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Compositional variations during phases of progradation and retrogradation of a Triassic carbonate platform (Picco di Vallandro/Dürrenstein, dolomites, Italy)

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Abstract In this paper data are presented on the composition of sediments deposited at the toe of slope during progradation or retreat of Triassic carbonate platforms in the Dolomites (Italy). For this purpose a succession was studied from the toe of slope of a Triassic (Carnian) carbonate platform (Picco di Vallendro/Dürrenstein, Dolomites, Italy). The microfacies analysis of selected calciturbidites sequences revealed a reduced input of oncolites and ooids during progradation and an increase in clasts. The main input, however, was derived from the reefs on the platform. Retrogradation of the platform showed an increase of filaments and radiolarians (open ocean biota) as well as carbonate mud and a reduced input of grains that originated within the reefs on the platform. Both during progradation and retrogradation parts of the platform were flooded and could produce excess sediment that could be exported to the surrounding basins. However, the absence of platform interior biota documents that progradation occurred from sediments of the reefal belt, probably during relative sea-level lowstands. Carbonate composition varies systematically with toe-of-slope progradation/retrogradation and, thus, argues for carbonate production as the main driver of the geometries observed at the toe of slope.

Key words Triassic · Southern Alps · Carbonate platform · Toe of slope · Progradation · Retrogradation · Sediment composition

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Introduction

In the literature, a large number of interacting factors are given as controlling the movement of platforms. Bosellini (1984), in describing the progradation of Triassic platforms in the Dolomites, proposed as the main factors: (a) the rate of basin sedimentation; (b) the width of the platform; (c) depth of the surrounding basin; and (d) eustatic variations of sea level. Modelling experiments of the Upper Triassic Latemar platform by Harris (1991) partly confirmed these factors. In addition, Harris (1991) showed that syndepositional relief and the balance between the rates of platform and basin sediment accumulation were the most significant factors that determined the extent of progradation. The amount (thickness) and timing of basinal sedimentation (which includes a significant volume of siliciclastics in his example) also proved to control the geometry of carbonate margins during modelling experiments (Harris 1991). All in all, it depends on the accommodation space present on the slope that needs to be filled by the input of the platform before progradation actually can take place. In other words, the stratal patterns and facies that develop within the system tracts vary depending on the accommodation space available (Jacquin et al. 1991; Vail et al. 1991).

Eberli and Ginsburg (1989) demonstrated that the initiation of platform edge migration on the Bahamas during the Cenozoic was dependent mainly on the factors sea-level change and seaway morphology, whereby progradation started only when the seaways had shoaled to approximately 500 m and/or the slopes had decreased to approximately 5°. According to Eberli and Ginsburg (1987, 1989), the Bahamian prograding sequence acted as a record of relative rise and highstand of sea level, when sediment production on the bank top was high and cross-bank currents moved excess sediment offbank. In the view of James and Kendall (1992) the most likely timing for the platform to prograde is during sea-level highstands. During this time the platform is able to develop thick prograding or forestepping wedges of slope sediment. Especially from the margin facies belt much sediment can be exported, most likely by coarse-grained sediment gravity flows (the “highstand shedding principle” of Droxler and Schlager 1985). The time of sea-level lowstand is a phase in which no large prograding wedges occur due to the fact that the carbonate factory is shut down. In times of transgressions vertical sediment accretion or facies backstepping are the most likely mode of sedimentation. Progradation also might occur, depending on the amount of offbank transport, i.e. if the rate of carbonate sediment production is able to fill the progressive addition of new accumulation space (James and Kendall 1992).

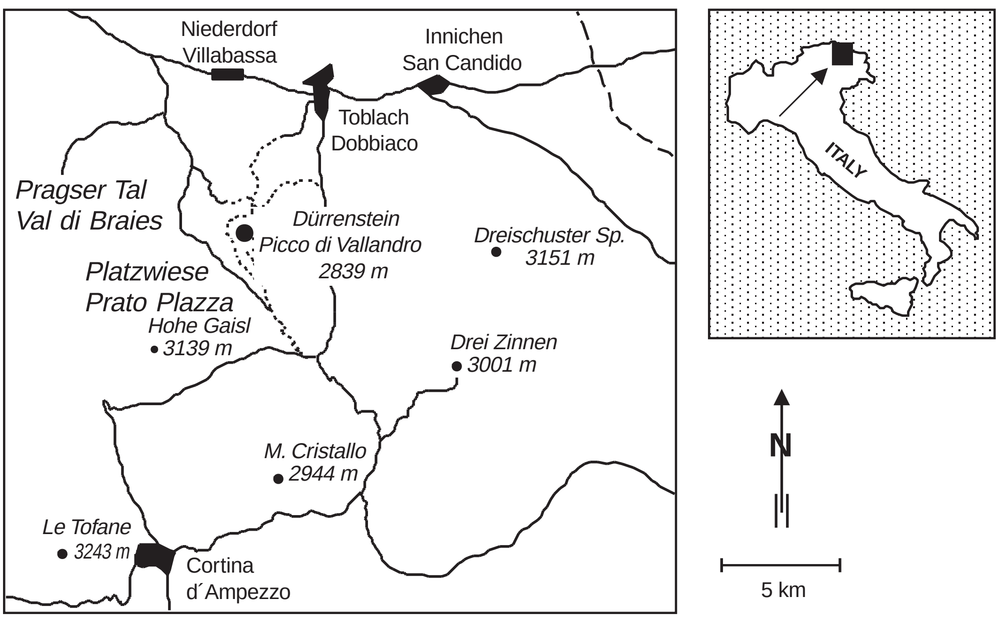
Relative sea-level variations and environmental factors determine the possibility of certain environments to produce excess sediment (Schlager 1991, 1993).

