rimmed platforms (depositional slope). Downslope sediment transport occurs predominantly via nonchannelized sheet flow. Carbonate slope sediments extend without interruption from the basin along gentle gradients (< 4°) up to a shallow platform margin.

- The existence of erosional slopes. Steep to vertical escarpment walls can be formed during sea-level lowstands and by tectonics. The upper part of these walls may be settled by luxuriant reef-building communities. The lower part of the cemented rock can exhibit ledges and ridges acting as a base for sediment deposition and the formation of microbially induced micrite crusts that can also be recognized in ancient slopes (Brachert and Dullo 1994).
- Incised parallel gullies, oriented perpendicular to the platform margin, and formed by erosion associated with downslope gravity flows. These gullies are a line source of sediment supply from the platform and upper slope to the lower slope.
- The angle between the platform margin and the slope controlling the facies belts parallel to the platform margin. Slope angles of modern slopes may be low (5°–15°), but are often relatively high (<40°) and may even be considerably steeper.
- Changes in dip from upper to lower slopes (steepened in mid-slope or lower slope settings).

Platform-margin to slope transitions and facies patterns of carbonate slopes: Fig. 15.17 shows stratigraphic profiles describing three generalized types of buildup and geometry in Phanerozoic platform margins. Differences in the size, position and composition of these margins are important for understanding depositional slopes because the sediments produced on the platform and at the platform edge are the main source for carbonate slopes. Types I and III correspond to rimmed carbonate platforms, type II to a homoclinal ramp. Note that Fig. 15.17 documents only the uppermost parts of slopes adjacent to the platform-margins.

The composition of slope sediments: Microfacies studies are essential for understanding the composition of slope sediments, differentiating allochthonous and autochthonous material, and recognizing sediments formed by specific depositional processes (e.g. turbidites, debrites, slope breccias). Carbonate slope sediments consist of allochthonous and autochthonous sediments and include:

- *Allochthonous shallow-marine platform material* composed of mud- and sand-sized particles (disintegrated calcareous algae, various skeletal grains, bioerosional chips, peloids, composite grains), and sand-, gravel- and boulder-sized lithoclasts derived from lithified platform or platform-margin carbonates. Submergence of the platform may result in an increased contribution of platform-margin material to slope deposits, leading to a higher input of lithoclasts.
- *Slope material:* Boulders, blocks and giant carbonate bodies deposited on the slope or at the toe-of-slope are eroded from platform margins or from higher parts of the slope. Sand- to boulder-sized carbonate lithoclasts may also have their source in eroded rocks from higher, lithified slope parts.
- Fine-grained shallow-marine material intermixed with pelagic carbonate grains forms *periplatform carbonates* that can accumulate as periplatform sands at the foot of steep platforms, as fine-grained periplatform turbidites interbedded with pelagic oozes in basins, or as soft periplatform ooze and mud deposited in deep basins. The emergence of platforms shut down the source area of platform material, and more pelagic sediment is deposited than peripelagic ooze.
- *Hemipelagic terrigenous material,* usually clay-sized particles, is transported across the shelf and deposited on slopes or in the basin. The material is intermixed with carbonate sediment, forming a mixed siliciclastic-carbonate facies or occurs in discrete clay-rich marly and argillaceous beds sandwiched between fine-grained limestone beds.
- *Autochthonous carbonate* on slopes is produced by organisms able to induce carbonate precipitation (e.g. microbes) or secrete calcareous skeletons (various invertebrates including foraminifera, sponges, corals, mollusks, serpulids). Some of these organisms contribute to the formation of extended reef structures, including mud mounds, reef mounds and coral reefs.

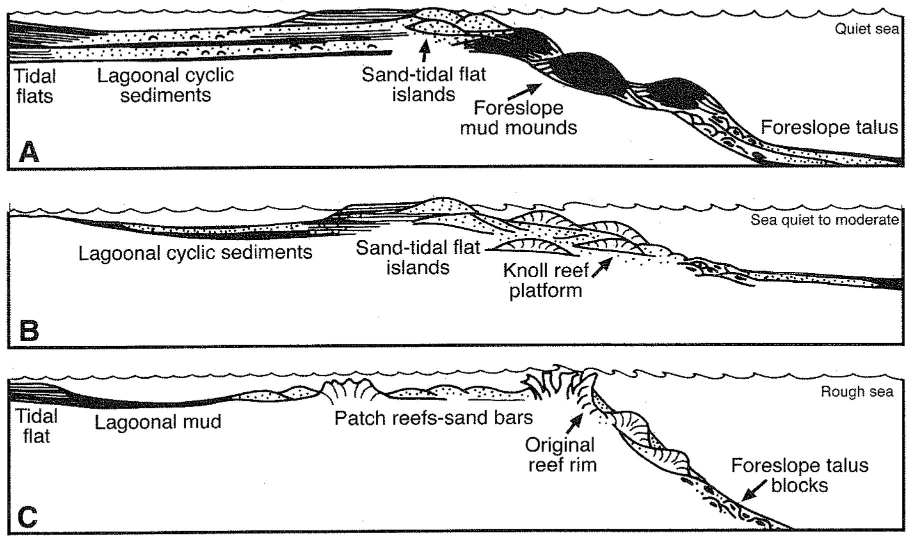

Fig. 15.17. *Basic types of platform margins* after Wilson (1974) distinguished by the stratigraphic profile, shape and position of sand bars or different kinds of reefs along the profile slope, and diagnostic facies patterns. This classification calls particular attention to the geometry of rock bodies and is a useful approach in hydrocarbon and mineral exploration. **A:** *Type I (downslope mud accumulations)* is characterized by linear belts of downslope lime mud accumulations forming foreslope mud mounds below the tidal wave base. Crestal deposits are sand bars or sand islands. **B:** *Type II ((knoll reef ramps)* includes linear ramps or non-rimmed platforms with patch reefs (knoll reefs), commonly formed on gentle slopes at the outer edges of shelf margins. Bioclastic interreef material is much greater in volume than the patches of in-situ framework. Crestal deposits are sand shoals, bars or mud flats behind the wide, gently sloping platform. **C:** *Type III (frame-built reef rims)* is a platform margin created by an organic reef rim of resistant framework built into the active wave base and forming the topographic crest of the profile. Types I and II appear to have been more common in the geological record than Type III.

15.7.2 Allochthonous Slope and Basin Deposits: Diagnostic Criteria

Depositional processes and products: Sediment is transported to and accumulated in slope and basin settings by

- *Settling of fine-grained platform-derived material from suspension* (often forming black, very fine crystalline and often laminated, rhythmically bedded limestones and shales).
- *Subaqueous rockfall and talus* (e.g. below steep escarpments). Carbonate rockfall sediments are characterized by clast- or mud-supported, poorly sorted sediments with angular clasts of different size. Rockfall produces forereef breccia, escarpment breccias, and various types of slope breccias.
- *Sediment gravity flows* (mass flows) characterized by a mixture of sediment and fluids comprise turbidites, grain and debris flow deposits, breccias, and conglomeratic deposits.
- *Submarine sliding* (movement of a rigid, internally undeformed mass along a discrete shear surface) is triggered by slope failures.
- *Downslope creeping* (slumping) is a characteristic long-term process within non- or semilithified sediment piles, caused by bedding-parallel translocation along well-defined surfaces or a diffuse shear zone. The sediment becomes simultaneously deformed and may develop distorted bedding and synsedimentary folds (e.g. slump folds).

