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REPORT

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Holocene coral reef rubble and its binding agents

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Abstract A literature review regarding reef rubble (defined as mechanically or chemically abraded parts of framebuilders or reef rock larger than sand fraction) and its binding agents is presented. Rubble is produced by natural and man-made events such as storms, wave agitation, earthquakes, bioerosion, ship groundings, and dynamite fisheries. The regeneration of reefs after rubble-forming processes requires rigid rubble binding, which is always preceded by preliminary stabilization. Preliminary stabilization can be achieved by a decline in hydrodynamic energy, interlocking of components, seagrass, and overgrowth by sponges or algae. Rigid binding is primarily achieved by diagenetic cementation. The literature indicates that binding by coralline algae or other organisms (corals, worms, bryozoans) is only of subordinate importance. Highest rates of rigid rubble binding are known from fore-reef areas with low sloping angles above fair-weather wave base; rigid rubble binding is particularly rare in deeper fore-reef environments and not described from the reef crest. Rigid binding by diagenetic cementation is generally known from inter- and supratidal near-shore ramparts as well as back-reef, reef-flat, and shallow fore-reef rubble accumulations, while coralline algae rigidly bind rubble only in very shallow fore-reef environments. Rubble binding does not appear to be easily achieved and fewer reports of bound rubble were found than of loose rubble.

Keywords Coral reef rubble · Binder guild · Diagenesis · Cementation · Coralline algae · Geology

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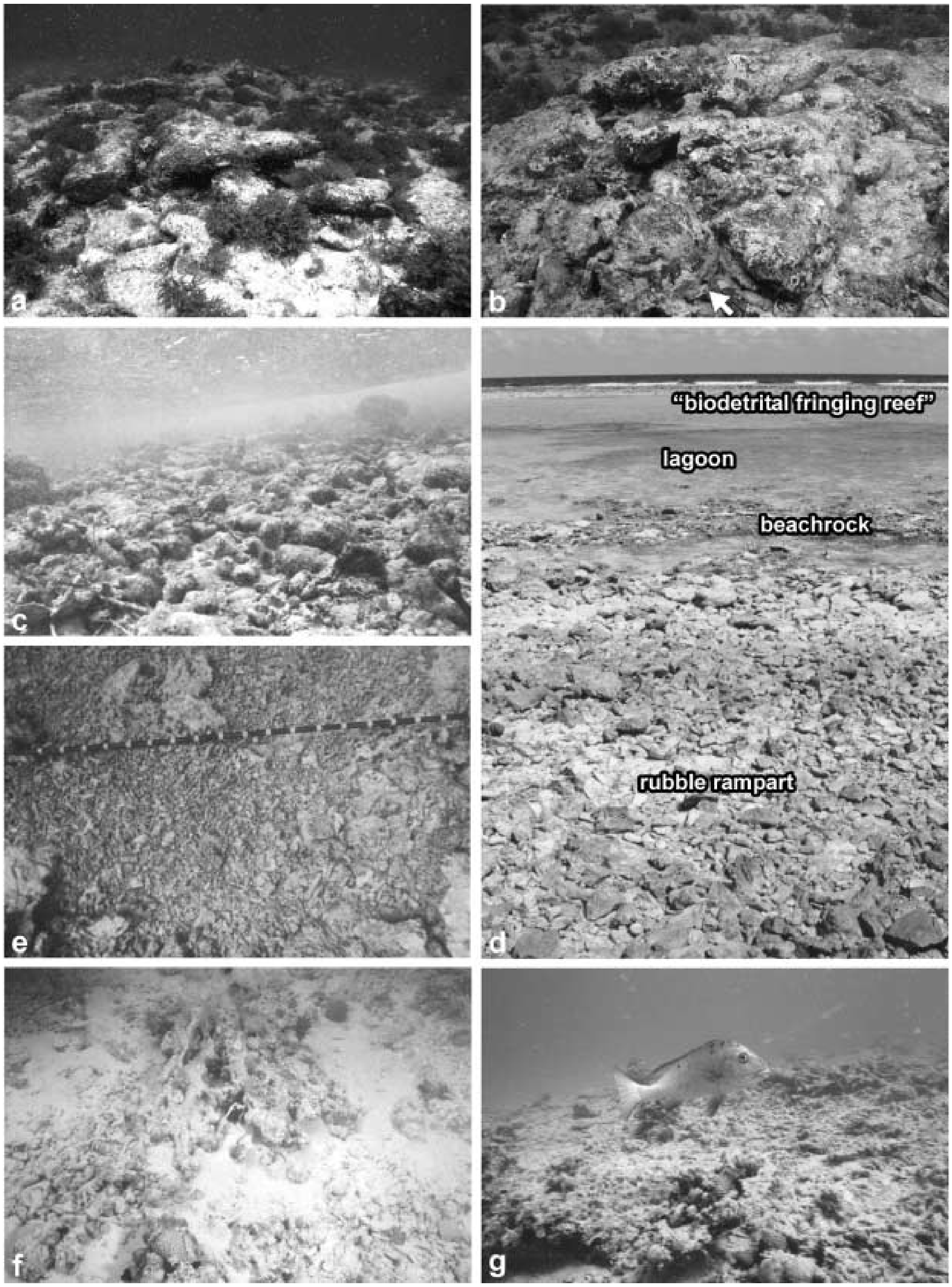
Introduction