The angles of repose of the clinoforms also give some indication of what sort of rock type/grains make up steep inclined beds as only grain-supported virtually mud-free sediments can maintain these high angles of repose (Kenter 1990). This leads to the question as to what sort of grains can be produced in the platform–basin transect. Progradation itself occurs in pulses that are believed to be related to sea-level changes (Eberli and Ginsburg 1989). Thus, the type of grains encountered in the single layers at the toe-of-slope could give some indication as to which environments were able to produce excess sediment. In the Dolomites, Bosellini (1989) distinguished two types of grains in the carbonate systems present: (a) “pathological” (erosion products); and (b) “physiological” (resulting from excess platform productivity) grains; thus, two types of progradation are expected (Masetti et al. 1991). Physiological prograda-tion resulting from redeposition of carbonate mud and sand previously accumulated at the platform edge, typically associated with sea-level highstands. Pathological prograda-tion takes place during sea-level lowstands. Subaerial exposure and increased erosion of the lithified platform top produce enough pathological sediments to enable the system to prograde (Masetti et al. 1991). The progradation of the Cassian and the Carnian platforms in the Dolomites are seen as representative for pathological progradation (Bosellini 1984, 1989; Masetti et al. 1991). Sarg (1988), however, describes the Carnian carbonate platforms as a typical example for progradation during the late highstand. Schlager et al. (1991, see their Fig. 6) suggested three different modes of platform progradation for the platform flank of the Picco di Vallandro/Dürrenstein in the Dolomites (Italy): (a) platform-margin growth upward, downward and downslope; (b) intermittent slope failure forming tongues of coarse debris at the toe of slope; and (c) cliff erosion when the platform top is exposed.

Calciturbidites have demonstrated their usefulness as recorders of facies changes on the platform. Recorded within the composition of the calciturbidites were changes related to either facies alterations or to variations in sea level (Haak and Schlager 1989; Everts 1991; Reijmer et al. 1991; Reijmer et al. 1992; Herbig and Bender 1992). For example, in the Vercors (SE France) small and large-scale cycles in clinoform composition were observed (Everts et al. 1995; Everts and Reijmer 1995). The larger cycles parallel the large-scale rhythm of progradation and retreat of the clinoforms, whereas the smaller cycles were probably related to small-scale shallowing upward cycles on the platform top. On a finer scale, Reijmer et al. (1994) demonstrated that the periodicity within the composition of a sequence of Triassic calciturbidites could be related to the small-scale sedimentation cycles on the platform, the so-called Lofer cycles (20–100 ka, fifth- and sixth-order-scale cycles sensu Vail et al. 1991).

As Eberli (1991) noted, controversy still surrounds the questions of when and what type of sediment is exported to the deeper waters to build prograding slopes. Harris (1994)

Fig. 1 Location map of Picco di Vallandro (Dürrenstein). (After Biddle et al. 1992)



showed that the slope facies of the Middle Triassic Latemar buildup consisted mainly of reef-margin-derived grains and clasts. Toe-of-slope deposits were made up of carbonate sands with platform-interior and reef-margin-derived grains. Blendinger (1994) favoured the idea that the slopes, the clinoforms themselves, were the main sediment producers.

In this study the question is addressed as to what type of sediments make up the toe-of-slope deposits of the Picco di Vallandro/Dürrenstein. The compositional variation of calciturbidites is used to analyse the Middle-Late Triassic platform–basin transition during various stages of slope development.

Study area

The sections studied are situated in the northeastern part of the Dolomites, at the Picco di Vallandro/Dürrenstein (Fig. 1). This mountain range shows an undisturbed succession of alternating platform slope, the Upper Schlern Formation, and basinal sediments, the Cassian Formation (Figs. 2, 3; Pia 1937; Bosellini et al. 1980; Schlager et al. 1991). The Carnian succession of depositional structures and textures was investigated in the 1970s by Cros (1971) and Schlager and Nicora (1979). The outcrop was also used for seismic modeling studies by Rudolph et al. (1989), and Biddle et al. (1992). In the seismic modeling the interfingering platform slope and basinal sediments appeared as "pseudo-unconformities" (Schlager et al. 1991). The toe-of-slope deposits consist of three large lobes with individual breccia wedges with bundles of individual breccia beds (Figs. 2, 3). The outcrops (Fig. 3A) display a clear hierarchy of bedding rhythms, the origin of which is still unclear (Schlager et al. 1991). Other large-scale features in the slope and at the toe-of-slope deposits are cipit boulders, slump levels and large debris flows (Biddle 1980; Schlager and Nicora 1979). The vertical transition from thick-bedded, coarse-slope breccias into decimetre-bedded basinal limestones and marl occurs within a few tens of metres as a result of a very rapid decrease in slope angle (Fig. 3B; Schlager and Nicora 1979; Rudolph et al. 1989).

Methods

Five sections that record platform progradation (section 1988-1, 1988-7 and 1991-C; Figs 2, 3) and retrogradation (section 1991-A and 1991-B) in the foreslope environment were measured and sampled bed by bed. In total, 120 thin sections were point counted. The compositional variation of the calciturbidites was analysed, using the point-count groups listed below. Although differences in biota exist between Carnian and Norian biota, the main point-count groups used in Reijmer and Everaars (1991) and Reijmer et al. (1991) for the analysis of a Norian turbidite sequence are still applicable. The main differences between the Norian and Carnian reefs (Fagerstrom 1987; Stanley 1988; Riedel 1990) are that pharetroniide sponges, especially "Sphinctozoans", encrusting organisms (cyanobacteria and filament algae), *Tubiphytes* and algae are common in the Carnian, whereas in the Norian a higher diversity within the biota groups exists (Stanley 1988). In comparison with their Norian counterparts, the Carnian reef communities are believed to have inhabited deeper parts of the platform and slopes. In addition, calcisponges, mostly Inozoans, corals (*Thecosmilia* type) and algae (Solenoporacean and spongiostromata algae) are abundant in the Norian (Fagerstrom 1987; Riedel 1990).

Fürsich and Wendt (1977) for the Cassian Formation (Dolomites, Italy), and Harris (1993, 1994), for the Latemar Reef (Dolomites, Italy), describe the following facies distribution along the platform–basin transect: (a) inner platform dominated by dasycladaceans, blue green algae, some fora-