The availability and volume of detrital material transported by gravity flows from neritic shelf environments to basins depend on an interplay between the production of biogenic material, climate, sea-level changes and tectonics. In carbonate systems the sea-level related timing of shedding from platforms and climate is the essential control (Droxler and Schlager 1985; Sarg 1988; Schlager et al. 1994). Climate can favor increased volumes of specific shelf carbonates (e.g. foramol/heterozoan carbonates during relatively cold phases) thus providing more source material for turbidites. One example is the Early Tertiary Zumaya series of the Gulf of Biscay, as shown by Gawenda et al. (1999).

15.7.2.1 Submarine Rockfalls

Rockfalls are characterized by free falling, and often large rock fragments that are transported across steep and moderate angles over short distances. The material is eroded from cliffs, escarpments or rocky shores (see Sect. 5.3.3.3).

Important criteria are:

- Depositional units characterized by distinct boundaries.
- Clasts are angular to subangular, uniform or polymict, and usually very closely packed.
- Sorting is poor to very poor. No grading.
- The size of the clasts varies between a few millimeters to tens of meters. Large clasts occur together with very small clasts.
- The fabric is usually clast-supported (e.g. at the base of oversteepened platform rims).
- The matrix consists of poorly sorted rock debris, fine-grained carbonate, or argillaceous material.

Microfacies: The clasts may exhibit different lithologies, different microfacies types and rocks of different stratigraphic age depending on the composition of the eroded rock sequences. Clasts occur together with isolated fossils (e.g. corals or rudists transported from reefs), or are mixed with exotic material brought in by rivers from the hinterland. Ancient carbonate rock fall deposits are known from near-coast and transitional environments (e.g. Thiedig 1975), rocky coasts, seamount cliffs (Seyfried 1980), and steep forereef slopes.

15.7.2.2 Breccias and Megabreccias

Sedimentary breccias are common constituents of carbonate slopes (Sect. 5.3.3).

The breccias are characterized by

- discontinuous lenses (meters to tens of meters) with sharp and undulated boundaries at the top and the bottom,
- polygenic compositions, yielding shallow-water and deep-water elements, and consisting of bioclasts and lithoclasts,
- variously shaped and usually poorly sorted clasts,
- clasts floating within a fine-grained matrix (composed partly of comminuted breccia material) or exhibiting fitted contacts,
- clasts sometimes showing a preferred orientation of longer clasts.

Megabreccias are matrix-supported breccias consisting of well-defined blocks, from meters to more than several hundred meters in size. Seismic shocks and gravity collapses of the outer parts of high-angle outer carbonate platforms may contribute to the development of huge breccia masses deposited in upper and mid-slope settings. Scalloped embayments and large-scale erosion features depicted in seismic reflection profiles record the catastrophic removal of many cubic kilometers of sedimentary units and explain the presence of major megabreccia sheets at the toes of slopes (Mullins et al. 1986; Mullins and Hine 1989; Hine et al. 1992; Stewarts et al. 1993; Sano and Tamada 1994). An excellent overview of the importance of megabreccias in the context of sequence stratigraphy was provided by Spence and Tucker (1997). Common features of megabreccias are the

- close association of breccias with various types of mass-flow deposits,
- occurrence of megablocks consisting of reworked limestone breccias together with breccias of variable size, embedded within fine-grained matrix (see Sect. 15.7.3.1 and Sect. 15.7.3.2).
- mixture of intrabasinal and extrabasinal blocks in size up to several hundreds of meters,
- disorientation of geopetal fabrics within individual blocks, indicating alternations of transport and resting phases,
- rounding of smaller and larger blocks caused by dissolution and biogenic encrustation,
- occurrence of cryptic, cavity-dwelling organisms and specific low-growing encrusters,
- joint occurrence of blocks exhibiting different diagenetic histories (e.g. blocks derived from subaerially exposed platform parts and blocks eroded in deep-water environments).

The development of breccias often starts with submarine rockfall deposits and avalanches, followed by the formation of megabreccias, and finally the deposition of turbidites.

15.7.2.3 Debris-Flow Deposits

Debris flows composed of clasts and supported and carried by a mud-water mixture lead to the deposition of sediments that have variously been called debrites, debris sheets or mass breccia flows (Hiscott and James 1985). Many so-called debrites have a granular matrix that is noncohesive. In these cases, transport by turbulence and grain interactions is more likely. Debris flows are capable of traveling over very gentle slopes and may represent a pre-phase of turbidite sedimentation.

Debrites range in thickness from a few decimeters to several tens of meters. Most debrites form sheet-like and lenticular bodies with conformable, sometimes also erosional contacts with the underlying fine-grained sediment. Upper contacts are sharp or the debrite bed passes upward into turbidites (Krause and Oldershaw 1979).

Many debrites are coarse-grained breccias or conglomerates characterized by poor sorting, lack of stratification and often random or chaotic clast fabrics. Clast packing is variable and shows matrix-support as well as clast-support. The source area of clasts can only be inferred by comparing clast microfacies with microfacies of various parts of platform and slope carbonates (Nebelsick et al. 2001). The common criteria of debrites in microfacies studies are:

- Sedimentary units are generally massive or coarse-bedded, often with significantly thick beds. Irregular top surface.
- Large clasts may project above from the bed.
- No preferred depositional fabric except for crude grading in the basal part.
- Limestone clasts are very poorly sorted and of variable size, usually of sand-grade or finer size.
- Angular or rounded clasts, or of mixtures of both types occur.

- Clasts are supported by fine-grained sediment consisting of micrite, calcisiltite of argillaceous material.
- Larger boulders or pebbles may be embedded within debris flow deposits.

A specific type of debris flow deposits are *disorganized limestone conglomerates*, consisting of shallow- and/or deep-water clasts forming extended sheets and channels.

Common criteria are:

- Sand- to boulder sized clasts; very poor sorting.
- Angular, subrounded or rounded clasts.
- Randomly distributed, often densely packed clasts.
- Monomict or polymict clasts, possibly derived from shallow-marine, slope or deep-marine sediments.
- Lime mud or argillaceous mud matrix.
- Internal structures within the beds rare or absent.
- Normal grading absent; inverse grading in the basal zone of the unit.

Examples of disorganized limestone conglomerates and breccias have been described from the Cambrian (Keith and Friedman 1977; McIlreath 1977; Cook and Taylor 1977), Devonian (Cook et al. 1972), Cretaceous (Cook and Enos 1977), Pleistocene (Crevello and Schlager 1980).

15.7.2.4 Grain-Flow Deposits

Grain flows are gravity flows in which material of different grain sizes is supported within the flow, mainly by the strength of a fluid matrix consisting of water and clay minerals.

