occur on the upper and middle slope as well. Tectonics were responsible for creating a steep depositional profile, and provided a triggering mechanism for the initiation of submarine slumps, slides, and debris flows. In addition, a fault scarp on the seafloor provided the relief necessary for the deposition of rock fall and debris fall deposits in sequence UK-5. Relative falls in sea level may have also been responsible for the erosion and deposition of margin-derived debris in the basin.

Prograding, draping, and backstepping slopes have different lateral and vertical distributions of slope sediment types. Prograding slopes have resedimented deposits in all system tracts reflecting the maintenance of high deposition slope angles. The overall facies stacking pattern shallows upward, in response to the progradation of shallower facies into the basin. The draping slope lacks coarse material, and is dominated by fine-grained submarine slumps, slides, and slope-derived megaconglomerates. Both draping and backstepping slopes record a decrease in resedimented deposits in the HST as compared to the LST and TST. This reflects the retrogradation of the shallow carbonate factory, and the decrease in depositional slope angle associated with the infilling of the basin through stratal onlap.

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