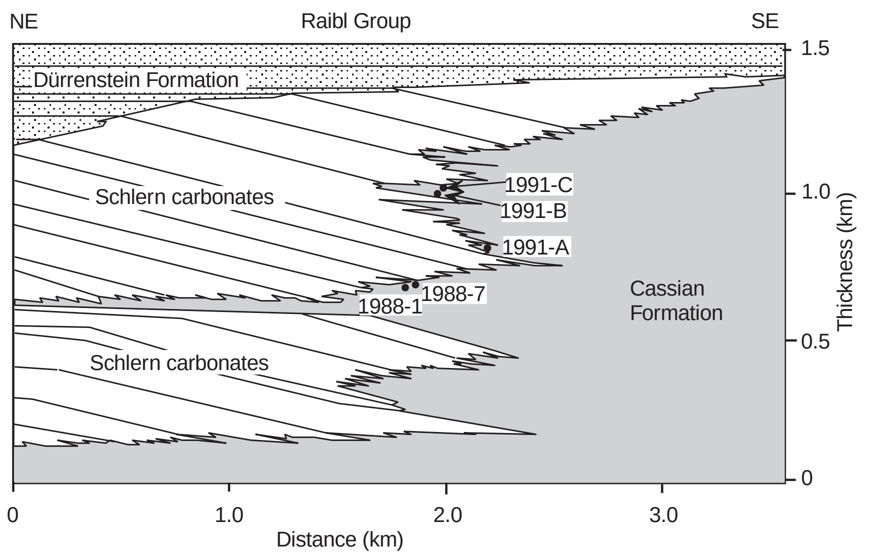


Fig. 2 Model of platform–basin transition. (After Biddle et al. 1992). The stratigraphic position of each section is indicated. *Dürrenstein Fm* well-bedded dolomite; *Upper Schlern Fm* massive dolomite and wedges of limestone breccia; *Cassian Fm* well-bedded limestone and marls with graded beds. Note that this is an idealized lithological model and that not all relationships are shown in outcrop

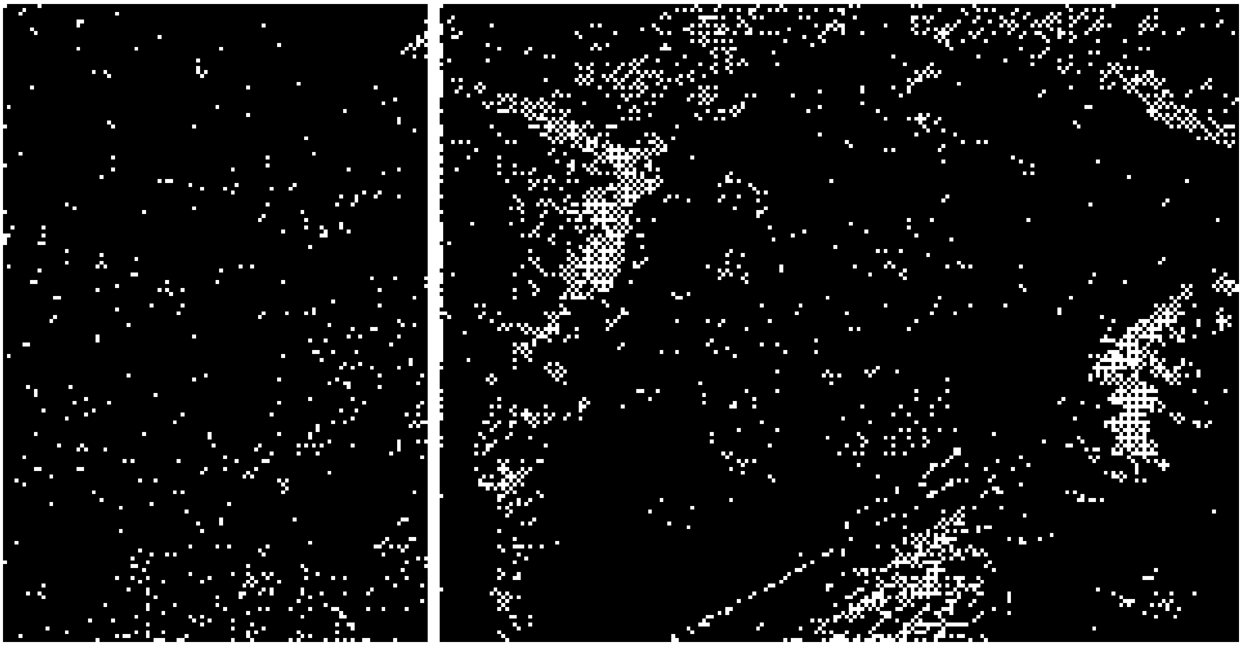


Fig. 3A, B Photos of the outcrop. **A** Section 1988-1 (progradation) is situated at left lower side of the picture (*black arrow*). Section 1988-7 (progradation) is at the upper right-hand side of the picture. Total length of the succession between the triangles is approximately 15 m. **B** The centre block contains section 1991-B (retrogradation) and 1991-C (progradation; *arrows*) at the right-hand side of the photograph. At the left, in the gully, section 1991-A (retrogradation) is situated

minifera, peloids, micritized grains micrite lumps; (b) back reef with algal/foraminifera- and calcareous sponge/coral patch reefs with highly diverse fauna of frame-builders and reef-dwellers; (c) reef-platform margin with abundant *Tubiphytes*, microproblematica, such as *Baccanella*, *Macrotubus*, *Baccinella* and peloids, “structure grumuleuse” sediment (Reid 1987); and (d) margin-foreslope transition with encrusting sponges, hexacorals (*Thecosmilia* group), peloids and a wide range of skeletal grains such as dasycladacean algae, gastropods, *Tubiphytes*, and micritic envelopes.

The platform deposits at the Dürrenstein/Picco di Vallandro are heavily dolomitized. Therefore, it is assumed that the platform showed a facies pattern similar to the other Carnian reefs in the Dolomites.

The point-count groups used are:

1. Ooids. Ooids with a distinct cortex are included in this group (Flügel 1982).
2. Oncoids. All types of oncoids described by Flügel (1982) are incorporated in this category.
3. Grapestones. Carbonate aggregrates with grapelike appearance, using the definition of Illing (1954), make up this group.
4. Platform-interior biota. This group comprises platform foraminifers (i.e. *Endothyranella* sp., *Pseudotaxis* sp., *Aulotortus* sp.) and dasyclads such as *Diplopora* and *Macroporella*. Dasyclads are the main component of this group.
5. Platform-reef biota. This group contains frame-building biota, the microproblematica *Tubiphytes, Lithocodium* and *Baccinella*; sessile foraminifers such as *Alpinophragmium* sp., *Glomospirella* sp., *Glomospira* sp. peloids are also allocated to this group.
6. Clasts. This group includes the so-called intra-reef clasts (peloidal structures) of Reid (1987), intraclasts (resedimented slope sediments), cemented clasts (redeposited biotic grains cemented with sparite) and lithoclasts (extraclasts).
7. Non-specified biota. Biota that are not diagnostic for certain palaeoenvironments are assigned to this group. It includes unidentifiable skeletal grains, echinoderms, crinoids, non-facies diagnostic foraminifers and microproblematica.
8. Open-sea biota. Filaments as well as thin-shelled Nodosariids, thin-shelled agglutinates and sponge spicules are included in this group.
9. Micrite. This group comprises the embedding sediment as defined by Folk (1959), Dunham (1962) and Flügel (1982).
10. Sparite. Cements following the definition of Folk (1959) and Flügel (1982) were included in this group.