Identification of grain flow deposits is difficult because most of the features are also produced by other transport processes. Very often grain flow deposits are associated with turbidites (e.g. Stauffer 1967; Eberli 1987).

Common criteria are:

- Thick massive beds.
- Deposits draping over irregularities and thinning up flanks of channels.
- Flat tops and flat base. Sometimes flute marks.
- Scours and injection structures at the base.
- Partial to complete clast support.
- Clasts floating in sandy or muddy matrix.
- Poor sorting.
- Grain orientation parallel to flow; faint, dish-shaped laminae.
- No parallel lamination or cross lamination.
- Normal grading absent or rare. Sometimes reverse grading near the base.

Calcareous debris flow sediments are predominantly deposited on deep-marine slopes or at the base of slopes, in contrast to turbidites that are deposited in proximal or distal positions depending on the position of the source areas. Grain flow deposits may pass rapidly into pelagic and hemipelagic sediments.

15.7.2.5 Turbidites

Turbidites are sedimentary deposits laid down by turbidity currents and intercalated in fine-grained sediments (Edwards 1993).

Turbidite successions vary greatly in sedimentary structures, bed thickness, and textural features. Variations are controlled by distance between the source and of the depositional area, point or line source, composition of the sediment available, topography of the depositional area and density of turbidity currents (low or high density suspensions).

Common criteria of turbidites are:

- Regular vertical sequence of units characterized by specific sedimentary structures (Bouma Sequence respectively Meischner Sequence).
- Graded bedding and lamination common.
- Bottom surface sharply defined, frequently with sole marks. Upper bed surface usually not well defined, showing transitions into the overlying beds.
- Biota consisting of allochthonous, redeposited fossils derived from shallow-water and slope environments. Autochthonous fossils rare, apart from trace fossils. Pelagic and deep-water benthic fossils occur in intercalated shales and may form a small part of the fossils occurring within the turbidites.

Bouma Sequence: An ideal turbidite sequence consists of a vertical succession of internal sedimentary structures. The Bouma Sequence (Bouma 1962), first studied in siliciclastic deposits, exhibits five intervals, from base to top:

- graded or massive unit (division) A,
- lower parallel laminated unit B consisting of thin laminae,
- unit C characterized by current ripple lamination with several sets of unidirectional foreset bedding and/or convolute bedding,
- upper parallel laminated unit D consisting of very thin, often obscure laminae within fine-grained sediment,
- very fine-grained unit E without primary sedimentary structures.

As a rule, complete Bouma Sequences should characterize proximal turbidites, incomplete Bouma Sequences distal turbidites (Walker 1967).

Limestone turbidites, allodapic limestones and the Meischner Sequence

Carbonate and siliciclastic turbidites: Limestone turbidites differ from siliciclastic turbidites in

- the size of the bioclastic particles; it is predominantly controlled by ecological constraints in the source area and by taphonomic criteria, and not by the range of grain transport as for siliciclastic grains;
- the abundance of lithified particles. Platform and shelf carbonates are rapidly cemented. Lithoclasts are therefore much more common than in siliciclastic turbidites;
- the variability of grains contributing to limestone turbidites; it is much higher than the rather uniform composition of siliciclastic turbidites. Transport and settling of skeletal grains is influenced by differences in size, shape, microstructure, porosity and density. Hydraulic sorting is common.
- Unlike siliciclastic turbidites, complete Bouma Sequences are rare in carbonate deposits. Some of these differences may be caused by the relatively weak thixotropy of calcareous muds as compared to clay muds.

Criteria of limestone turbidites: Carbonate turbidites occur in deep-marine and shallow-marine, but also in lacustrine settings. Sequences containing turbidites are interpreted as fan deposits, or described by apron models.

Common criteria are:

- Thick or thin allochthonous limestone beds intercalated within micritic carbonates, marls and argillaceous sediments.
- Graded calcarenites or calcisiltites; calcirudites.
- Lower bed boundary sharp, but sometimes with bottom marks (groove and flute casts, erosional marks).
- Gradual transition of top surfaces into overlying beds.
- Vertical sequence consisting of sedimentary units (zones) characterized by specific sedimentary structures (Meischner Sequence).
- Grading and lamination common.
- Cross-bedding and convolute lamination relatively rare.
- Internal size grading.
- Sizes of lithoclasts range from silt to boulders, sizes of skeletal grains between coarse sand and silt.
- Grain size decreases parallel to the decrease of bed thickness.
- Sorting in coarse parts good, in laminated parts moderate to good.
- Particles are skeletal grains, peloids and ooids as well as lithoclasts and sometimes also extraclasts.
- Lithoclasts are often concentrated at the base, bioclasts in higher parts of the turbidite bed.
- Skeletal grains include benthic organisms derived from shallow-marine and slope environments, fragments of reef organisms, and some pelagic fossils.
- Secondary silicification is common. Late diagenetic silification occurs along sedimentary structures due to the high porosity. Pore waters are enriched in silica because of the rapid burial of the sediment. Silicification is often preceded by calcite cementation (Hesse 1987).

Source areas of limestone turbidites are shallow-water environments (platforms, platform-margins, banks, reefs) and slope environments. Limestone turbidite beds can be followed over several hundred meters to several kilometers. Bed thickness ranges between < 1 cm and several meters. Amalgamation of thick beds is common.

Allodapic limestones: This term, suggested by Meischner (1964), denotes limestone beds consisting of graded carbonate debris, transported and redeposited by turbidity currents. The term 'allodapic' refers to detrital material 'which originated elsewhere'. Originally coined for limestone turbidites yielding grains derived from platform rims or reefs, the term is now used more or less as a synonym for carbonate turbidites.

- *Internal sequence:* The *Meischner Sequence* (Fig. 15.18) summarizes the criteria of an ideal allodapic bed. The composition and sequence of allodapic beds is determined by the amount of transported material, the distance from the source area, the rate of accumulation, the intensity of background sedimentation.
- *Geometry:* Each bed forms a lenticular body. The coarser basal parts reach their maximum thickness upstream. The fine-grained upper parts have their maxima further down stream.
- *Fossils:* The coarse-grained parts of allodapic limestones usually contain benthic biota, both macrofossils and microfossils. Mixing of ecologically different types may occur. Microfossils can exhibit hydraulic sorting resulting in a fractionation of foraminifera depending on size, density and settling potential (Herbig and Mamet 1994). Planktonic fossils occurring in fine-grained parts are sometimes strikingly well preserved.
- *Diagenetic overprint,* e.g. compaction, can destroy primary depositional boundaries. Care must be taken in differentiating depositional lamination and lamination caused by stylolitization. Pressure solution can destroy primary sedimentary structures on bed tops and bottoms and obliterate internal structures e.g. in turbidites. 'Bedding' can be created by diagenetic remixing of carbonates (Eder 1971).