The high diversity in coral reefs is generally seen as a reflection of disturbances and continuous cycles of destruction and renewal (reviewed in Rogers 1993). Such disturbances may occur as hurricanes and tsunamis, plagues of predators, and human impacts such as ship groundings or dynamite fishery (e.g. Scoffin 1992, 1993; Blanchon et al. 1997; Riegl and Luke 1998). Severe impacts and permanent low-level disturbance not only alter the structure of the biotic reefal assemblages, but also have the potential to create rubble, i.e. transforming parts of (or even the entire) reef framework into loose pieces.

Depending on the nature and intensity of disturbance, substantial amounts of reef rubble can be created (Fig. 1). In extreme cases, ridges of several meters height and several kilometers length can be formed. Rubble can cover extensive areas of live reefs and thus form a substratum unsuitable for regeneration, since most sessile benthos needs a stable substratum for successful attachment.

While the formation and deposition of rubble, especially during storm events, has attracted several studies (e.g., Scoffin 1993; Bourrouilh-Le Jan 1998; Hughes 1999), only a few studies deal with the stabilization of rubble (e.g., Wulff 1984; Blanchon et al. 1997). The primary coral reef framework is bound by agents of the binder guild (Fagerstrom 1987, 1991), which include predominantly laterally growing organisms that unite the various components of the reef framework and the intervening baffled/trapped sediment, as well as early diagenetic cementation. Although this definition includes the binding of coral reef rubble, knowledge of this process is relatively poor.

Since the binding of rubble is of critical importance for several geological and biological processes, this paper presents a review of present knowledge of Holocene coral reef rubble and its binding agents. We discuss the dynamics of coral reef disturbances, rubble formation, and reef regeneration; we outline geological aspects of



coral reef rubble and the processes and occurrences of preliminary stabilization and rigid binding. Finally, we provide a synthesis of (1) the necessity of rubble binding, (2) agents of preliminary stabilization, (3) agents of rigid binding, (4) duration of binding, (5) places where rubble binding can be expected, and (6) geological implications of rubble occurrences and their interpretations. Rubble is herein defined as fragments derived by mechanical or chemical factors from either coral skeletons or reef rock, which is in size fraction larger than sand and can include boulders. Rubble is usually dead, but in the case of coral fragments, rubble may be covered by live tissues. The definition of what exactly constitutes a reef remains elusive and in the present paper ''reef derived'' can signify provenance from both biostromal or biohermal framestone systems (Riegl and Piller 2000) or any ''...biologically influenced buildup of carbonate sediment which affected deposition in adjacent areas...and stood topographically higher than surrounding sediments during deposition...'' (Longman 1981, p. 10).

Dynamics of reef disturbances and rubble formation

The high diversity of coral reefs is generally attributed to the system's relative instability and several disturbance