In each thin section 200 points were counted using the method of Van der Plas and Tobi (1965). Basic numerical methods were used to analyse the statistical behaviour of the various point-count groups within each succession. Summary statistics and numerical classification, such as Dynamic Cluster Analysis (DYCLAN) and Correspondence Analysis (CORRES), were obtained using of computer programs developed by Sprenger and Ten Kate (1991). DYCLAN and CORRES use the same measure of similarity, i.e. the chi-square distance function. DYCLAN answers the function as to whether the collection of samples is classifiable in subsets, the so-called strong patterns, but does not indicate the reason. CORRES is a particular form of principal component analysis. It combines Q and R mode and has the capability of illustrating graphically the connection between samples and variables (for more information see Ten Kate and Sprenger 1992; Davis 1986).

Results

Sedimentology

Several differences between the prograding and the retrograding strata, the two types of systems (progradation vs retrogradation), are observed in the field measuring the successions. Firstly, the lower prograding system of the Picco di Vallandro platform (sections 1988-1 and 1988-7) is coarse-grained, whereas the retrograding and prograding systems further up in the sequence (sections 1991-A to -C) are mud dominated. In general, pack- to grainstones are more abundant in the progradational phases, whereas mud- to wackestones dominate the retreating intervals.

The fine-grained retrograding sections display more microfaults than the prograding sections (Everaars and Reijmer 1992). The prograding part shows deposits indicating large-scale slope failure such as slumps and debris flows, whereas the retrograding sequence is dominated by mudflows and liquefied flow. These different types of redeposition reflect different slope processes as a result of the contrast between the mud-dominated as opposed to the coarse-grained slope. In outcrop the oblique trend of the faults towards the slope direction is clearly visible (Everaars and Reijmer 1992). The faults indicate that continuous slope adjustment processes took place.

Point-count analysis

The point-count analysis detected several compositional differences in the calciturbidites of the progradational vs the retrogradational strata. During progradation a reduced input of oncoids and ooids (sections 1988-1, 1988-7, 1991-C) occurred. In addition, clasts were more frequently encountered (Figs. 4, 5A, Table 5). Retrogradation of the platform (sections 1991-A, 1991-B) showed a reduced input of grains that originated within the reefs on the platform. In addition, open-sea biota (mainly filaments) and micrite showed an increase (Figs. 4, 5B, Table 5).

The aforementioned variations are quantified by various statistical measures and plots (Figs. 6, 7; see Tables 1–5). Comparison of the coefficients of variation (relative standard variation) reveals that grapestone and platform-interior biota, despite their low standard variation and modest numbers, vary considerably within the sections (Table 1). Micrite varies very little with a high standard deviation. The highest coefficient of variation is present within grapestone. Inequality of mean, median and modal values, as well as the values of skewness and kurtosis, indicate non-symmetrical frequency distributions to be present within all.

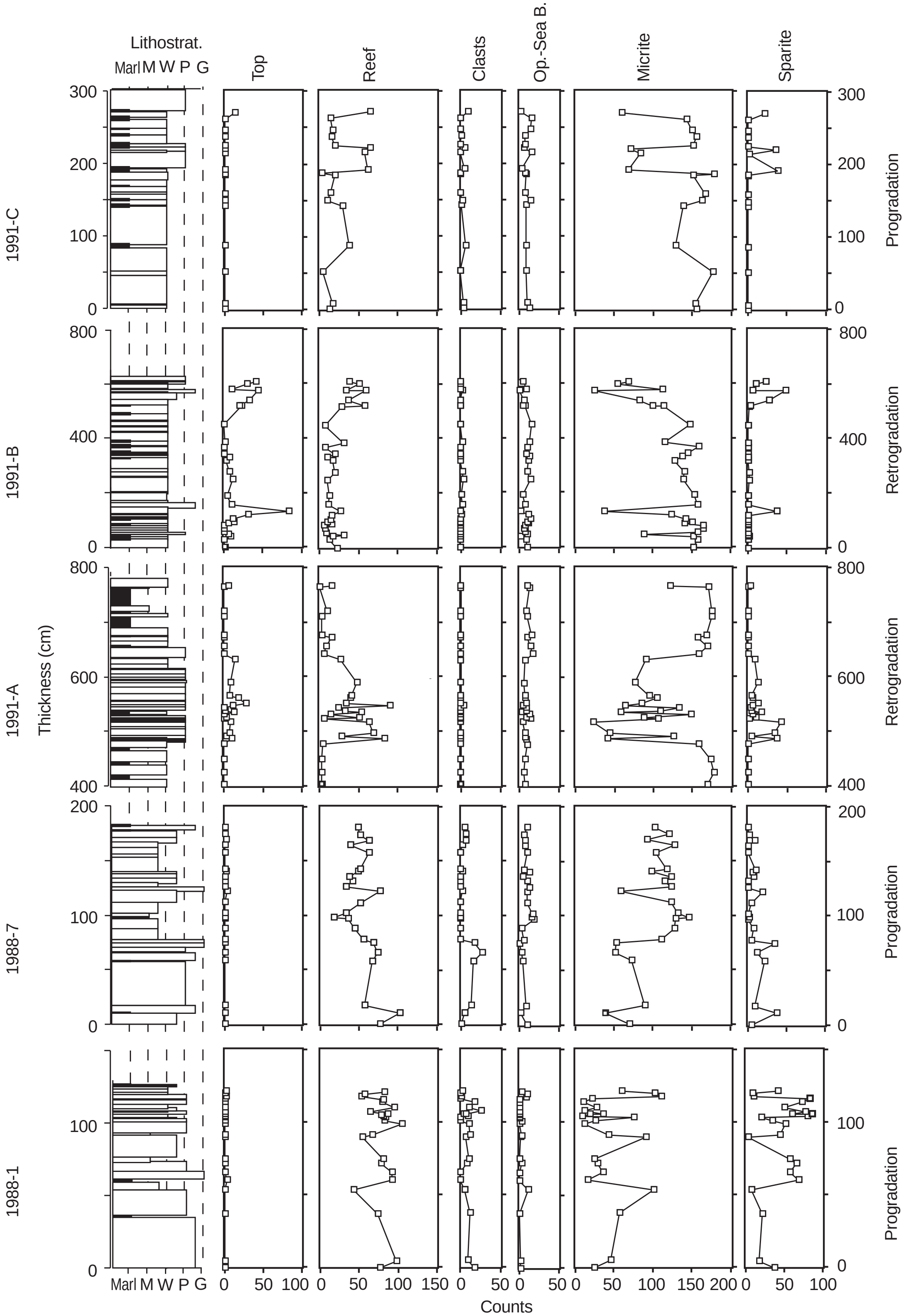
Some groups co-vary and others show anatagonistic behaviour (Fig. 4). Tests on normality were rejected for all point-count groups; therefore, Spearmanís rank correlation was used, (Davis 1986). High correlation is shown between ooids and oncoids and grapestone (0.6 and 0.64), as well as open-sea biota and micrite (0.6; Table 2). The highest negative correlation exists between micrite and platform reef (82.8% $[(-0.91)^2 \times 100]$). In addition, sparite and micrite, and sparite and platform reef, show high correlation, the first –0.90 and the latter 0.84. Bed thickness displays neutral behaviour, but weak negative correlation exists to platform reef input and weak positive correlation to ooid, grapestone and micrite.