Meischner Model and Bouma Model: Zone 1a and Zone 1b of the Meischner Sequence correspond to Division A of the Bouma Sequence. Zone 1c exhibits criteria of Division B. Zone 2a and Zone 2b correspond to Division C. Zone 3 has criteria of Division D of the Bouma Sequence. The uppermost pelitic Division E of turbiditic and hemipelagic origin is not included within the Meischner Sequence. The models are similar, but exhibit some differences. In comparison with the Bouma Sequence, Zone 1 of the Meischner sequence is characterized by ruditic rather than arenitic allochthonous grains. Reverse grading near the base of Zone 1 seems to be more common than in Division A of the Bouma Sequence. The differentiation of lower plane-parallel laminated (Division B), middle ripple or convolute laminated (Division C), and upper parallel laminated parts (Division D) of the Bouma Sequence is much less developed in Zone 2 of limestone turbidites.

Differentiation of turbidites: Turbidites are differentiated into several depositional types:

- *Proximal turbidites,* deposited relatively close to the source area are massive, relatively weakly graded, and exhibit only poorly developed tractional structures and little interbedded pelagic sediment.
- *Turbidites characterized by the Bouma Sequence,* have distinct graded bedding, oriented erosion and fill markings at the base, interbedded pelagic sediment and a characteristic succession of sedimentary structures.
- *Distal turbidites,* formed far away from the source region, are characterized by thin, fine-grained graded layers, well-developed cross-lamination and absence of massive intervals and parallel laminations.

Some of the more important characteristics for the proximality and distality of limestone turbidites are summarized in Tab. 15.2. Ideally, proximity indicators work for turbidite sequences deposited only from a single source by longitudinal sheet flows. In turbidite fans, turbidites with proximal and distal features may be juxtaposed. Meandering of turbidity currents may produce strong deviations from general proximal-distal patterns. Some of the deviations are caused by differences in the sedimentation in deep and large versus shallow and small basins, point or line sources, and in the different settling behaviors of carbonate particles (Sarnthein and Bartolini 1973).

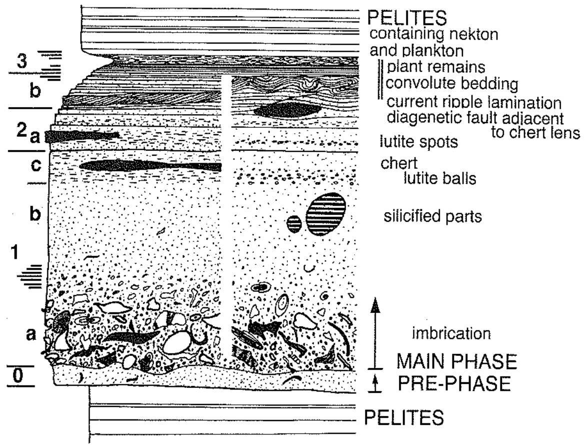

Fig. 15.18. *The Meischner Sequence describing an ideal 'allodapic' limestone turbidite.* The turbidite bed is intercalated between beds formed by the basinal background sediment (fine-grained 'pelites', i.e. marls or micrites containing nektonic and planktonic fossils). The *'pre-phase' (zone 0)* is characterized by micrites or marls with scattered small lithoclasts and rather large rock fragments. The genesis of the pre-phase is controversial. Solution and reprecipitation of carbonate may be important. The contact to the underlying pelagic zone is sharp. The upper surface of the pre-phase may be wavy and irregular. The *'main phase' (zone 1)* exhibits three parts: *Part 1a* is a distinctly graded limestone with shallow-water fossils and lithoclasts. Reverse grading and grain imbrication may occur. Sorting increases upward. *Part 1b* is a fine-grained micrite. The upper *part 1c* may be faintly laminated and includes angular limestone clasts and micrite pebbles. *Zone 2* is a micrite characterized by planar bedding planes with densely spaced laminations (2a), overlain by a unit with current ripple lamination (2b), and sometimes also with convolute bedding. *Zone 3* is represented by marls that may exhibit flaser textures. This zone merges gradually into the overlying marly or pelagic sediment. Bed thickness is about 1 m. Bed thickness is high in the near-source proximal position, and decreases in distal depositional areas. After Meischner (1964).

Fluxoturbidites: Turbidites can be underlain by beds characterized by large, very poorly sorted and inversely graded components forming breccias. These fluxoturbidites are overlain by normally graded turbidites. Fluxoturbidites contribute to a traction carpet, signifying the begin of allochthonous sedimentation in proximal depositional sites on slope or base-of-slope environments (Stanley and Unrug 1972; Sallenger 1979; Steiger 1981).

Deep-water source turbidites: Limestone turbidites with grains derived not from shallow-marine environments but rather from upper slope or deep-water buildups exhibit features known in allodapic limestones, but also show significant differences when compared with the Meischner or Bouma Model. Differences involve the sequence of internal structures and the greater varia-

Tab. 15.2. *Criteria of proximal and distal limestone turbidites.* The mean maximum grain size (decreasing in a downstream direction), the ABC-Index (percent of beds beginning with Division A plus half the percent of beds beginning with Division B), and the ratio of the thickness of Division A to the mean maximum grain size may also be used. Grading curves and proximality curves exhibiting the differences in maximum grain sizes at different vertical positions of the turbidite bed have also proved useful (Engel 1974; Steiger 1981).

	Proximal	**Distal**
Field Aspects		
Distribution of turbidite beds	Densely spaced; isolated or amalgamated; background sedimentation limited	Scattered, isolated; background sedimentation high
Ratio of turbidite and pelagic sediment	High	Low
Geometry of turbidites	Lenticular beds of varying thickness; medium- to thick-bedded	Regular, planar parallel beds; thin-bedded (thinner than a few tens of cms)
Associated sedimentary structures	Slumping structures; breccias; conglomerates	Breccias rare
Base of turbidite beds	Sharp; sometimes scours, tool marks,washouts, reworked pebbles, sometimes erosive	Sharp
Fluxoturbidite at the base of the bed	Abundant	Absent or rare
Top of turbidite beds	Gradual	Sharp and gradual
Internal Sequence		
Complete Bouma/Meischner Sequence	Relatively common	Rare
Graded part (Zone 1a)	Well-developed, thick	Decrease in thickness
Grading	Graded, poorly graded or not graded Graded zone thick	Grading common
Inverse grading	Common	Absent
Coarse-tail grading	Common	Absent
Base of basal detrital parts	Generally sharp	Sharp
Top of basal detrital parts	Often sharp	Grades into finer sediment
Lamination (Zone 1c and 2a)	Less common, often restricted to thicker beds	More common
Ripple and convolute lamination	Restricted to thicker beds Bedding (Zone 2b)	Less common to absent
Micritic upper parts of turbidite beds	Thin or absent	Well-developed
Lowermost units of turbidite beds	Zone 1a (Division A)	Zone 1b or Zone 1c
Grain size		
Average grain size	Rudite and arenite	Arenite and smaller
Significant vertical breaks in dominant grain sizes	Common	Absent
Matrix		
Matrix between grains in detrital parts of the turbidite	Sparry calcite	Micrite
Ratio of turbidite and pelagic sediment	High	Low
Microfacies		
Clasts	Lithoclasts, extraclasts, fossils, ooids, peloids	Lithoclasts, fossils, ooids, peloids
Fossils	Benthic shallow-water fossils derived from platforms and platform margins; slope-derived fossils, rare pelagic fossils	Benthic platform- and slope-derived fossils; autochthonous deep-water fossils
Microfacies of clasts	Variable to highly variable	Relatively uniform

tion in ecological types of fossils (Tucker 1969; Remane 1970; Steiger 1981). Crinoidal turbidites are characterized by the dominance of horizontal lamination, scarceness of the graded parts, the lack of the uppermost fine-grained unit, and a sharp contact with the shales above. Deep-water calciturbidites can originate from the transport of pelagic sediment, primarily deposited on the tops or flanks of a sea-floor relief, to intrabasinal depressions. A well-described example are the Late Jurassic *Saccocoma* calciturbidites from Poland (Matyszkiewicz 1996).