Cluster analysis yielded three big clusters, A, B and C, with 9, 79 and 32 samples, respectively (Fig. 6). Clusters B and C are related to each other on a higher level, whereas cluster A is more independent. The turbidites classified in cluster A occur only in the retreating successions. Turbidites of cluster C are present in prograding successions (27 of 32). Cluster A, the smallest group, is characterized by a high amount of ooids, oncoids and grapestone, whereas open-sea biota and micrite are minor components (Table 3 and 5; Figs. 5A, 6). Cluster B shows a small decrease compared with the mean of the total data set, in platform reef and sparite, but a small increase in micrite and open-sea biota. High platform reef input and sparite characterizes cluster C, together with a relative increase in clast and platform-interior biota, as well as a sharp decrease in open-sea biota and micrite (Table 3and 5; Figs. 5B, 6)).

Table 4 summarizes the results of the correspondance analysis. The first two factors explain 73.58% of the total variation. Factor 1, which accounts for 53.30% of the total variation, is controlled by the variable groups micrite and open-sea biota vs platform reef, clasts and sparite. Ooids, oncoids and grapestone contribute mainly to factor 2, which explains 20.28% of the total variation.

The factor analysis plot (Fig. 7) displays the projections of the individual samples and variables along factors 1 and 2. The antagonistic behaviour of micrite vs sparite and platform reef determine factor 1, whereas ooids, oncoids and grapestone vs all others dominate factor 2. Clusters B and C form a continuous range along factor 1. Cluster A represents a solitary group dominated by the input of ooids, oncoids and grapestone, and varies independently of the other two clusters.

Fig. 4 Lithostratigraphic column and the compositional variation along representative parts of the successions studied. Section 1988-1, 1988-7 and 1991-C are situated in prograding parts of the toe of slope sediments, sections 1991-A and 1991-B in retrograding parts (see Fig. 2). Point-count groups representing certain paleaoenvironments indicated at the top. Ooids, oncoids and grapestone are combined into "top". Horizontal scale in counts, vertical scale in centimetres. Note that the sections are entities and that the thickness scale varies


Lithostrat.
Marl M W P G
Top
Reef
Clasts
Op.-Sea B.
Micrite
Sparite
1991-C
1991-B
1991-A
1988-7
1988-1
Thickness (cm)
Progradation
Retrogradation
Retrogradation
Progradation
Progradation
Counts
0 50 100
0 50 100 150
0 50
0 50
0 50 100 150 200
0 50 100

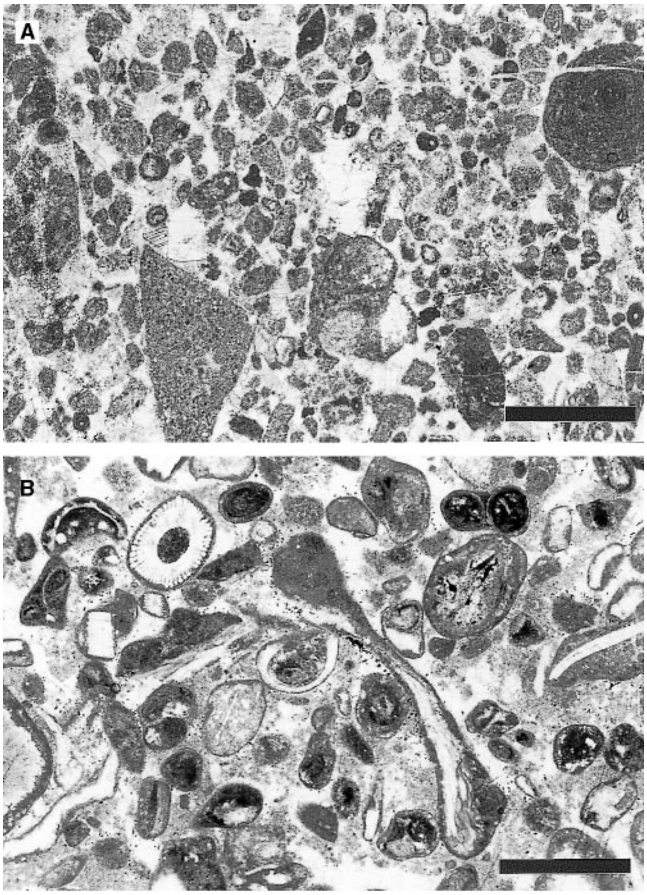


Fig. 5 Representative photomicrographs of thin sections of **A** cluster **C** and **B** cluster **A**. **A** Note the high portion of reef-derived grains and clasts in a sparite cement (progradation). **B** Typical micrite-rich, ooid–oncoid–grapestone bearing sample characteristics for the retreating phase of the platform. *Scale bar* 1 mm