Practical advice for studying limestone turbidites

The investigation of allodapic limestones requires that field observations and data extracted from thin sections and fossils be well integrated. The following text

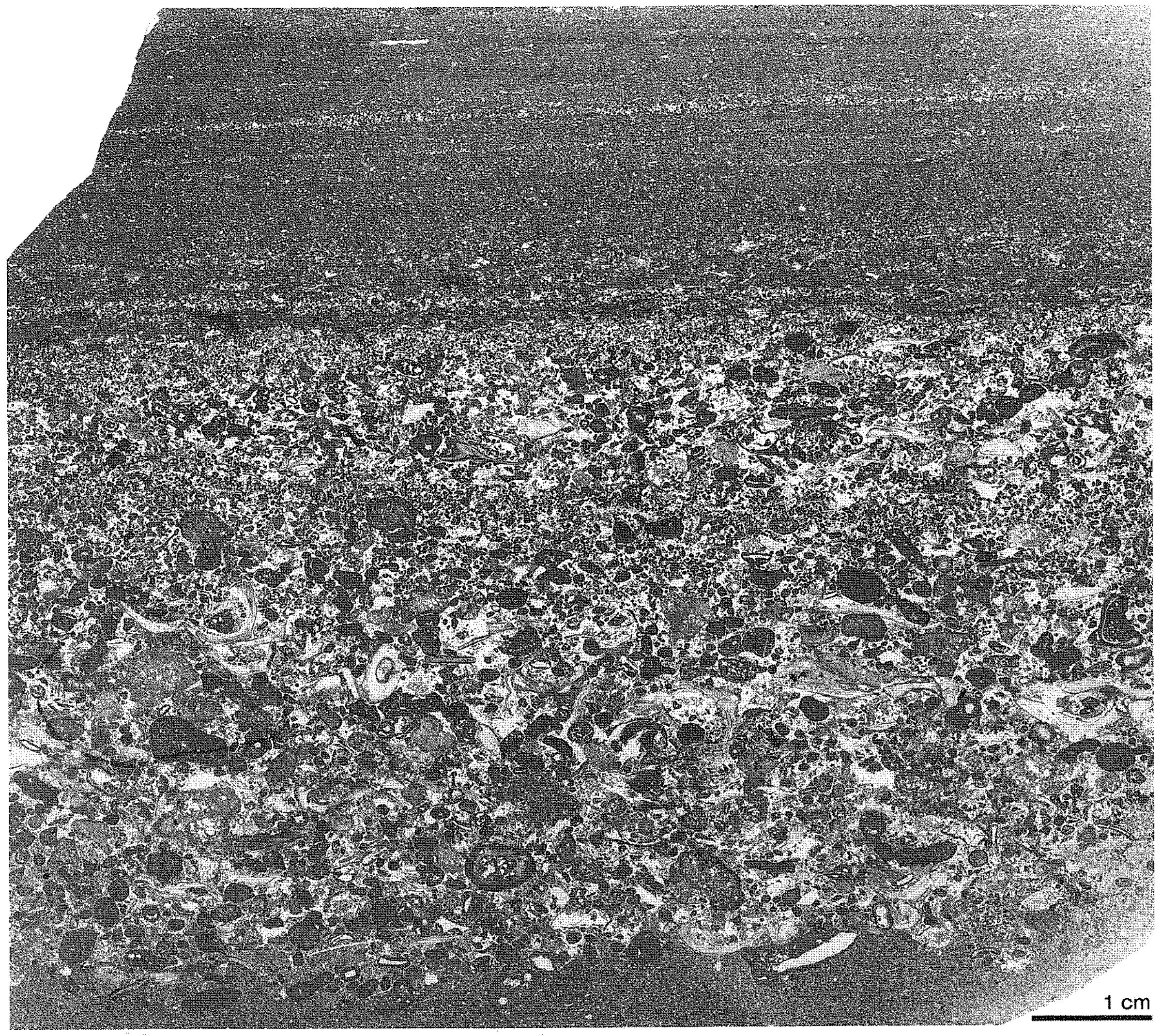

Fig. 15.19. *Turbidite or tempestite?* Turbidites and storm-induced tempestites may exhibit similar structures (see Fig. 15.20).This sample comes from limestone beds deposited in a base-of-slope position in a shallow inter-reef environment close to the margins of coral reefs (Flügel 1975).

The stratigraphic section consists of bedded micritic limestones alternating with abundant intercalations of bio- and lithoclastic beds exhibiting coarse- and fine-grained skeletal grains. The thickness of the allochthonous beds varies between a few millimeters up to 30 centimeters. Skeletal grains were derived from shallow-water environments (dasyclad algae, various porostromate algae; lituolid foraminifera).

The source of coral debris and shells of bivalves, gastropods, brachiopods and echinoderms were small patch reefs. The frequency of skeletal grains varies within the allochthonous beds. Some beds yield up to 70% porostromate calcimicrobes, some beds 40% bivalve shells and about 25% micritic intraclasts, peloids and oncoids, and other beds are predominantly composed of oncoids, peloids and intraclasts.

The sequence shown in the figure starts with an erosional surface at the base separating the underlying micrite from the bioclastic grainstone. The grainstone unit, consisting of bioclasts (predominantly calcimicrobes, foraminifera, mollusk shells) peloids and some lithoclasts, is graded. Grading is reflected by the upward decrease in grain size. The upper surface of the graded unit is sharp. The overlying sediment consists of packstone in the lower part, grading into micritic and fine-peloidal mudstone in the upper part. Lamination is indicated by thin dark laminae and slightly thicker light laminae. Skeletal grains in the lower part are disoriented. The tiny shell fragments occurring in the upper part of the sample have a parallel orientation.

The sample is a turbidite, as indicated by the erosive base of the graded unit (corresponding to the boundary between Zone 0 and Zone 1a of the Meischner Sequence), the normal grading (corresponding to the transition from Zone 1a to 1b), the differentiated lamination of the upper part (corresponding to Zone 1c and Zone 2), and the difference in the background community that indicate the low-energy basinal depositional environment. Late Jurassic (Early Tithonian): Kapfelberg near Kelheim, Bavaria, Germany.