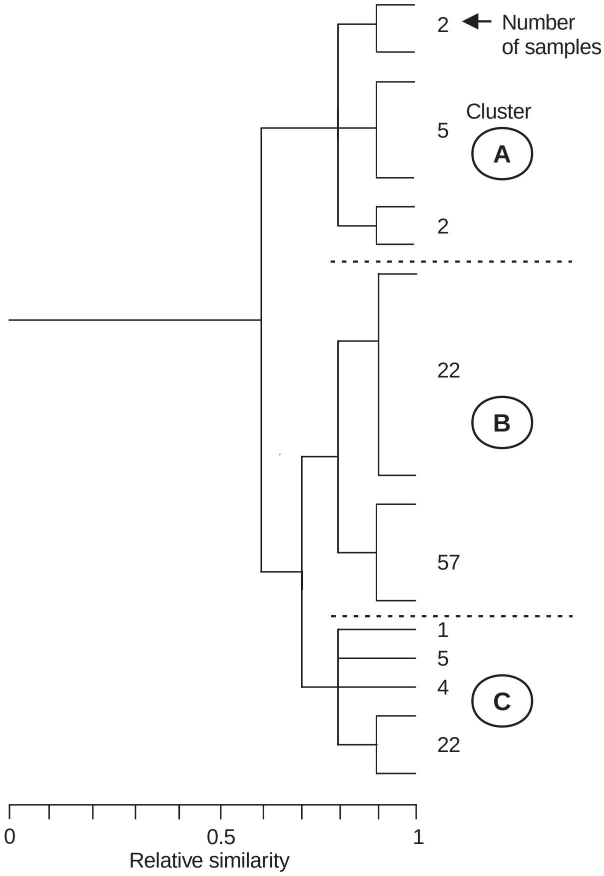


Fig. 6 Dendrogram of dynamic cluster analysis. Individual clusters are given a label, also used in the correspondence analysis. Number of samples within each cluster is indicated. When clusters follow the same path in the dendrogram, the similarity between the individual clusters increases from left to right. The clusters are described in Table 3

Table 1 Summary of the basic statistics of the ten point-count groups and the bedding thickness measured in the field. In each thin section 200 points were counted. Total data set 120 samples

	Ooids	Oncoids	Grapestone	Platform interior biota	Platform reef biota	Clasts	Biota non-specified	Open-sea biota	Micrite	Sparite	Bed thickness
Min. value	0.00	0.00	0.00	0.00	0.00	0.00	7.00	0.00	9.00	0.00	1.00
Max. value	43.00	15.00	28.00	2.00	105.00	27.00	74.00	18.00	178.00	85.00	55.00
Mean	3.06	0.80	0.82	0.09	40.56	2.93	25.58	7.38	104.62	14.18	9.99
Median	1.89	0.67	0.71	0.08	35.52	1.69	22.32	8.04	113.12	7.46	6.56
Modal	1.43	0.54	0.64	0.07	11.38	1.27	18.79	9.67	150.84	5.27	3.64
Variance	41.55	5.61	9.50	0.12	825.95	29.92	157.71	21.82	2465.15	474.76	109.85
SD	6.45	2.37	3.08	0.34	28.74	5.47	12.56	4.67	49.65	21.79	10.48
Coefficient of variation	210.77	295.98	377.32	374.07	70.86	187.00	49.10	63.33	47.46	153.62	104.89
Skewness	3.10	4.49	6.38	3.99	0.38	2.42	1.37	0.08	–0.36	1.70	2.04
Kurtosis	12.42	21.28	49.68	16.19	–1.06	6.02	1.97	–0.72	–1.09	1.91	4.47

Table 2 Matrix of Spearman's rank correlation coefficients determined by the point-count values and bed thickness. Marked in bold are the coefficients exceeding minus or plus 0.40

	1	2	3	4	5	6	7	8	9	10	11
Ooids	1.00										
Oncoids	**0.60**	1.00									
Grapestone	**0.64**	**0.45**	1.00								
Platform interior biota	0.16	0.13	0.07	1.00							
Platform reef biota	0.00	0.10	–0.10	0.28	1.00						
Clasts	–0.19	–0.03	–0.18	–0.02	**0.55**	1.00					
Biota non-specified	0.26	0.09	0.02	0.10	0.14	–0.09	1.00				
Open-sea Biota	–0.05	–0.12	–0.07	–0.32	**–0.60**	**–0.42**	0.04	1.00			
Micrite	–0.18	–0.18	–0.07	–0.29	**–0.91**	**–0.50**	–0.30	**0.60**	1.00		
Sparite	0.12	0.13	–0.02	0.31	**0.84**	**0.47**	0.08	**–0.68**	**–0.90**	1.00	
Bed thickness	0.26	0.14	0.24	–0.07	–0.31	–0.09	–0.03	0.06	0.28	–0.29	1.00

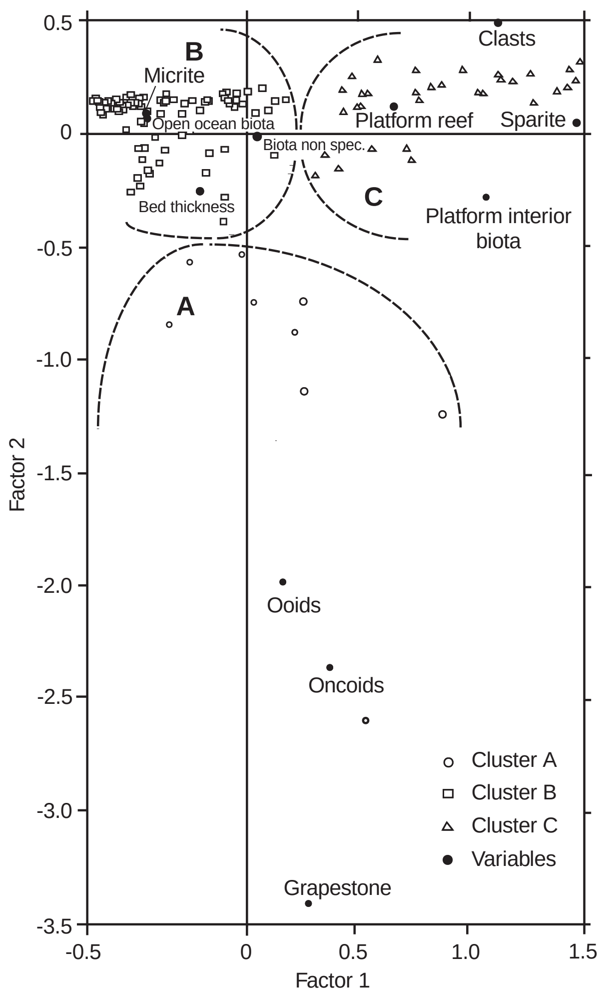


Fig. 7 The projection of sample points and original variables on the plane through the first and second factor axis of correspondence analysis. The first two axes (factors 1 and 2) explain 73.6% of the total data variation in the data set. The characteristics of the factor axes and the variables are shown in Table 4. The samples belonging to the same cluster are given an identical symbol and the contours of the individual clusters are indicated. Cluster A is dominated by ooids, oncoids and grapestone. Cluster B is micrite dominated and has slightly reduced platform reef input. Cluster C combines a high platform reef input with relatively high values for sparite, clasts and platform interior biota (see Table 3)