		Turbidites	Tempestites
Sedimentary structures in beds Top	Wave ripples and ripple cross lamination	Absent	Common in proximal parts
	Current ripples and current ripple bedding	Common	Less common than in turbidites
	Convolute lamination	Common	Rare
	Hummocky cross stratification	Absent	Common
	Traction carpet with inverse grading	Common in proximal parts	Absent
Bottom	Sole marks	Uni-directional	Often bipolar, irregular scouring, gutter cast channeling
Biofacies	Benthic background community	Deep-water facies	Shallow-water facies
	Displaced fossils within event beds	Shallow- and deep-water species	Shallow-water species only
	Autochthonous post-event fauna and bioturbation	Episodic colonization by specific fauna preceding return to background conditions	Fauna similar to pre-event fauna if similar substrata are available
Stratigraphic context	Amalgamation	Less common	Very common and pronounced
	Lateral continuity of single beds	Often over long distances	Usually limited
	Thickness of sequence	Often large, commonly but not always associated with deep-water facies	Limited, associated with shallow-water facies

Fig. 15.20. *Turbidite and tempestite criteria.* High-energy events can produce similar or identical textures and sedimentary structures. The vertical sequence of turbidites as well as that of storm deposits (see Sect. 12.1.2.1) is characterized graded and laminated structures. Differentiating turbidite and tempestite beds requires consideration of various aspects of sedimentary structures, biofacies and the stratigraphic context. See Fig. 15.19 for an example.

may act as a guide for sampling and studying limestone turbidites. Box 15.3 lists papers containing methodological advice on the advantages and disadvantages of using calciturbidites as facies indicators.

How to investigate limestone turbidites?

Use criteria displaying diagnostic features on different scales. Note similarities with tempestites (Fig. 15.19, Fig. 15.20).

Sampling

Sampling of turbidite beds must consider the great variation in turbidite sequences. Densely spaced samples should be taken from the base and the top of the bed, and within the depositional units of the sequence. Equal distance sampling within the units is recommended.

Many calciturbidites are stylolitized. Take samples from individual stylobeds for recognizing significant changes in grain sizes. Additional samples must be taken from the background sediment. Try to investigate the total thickness of turbidite beds. This is easily done because many beds are only a few tens of centimeters thick.

Field aspects

- Determine the geometry, lateral extension and thickness of the turbidite beds.
- Evaluate the frequency of turbidite beds within a given section. Measure the distance between turbidite beds. Do turbidites prevail over beds formed by normal pelagic sedimentation (common if the turbidites have been formed in a position proximal to the source area) or are turbidite beds limited to only a few beds within a sequence consisting predominantly of basinal sediments (common in distal position)?
- Look for indications of pressure solution that may strongly alter appearance of bedding (see Sect. 7.5.2).

Bouma/Meischner Sequence units

- Try to recognize the Zones 1 to 3 of the Meischner Sequence or the divisions A to E of the Bouma Sequence. Which zones are missing? Have a look at the boundaries between the zones, which may be sharp, gradual or faint.
- Describe the units by means of texture considering the size of the dominant transported grains. Differentiate between textures made by silt-sized and sand-sized particles, or fine- and coarse-sized particles.

- Measure the thickness of the units and compare the thickness with the thickness of the layers representing the background sedimentation.

Microfacies

- Use vertically and horizontally oriented thin sections. Vertical sections exhibit the composition and boundaries of individual internal units. Sections parallel to bedding planes allow sediment transport to be recognized.
- Determine the type and frequency of skeletal grains, lithoclasts, extraclasts and other particles. Frequency should be determined by point counting (Sect. 6.2.1.1). Differentiate between particles that were already lithified at the time of erosion and redeposition, and particles that were not lithified.
- Note the shape and roundness of litho- and extraclasts. Distinguish lithoclasts of different texture and microfacies.
- Look for orientation patterns of particles indicating type of grain settling and current transport.

Grain size and packing

- Perform a thorough grain-size analysis. The maximum grain size of lithoclasts and bioclasts reflects the degree of transport energy. At least 50 grains should be averaged. Relate maximum grain size and grain size ranges with bed thickness and the thickness of sedimentary units within the turbidite bed. Consider differences in porosity and the density of grains that could influence settling behavior.

Calculate grain-size parameters (Sect. 6.1), particularly the mean, standard deviation and skewness (see Table 6.1). Parameter diagrams indicate the type and strength of transport energy. Sect. 6.1.2.2 gives an example using Barmstein limestone samples.

- Use packing indices (Sect. 7.5.1), e.g. the number of grain cross sections per square centimeter. A high grain number indicates the deposition of many small grains; low grain numbers indicate the predominance of coarse grains.

Biota

- Differentiate between benthic and planktonic fossils. Benthic fossils should be determined by their assignment to groups or taxonomic units. The occurrence of dasyclad green algae in calciturbidites should indicate a source area in very shallow, well-lighted, platform interior environments. Specific foraminifera can be used to distinguish source areas within different parts of reef complexes (see Sect. 14.2.2.2 and Pl. 111). Consider the assemblages of microfossils that may reflect the major source environments, e.g. platform interior, high- and low-energy reefs, or upper and lower parts of slopes (see Sect. 15.7.5).
- Consider the preservation of fossil shells. Strongly bored and worn shells may indicate a source area with reduced sedimentation and high nutrient input (e.g. lagoons).
- Look for burrowing at the top of the turbidite or within individual sedimentary units. The latter indicate an arrested deposition of turbidite material.

15.7.2.6 Sliding and Slumping

A slide is the movement of a rigid, internally undeformed mass. A slump originates from mass sliding and the creeping of semi-consolidated sediment. The detachment surface of slides is called an intraformational truncation surface. The study of detached submarine slide masses aids in recognizing slope failures. Slide masses can be preserved either downslope or within the adjacent basins. The reasons for sliding are varied and interrelated (Vortisch 1964; Bernoulli and Jenkyns 1970; Schwarz 1975; Nardin 1979; Mills 1983; Eberli 1988; Coniglio and Dix 1992). Sediment overloading and seismic activity as well as excessive pore pressures are the most obvious reasons. Evidence of slide masses

Box 15.3. Selected references on ancient carbonate turbidites. Many of these papers include descriptions not only of turbidites but also of other gravity flow deposits.

Tertiary: Betzler et al. 2000; Engel 1974; Gawenda et al. 1999; Reijmer et al. 1992; Skaberne 1989; Westphal 1998.

Cretaceous: Carrasco and Baldomero 1977; Cazzola and Soudt 1993; Colacicchi and Baldanza 1986; Everts 1991, 1994; Ferry 1979; Harloff 1989; Hesse and Butt 1976; Mutti et al. 1978; Sagri 1979.

Jurassic: Bosellini 1967; Carozzi 1955; Eberli 1987, 1988; Ebli 1997; H.W. Flügel and Fenninger 1966; H.W. Flügel and Pölsler 1965; Garrison and Fischer 1969; Marcinowski 1970; Matyszkiewicz 1996; Misik and Sykora 1982; Mutti et al. 1978; Scheibner and Reijmer 1999; Schlager 1980; Steiger 1981.

Triassic: Matzner 1986; Reijmer and Everaars 1991; Reijmer et al. 1994; Watts 1988.

Permian: Brown and Loucks 1993, Flügel et al. 1991.

Carboniferous: Davies 1977; Franke et al. 1975; Hemleben and Reuther 1980; Herbig and Bender 1992; Herbig and Mamet 1994; Izart et al. 1997; Meischner 1962, 1964; Yurewicz 1977

Devonian: Babek and Kalvoda 2001; Carozzi and Banaree 1984; Cook et al. 1972; Eder 1971; Junge 1992; Lütke 1976; Szulczewski 1968; Tucker 1969, 1974.

Ordovician: Pohler and James 1989.

Cambrian: Cook and Taylor 1977; Demicco 1985; Reinhardt 1977.

includes hummocky surfaces created by creep lobes, initial dissection of strata, and compressional folds. Large-scale gravity slides are associated with extended megatruncation surfaces forming megabreccia sheets. Examples have been described from the Cambrian and Cambro-Ordovician (James 1981; Stewart et al. 1993), Silurian (Surlyk and Ineson 1992), Late Paleozoic (Franseen et al. 1989) and Triassic (Bosellini 1984, 1989; Heck and Speed 1987).

Sliding and slumping of carbonate sediments occurs in deep-water as well as in shallow-water environments (e.g. tidal zones).

Common features that can be studied on an outcrop scale are

- deformed beds occurring as distinct intercalation between undeformed beds;
- welded upper contact in the deformed bed, characterized by a depositional fit between the irregularities of the upper surface and the base of the overlying bed;
- the deformed bed may be overlain by limestone consisting of graded or non-graded calcarenites or calcirudites;
- deformation of beds as shown by folding patterns;
- thickening or thinning of folded strata;
- folded anticlines may be eroded at the upper surface of the deformed bed;
- preferred orientation of folding axes unrelated to the tectonic strike;
- deformed beds displaying a broad spectrum of structures comprising simple sliding of intact sets of layers, convolution and distortion of beds, rolled-up structures, and intensive shearing of dislocated beds.

Most limestones with pronounced slumping structures are micrites.

Usually no differences can be detected between the microfacies of slumping beds and the underlying beds. Some differences have been found in the insoluble residues of the limestones. Larger amounts of clay-sized particles in the non-carbonate constituents could have been responsible for a retardation of early diagenetic cementation and for changes in the thixotropic behavior of the sediment (Backhaus and Flügel 1971; Kenter and Schlager 1989).

15.7.3 Microfacies of Slope Carbonates: Case Studies

The following case studies describe microfacies types of limestones formed in various parts of high-angle and low-angle slopes and in base-of-slope settings.

15.7.3.1 Permian of Sicily: Megablocks and Base-of-Slope Carbonates

The case study reveals the complex history of allochthonous sedimentation (Fig. 15.21).

The Late Permian of western Sicily is famous for its abundance of well-preserved fossils. The fossils are concentrated in large- and small-scale allochthonous carbonates represented by limestone breccias and calcarenites forming megablocks and megabreccias intercalated within basinal sediments. The breccias result from multi-phase debris flows and turbiditic sedimentation. Microfacies criteria and paleontological data provide evidence of long- and short-term erosion of Middle- to Late Permian platform-margin and upper-slope reefs and platform carbonates. Subsequent to recurrent erosion, lithified carbonate material was transported downslope by gravity flow processes and finally deposited as fillings in depressions and channels incised in basinal sediments adjacent to the base-of-slope.

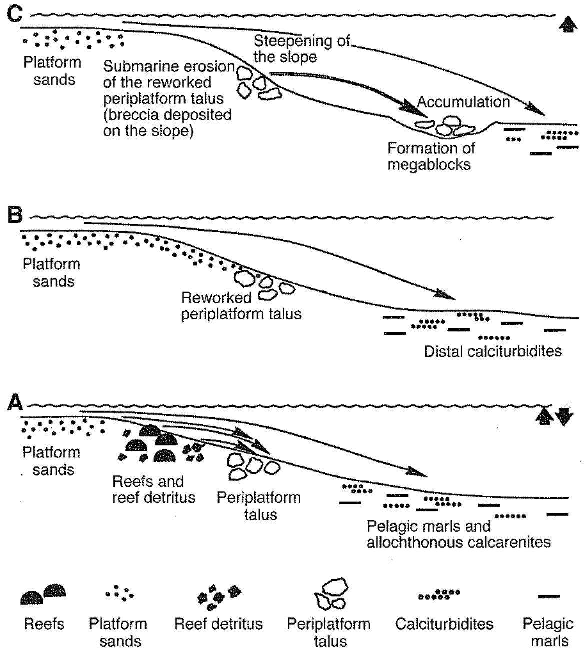

Fig. 15.21. *Facies model of Permian allochthonous slope carbonates.* Factors that might have controlled the formation of the Permian Pietra di Salomone megablock in western Sicily (modified from Flügel et al. 1991).
Phase **A**: Middle Permian shallow-marine platform with a reef zone and a periplatform talus zone. Platform- and reef-derived material is deposited in periplatform position as debris flows and in parts of the pelagic basin as fine-grained calciturbidites. Phase **B**: Disappearance of the reef zone, possibly caused by sea-level fluctuations, and reworking of the periplatform talus, associated with input of platform sands to the basin. Phase **C**: Steepening of the slope and redeposition of slope breccias within depressions of the marly basin resulting in the formation of the multi-phase megabreccia now recorded by the Pietra di Salomone megablock embedded in Late Permian radiolarian-bearing argillaceous sediments. Phases A and B took place during the Wordian, phase C sometime in the Capitanian or later. This is a time range of approximately 10 ma.

The largest of the megablocks is the Pietra di Salomone block about 40 km south of Palermo. It is about 200 m long, up to 100 m wide and 30 m high. Textural types represented in the breccias (Fig. 15.22A) are, in decreasing order, lithoclastic and lithobioclastic rudstones, boundstones with sponges, *Tubiphytes* and biogenic crusts (e.g. *Archaeolithoporella*), bioclastic floatstones and grainstones. The latter vary in predominant grain size and composition. Skeletal grains are derived from platforms and deposited in thin distal calciturbidite beds (Fig. 15.22B).