Table 3 Mean values of the clusters resulting from the dynamic cluster analysis

	Cluster A	Cluster B	Cluster C	Total data set
Ooids	20.78[a]		1.56	3.06
Oncoids	6.89[a]	0.27	0.41	0.80
Grapestone	9.00[a]	0.22	0.00	0.82
Platform interior biota	0.22	0.00	0.28[b]	0.09
Platform reef biota	38.33	25.49[c]	78.38[a]	40.56
Clasts	0.33	1.08	8.22[b]	2.93
Biota non-specified	25.00	25.48	25.97	25.58
Open-sea biota	4.78[c]	9.68[c]	2.41[d]	7.38
Micrite	76.78[c]	134.01[b]	39.88[d]	104.62
Sparite	17.89	2.22[c]	42.91[a]	14.18
Bed thickness	16.44[b]	10.59	6.71	9.99

Point-count groups displaying a relative increase or decrease compared with the mean of the entire data set:
[a]Maximum increase (greater than mean plus 1.0 SD)
[b]Modest increase (mean plus 0.5 SD to mean plus 1.0 SD);
Standard Deviation (SD) neutral (mean minus 0.5 SD to mean plus 0.5 SD
[c]Modest decrease (mean minus 0.5 SD to mean minus 1.0 SD)
[d]Maximum decrease (greater than mean minus 1.0 SD)

Discussion

Microfacies analysis of prograding and retrograding successions at the toe of slope of the Dürrenstein/Picco de Vallandro carbonate platform revealed that the composition of the calciturbidites varies between two distinct end members, pack- to grainstones with platform reef components (cluster C) and mud- to wackestones with open-sea biota (cluster B; Fig. 7). A third group of calciturbidites consists of wacke- to packstones with a very high input of non-bioclastic grains, e.g. ooids and oncoids (cluster A). The latter group is almost completely restricted to the retreating intervals. The other two facies occur in both types of intervals (Fig. 4).

Table 4 Correspondence analysis. Listed are the Eigenvalue of the individual factor axes, as well as the percentage of total variation explained by each axis and the cumulative percentage

Factors Principal axis	Eigenvalue	Percentage	Cumulative percentage	
1	0.3537	53.30	53.30	
2	0.1346	20.28	73.58	
3	0.0481	7.24	80.83	
4	0.0447	6.74	87.56	
5	0.0275	4.15	91.71	
Absolute contributions	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Ooids	0.12	42.34	1.42	0.03	0.27
Oncoids	0.16	15.75	0.00	0.05	0.36
Grapestone	0.09	33.47	0.69	1.75	6.30
Platform interior biota	0.14	0.03	0.21	0.02	1.27
Platform reef biota	23.02	1.80	8.85	4.00	0.10
Clasts	4.91	2.46	7.75	13.44	63.70
Biota non-specified	0.05	0.02	38.52	4.61	0.40
Open-sea biota	2.06	0.20	1.42	0.53	0.18
Micrite	28.30	1.49	4.33	8.98	1.00
Sparite	40.52	0.06	13.22	21.42	5.18
Bed thickness	0.64	2.38	23.58	45.16	21.22
Relative contributions					
Ooids	0.65	91.37	1.09	0.02	0.12
Oncoids	1.71	65.90	0.01	0.08	0.31
Grapestone	0.60	84.84	0.63	1.48	3.26
Platform interior biota	15.81	1.21	3.25	0.31	11.40
Platform reef biota	81.37	2.42	4.25	1.79	0.03
Clasts	35.34	6.74	7.59	12.23	35.69
Biota non-specified	0.64	0.10	61.16	6.81	0.37
Open-sea biota	53.88	1.95	5.07	1.74	0.36
Micrite	91.87	1.84	1.91	3.69	0.25
Sparite	87.52	0.05	3.88	5.85	0.87
Bed thickness	5.24	7.43	26.33	46.88	13.56

A clear relation exists between the composition of the individual calciturbidites and the stage of platform development, progradation vs retrogradation as registered at the toe of slope. When comparing the input of the individual point-count groups with the prograding/retrograding trends visible in the field, the microfacies variation shows the same type of gradual changes (Fig. 4). For example, towards the end of the first progradational phase investigated (sections 1988-1 and 1988-7), more and more micrite is incorporated in the calciturbidites and the input of ooids and oncoids starts. This suggests that the platform becomes flooded and sediment production starts. The composition of the gravity flows in succession 1991-C clearly displays the transition from retreat to forward stepping, i.e. ooid and oncoid input decreases, while more clasts and platform-reef-derived grains are encountered (Fig. 4). This might indicate a decrease in the platform interior production combined with a relative sea-level fall. The weak positive correlation of bed thickness (maximum 0.28) with micrite and the non-bioclastic grains in contrast to the weak negative correlation (maximum –0.31) with platform reef and sparite suggest a higher production during sea-level highstands (Table 2). This scenario is comparable to the present situation on the platform top of the Bahamas: high production of carbonate mud and non-biota grains (Neumann and Land 1975; Droxler and Schlager 1985; Haak and Schlager 1989).

The observed differences in grain composition show that during progradation at the toe-of-slope the system is receiving a high input from the reef with little or no input from the interior, whereas during aggradation to retrogradation there is a significant contribution from the platform interior; thus, it seems that progradation is related to reef growth. This scenario is different to the modern situation where progradation is controlled by production of the platform interior (e.g. Eberli et al. 1997). However, it is not known if – and how – the phenomenon observed at the Picco di Vallandro/Dürrenstein relates to sea-level stand on the platform. It may be that the prograding phases record a situation where the reef keeps up with sea level while the interior stays behind (early transgression, semi-drowned state). It may also be that the prograding phases record periods with fringing reefs at the platform edge with the interior emerged or too shallow to allow the"carbonate factory" to operate fully, i.e. during a relative lowstand of sea level. Finally, it may be that the entire pattern of progradation–retrogradation at the toe of slope relates to productivity cycles of the marginal reefs and/or in the interior (e.g. autocycles sensu Ginsburg 1971), which are independent of sea level. The problem with pinning down sea level is that due to dolomization the stratal patterns in the platform top realm (where accommodation is the dominant controlling factor) cannot be observed.