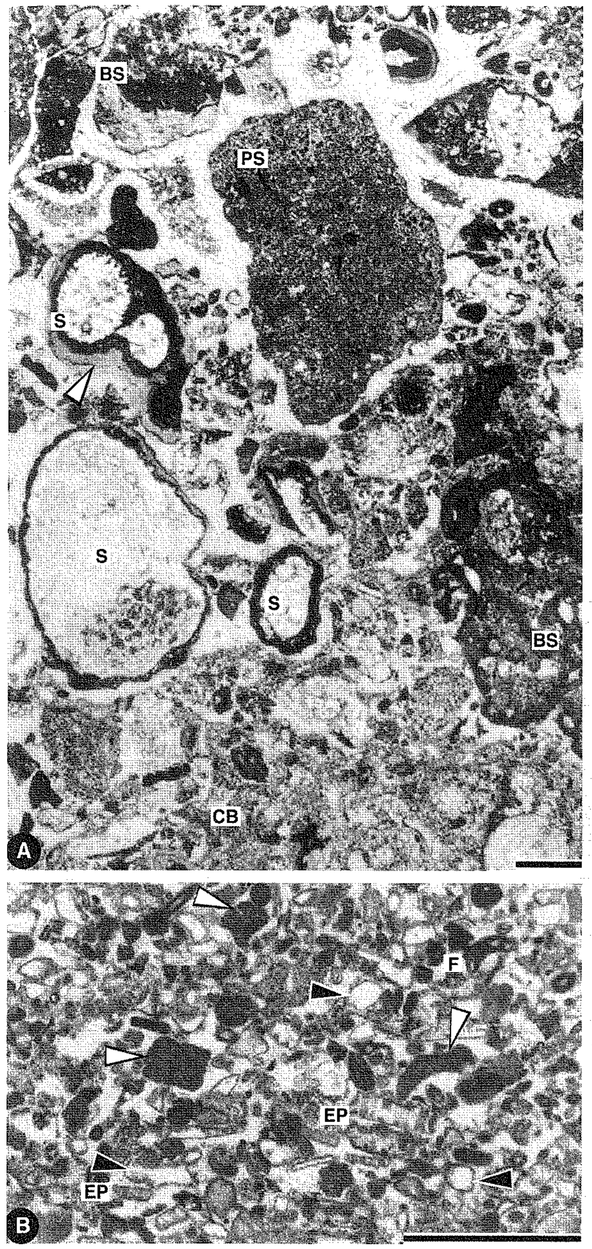

Fig. 15.22. *Permian megabreccia and calciturbidites.*
A: The constituent of a megabreccia deposited at the base of a slope (see Fig. 15.21 for the complex history of the megabreccia). The poorly sorted, disorganized breccia consists of lithoclasts exhibiting different microfacies types and transported fossils. Most of the clasts are derived from platform-margin reefs, but some clasts record the erosion of slope material. Lithoclasts are packstones (PS) and boundstones (BS). The dark packstone clasts correspond to fine-grained sediment formed in an upper slope position. Boundstone clasts consist of *Tubiphytes*, sponges and organic crusts indicating reef facies. Smaller lithoclasts and fossils bound together by early lithification form a composite breccia (CB). Isolated fossils are represented by sclerosponges (S) associated with biogenic crusts. The arrow points to cement layers overgrowing *Archaeolithoporella* crusts.
B: Bioclastic fine-grained grainstone consisting of dasyclad algae (EP: *Epimastopora*), fragments of organic crusts (white arrows) and shell fragments preserved due to thin micrite envelopes (black arrows). Minor constituents are benthic foraminifera (F). Note weak imbrication and parallel orientation of grains indicating some current transport. Distal calciturbidite. Both samples from the Late Permian of Pietra di Salomone near Palazzo Adriano, western Sicily, Italy. After Flügel et al. (1991). Scale is 2 mm for A and B..

15.7.3.2 Triassic of the Southern Alps: Allochthonous Slope Sediments

Middle Triassic (Ladinian) and early Late Triassic (Carnian) sequences in the Dolomites are excellent examples of the export of platform and platform-margin carbonates to slope and basinal environments. The flanks show well-developed clinostratifications, with angles of 30° - 40°. These steep angles contrast significantly with the horizontal bedding of the platform interior sediments. The allochthonous material was transported by various processes, including collapse of platform margins, sliding, debris and grain flows, turbidity flows, and rockfalls. Progradation generated large-scale inclined beds (clinoforms) with depositional slope angles up to 40°. Allochthonous carbonates occur as isolated blocks (Fig. 15.23), extended megabreccias (Fig. 14.17), calciturbidites (Pl. 137) and debris flows (Pl. 115/2). Foreslope and slope facies types have been described by Brandner et al. (1991), Harris (1994) and Russo et al. (1998). Common sediment types are fine- to coarse-grained limestone breccias and rudstones, calcarenites (skeletal grainstone, Erik Flügel

Microfacies of Carbonate Rocks

Analysis, Interpretation and Application

With 330 Figures and 151 Plates, some in color

Springer

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Preface

The objective of this book is to provide a synthesis of the methods used in microfacies studies of carbonate rocks and to show how the application of microfacies studies has contributed to new developments in carbonate geology. In contrast with other textbooks on carbonate sedimentology this book focuses on those compositional and textural constituents of carbonates that reflect the depositional and diagenetic history and determine the practical usefulness of carbonate rocks.

The chapters are written in such a way, that each one can be used as text in upper level undergraduate and graduate courses. The topics of the book also apply to research workers and exploration geologists, looking for current information on developments in the use of microfacies analysis.

Since microfacies studies are based on thin sections, instructive plates showing thin-section photographs accompanied by thorough and detailed explanations form a central part of this book. All plates in the book contain a short summary of the topic. An –> sign leads the reader to the figures on the plate. The description of the microphotographs are printed in a smaller type. Care has been taken to add arrows and/or letters (usually the initials of the subject) so that the maximum information can be extracted from the figures.

Rather than being a revised version of 'Microfacies Analysis of Limestones' (Flügel 1982) 'Microfacies of Carbonate Rocks' is a new book, based on a new concept and offering practical advice on the description and interpretation ofmicrofacies data as well as the application of these data to basin analysis. Microfacies analysis has the advantages over traditional sedimentological approaches of being interdisciplinary, and integrating sedimentological, paleontological and geochemical aspects.

'Microfacies of Carbonate Rocks':

- analyses both the depositional and the diagenetic history of carbonate rocks,
- describes carbonate sedimentation in various marine and non-marine environments, and considers both tropical warm-water carbonates and non-tropical cool-water carbonates,
- presents diagnostic features and highlights the significance of microfacies criteria,
- stresses the biological controls of carbonate sedimentation and provides an overview on the most common fossils found in thin sections of limestones,
- discusses the relationships between diagenetic processes, porosity and dolomitization,
- demonstrates the importance of microfacies for establishing and evaluating sequence stratigraphic frameworks and depositional models,
- underlines the potential of microfacies in differentiating paleoclimate changes and tracing platform-basin relationships, and
- demonstrates the value of microfacies analysis in evaluating reservoir rocks and limestone resources, as well as its usefulness in archaeological provenance studies.

Structure of the Book

Microfacies of Carbonate Rocks starts with and introductory chaper (Chap.1) and an overview of modern carbonate deposition (Chap. 2) followed by 17 chapters that have been grouped into 3 major parts.

Microfacies Analysis (Chap. 3 to Chap. 10) summarizes the methods used in microfacies studies followed by discussions on descriptive modes and the implications of qualitative and quantitative thin-section criteria.

Microfacies Interpretation (Chap. 11 to Chap. 16) demonstrates the significance of microfacies studies in evaluating paleoenvironment and depositional systems and, finally,

Practical Use of Microfacies (Chap. 17 to Chap. 19) demonstrates the importance of applied microfacies studies in geological exploration for hydrocarbons and ores, provides examples of the relationships between carbonate rock resources and their facies and physical properties, and also illustrates the value of microfacies studies to archaeologists.

Important references are listed at the end of chapters or sections under the heading 'Basics'. The code