On the Latemar platform distinct cycles are present in the platform interior that probably were caused by variations in sea level. Harris (1994) showed that the high-frequency sea-level changes observed on this Triassic platform influenced slope deposition. However, whether or not the cycles stacking pattern resulted from allocyclic or autocylic processes remains a point of discussion (Goldhammer et al. 1987, 1990, 1993; Brack et al. 1996). This also might be partly the cause that no rhythmic signature was found on the slope. The data presented in this study do show small-scale variations in sediment composition (see Figs. 3A, 4), but if these cycles resulted from productivity cycles or were caused by sea-level remains unclear.

Blendinger (1994) proposes in his extension of the Gaetani et al. (1981) model that clinoforms can be seen as the principal source of slope carbonates. He takes the absence of diagnostic shallow-water grains as an indicator of in situ production on the slope. As demonstrated in studies by Haak and Schlager (1989), Everts et al. (in press) and this study, the export of sediment towards the basin is controlled by a large variety of factors, i.e. platform topography, the mode of platform development (progradation/retrogradation) and accommodation space that filter the type of sediment exported. In addition, various domains along the slope show different facies patterns each with its specific type of sediment grains (Kenter and Campbell 1991; Reijmer et al. 1996). Thus, the conclusion of Blendinger (1994) that the absence of certain types of grains within certain slope environments are an indication for the reduced production of this environment can be explained by selective deposition along the platform-to-slope transect in combination with the variations in sediment production during different stages of platform development. Platform modelling studies confirm the latter interpretation and develop a similar pattern along the slope in response to sea-level variations, slope angle, production potential of the reef and accommodation space (Harris 1991; Bosscher and Schlager 1992; Bosscher and Southam 1992). Brachert and Dullo (1994) in their study of Ladinian foreslopes showed that microbial carbonate production takes place at the deeper fore reef but can be seen as an indication of low rates of net sedimentation.

The progradation and retrogradation pattern visible at the toe of slope could be caused by either variations in supply of terrigenous material or variations in input from the platform. Filling of the basin might occur by the increased input of clay resulting from climatic changes (Pittet 1996). An increase in the input of this type of sediment might cause a relative change in the depositional geometry at the toe of slope and enhance the possibility for the platform to prograde (Eberli and Ginsburg 1989). Presently, it is not clear to what extent terrigenous input modified the prograding and retrograding trends seen at the toe of slope. The variation in composition in the slope sediments shown in this study, however, argues for variation in input from the platform causing the toe-of-slope sediments to step forwards towards the basin or to retreat. Small-scale compositional cycles are observed superimposed on the large-scale trend. These input cycles with different magnitude most likely can be correlated, as suggested for the Carnian record by Burchell et al. (1990) and Masetti et al. (1988, 1991), to a third-order sea-level fluctuation with superimposed fourth- and fifth-order fluctuations. The small-scale bundling seen in Fig. 3A is taken as an indication for this pat-

Table 5 Mean of the individual point-count groups, bed thickness and the number of samples researched within the individual sequences. Total data set 120 samples

Section	No. of samples	Ooids	Oncoids	Grape-stone	Platform interior biota	Platform reef biota	Clasts	Biota non-specified	Open-sea biota	Micrite	Sparite	Bed thickness
1988-1	23	0.09	0.09	0.00	0.26	77.12	8.13	23.96	2.13	42.48	45.70	5.27
1988-7	23	0.13	0.30	0.00	0.00	53.70	4.61	22.91	8.78	101.13	8.44	6.87
1991-A	28	3.93	0.43	0.36	0.04	27.43	0.14	31.25	9.32	119.86	7.25	6.80
1991-B	29	8.28	2.55	3.03	0.07	21.72	0.52	26.45	7.62	124.28	5.48	17.26
1991-C	17	0.71	0.06	0.00	0.12	27.00	2.29	20.53	8.94	134.77	5.59	13.47

tern. The input cycles of the individual point-count groups show gradual waxing and waning trends and no asymmetrical cycles. Masetti et al. (1991) recorded the same type of pattern in his cycle analysis of the Carnian. We, however, could not find such a clear correlation between grains of pathological origin and progradation as proposed by Bosellini (1989) and Masetti et al. (1988, 1991). Progradation as registered at the toe of slope of the Dürrenstein/Picco di Vallandro contains mainly grains of physiological origin exported from an active platform; thus, there is a correlation of the type of grains with progradation.

In summary, the entire sequence records the subtle interplay of different individual sources on the platform related to the ability of certain environments to produce and export excess sediment. Accommodation space available in the different environments plays an important role in this respect. The platform productivity itself is another vital factor. The latter is influenced by many factors, e.g. eustatic sea-level changes, currents and subsidence (for an overview see Schlager 1993). The lateral growth potential of a carbonate platform is controlled by a large number of factors, e.g. platform/basin profile, bank-margin type, climate, duration, magnitude and direction of physical energy on the platform and adjacent seaways. This study showed that sediment supply and export is another important factor in this subtle process of relative forward and backward movement of the platform. It also shows that input from the edge of the platform can be sufficient enough to allow for progradation of the platform.

Conclusion

The microfacies analysis of calciturbidites deposited at the toe of slope of the Dürrenstein/Picco di Vallandro revealed that progradation and retrogradation of the carbonate platform had different input characteristics. Prograding sequences were characterized mainly by pack- to grainstones with (a) reduced input to complete absence of oncoids and ooids, (b) clasts that were more frequently encountered and (c) a high input of reef-derived grains. Retrogradation showed mud- to wackestones with (a) a reduced input of grains that originated within the reefs on the platform, (b) relatively high input of ooids, oncoids and grapestones, and (c) absence of clasts. Therefore, during both progradation and retrogradation parts of the platform were flooded and produced excess sediment that could be exported to the surrounding basins. Variations in supply of terrigenous material could also be the cause for the progradation and retrogradation pattern visible at the toe of slope. They could create onlap and could cause a relative retreat of the toe-of-slope sediments. The link between variations in composition in the slope sediments and platform development at the toe of slope as shown in this study, however, argues for variations in input of the platform causing the toe-of-slope sediments to step forwards towards the basin or to retreat. Our data indicate clearly that one does not need a distinct input from the platform interior to cause progradation.

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