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Fig. 1. Coral reef rubble accumulations in different reef environments. **a** Unbound rubble, consisting largely of *Acropora palmata* fragments in the size range of tens of centimeters, broken during Hurricanes Hugo and Marilyn, south of Buck Island, USVI, 4 m depth, fore-reef environment (May 2001). **b** Rubble binding. Note the smooth coralline algae draping (*arrows*) over several pieces of rubble (largely *A. palmata* fragments); it is not known whether binding was first effectuated by diagenetic cementation or the red algae. South of Buck Island, USVI, 4 m depth. This photo was taken within 50 m of **a**, at same water depth (also May 2001). **c** The "fringing reef" of Grand Cayman (central Caribbean) is actually a biodetrital (sensu Gerhard 1991) structure consisting largely of coral rubble tossed onto the shelf by hurricanes (see Blanchon et al. 1997); photo of March 2000. The rubble consists primarily of coral fragments stemming from the mid-shelf reef and *A. palmata* zone. **d** On Little Cayman (central Caribbean), rubble accumulations form beach ramparts and a similar biodetrital "fringing reef" as in Grand Cayman; photo of Jan 2000. **e** Fine rubble, created by dynamiting (fish-bombing) of a windward *Acropora* assemblage in the Egyptian Red Sea near Gazirat Wadi Gimal (see Riegl and Luke 1998). This fine rubble at high angle of repose is unstable and remobilized during storms. *Scale bar* is 2 m long, marked at 10-cm intervals; photo of June 1996. **f** Rubble formation by breakdown of *Acropora clathrata* killed by dredging near Ras Ghantoot, Abu Dhabi, Arabian Gulf. Repetitive SST anomalies lead to natural large-scale kills of *Acropora* in the Arabian Gulf and important rubble generation by subsequent skeleton breakdown such as illustrated here; photo of Sept 1999. **g** Dense rubble beds, when stabilized or washed together by currents, can be bound by cementation and form hardground (near Jebel Ali, Dubai, Arabian Gulf). The eroded ledge in the *left foreground* suggests rigid binding having already started. The fish is a Painted Sweetlip (*Diagramma pictum*); photo of Jan 1996. (All photos by the authors)

hypotheses (e.g., intermediate disturbance, temporarily varying mosaic, compensatory mortality) provided the theoretical framework (among many others: Bak and Luckhurst 1980; Grigg 1983; Sousa 1984; Mah and Stearn 1986; Dollar and Tribble 1993; Rogers 1993). At the core of these hypotheses is the postulate that reef coral communities undergo cycles of destruction and renewal. Diversity is maintained by changing species compositions in response to disturbances, whereby reef regeneration after disturbances depends on various physical and biological factors (Woodley et al. 1981; Mah and Stearn 1986; Brown 1987; Hughes 1989; Lapointe 1989; Done et al. 1991; Scoffin 1994; McCook 1999).

In reefal systems, the diversity-maintaining disturbance usually also translates to at least partial destruction of coral skeletons and/or reef rock, and thus the generation of varying quantities of rubble. According to Woodley et al. (1981), the amount of damage and rubble formed depends not only on the causing factors, but also on the shapes, sizes, and mechanical properties of the affected organisms and/or structures. The fate of the destroyed framework components is not only influenced by subsequent erosion and redeposition. It is also subject to taphonomic processes which include constructional processes such as framework growth, sedimentation, and burial as well as marine diagenetic cementation, on the one hand, and destructional processes such as mechanical erosion, biological erosion, and post-depositional diagenesis on the other (Scoffin 1992; Pandolfi and Greenstein 1997).

Heavy storms are frequent events in terms of a geological time scale and tend to produce large amounts of onshore and/or offshore rubble from broken reef framework (e.g., Baines and McLean 1976; Scoffin 1993; Sorokin 1995; Treml et al. 1997; Spiller et al. 1998; Rogers 2000; Rubin et al. 2000). According to Hubbard et al. (1994), reef destroying "Hugo-type" hurricanes recur every 100 years in the Virgin Islands, and Maragos et al. (1973) suggested that cyclonic storms, which created enormous rubble piles at Funafuti Atoll, may recur as frequently as every 30 years. Thirty-eight hurricanes have passed within 80 km of Grand Cayman over the last 264 years (Blanchon and Jones 1997), indicating a recurrence period of roughly 7 years. The most damaging storms pass within 10 km of the island, with an average 20-year recurrence interval. However, the recurrence time gap ranges from 1 to 55 years (Blanchon et al. 1997), which is the disturbance-free window for coral growth in shallow water. Harmelin-Vivien and Laboute (1986) estimated that the deeper limit of mechanical erosion by direct influence of hurricane-induced waves is about 20 m. While studies of Goreau and Goreau (1973) suggested that deposition of catastrophically produced clasts is confined to the shallowest parts of the reef, Woodley et al. (1981), Harmelin-Vivien and Laboute (1986), and Hughes (1999) showed that the influence and deposition of storm-generated rubble depend on the physiogeographic setting of the reef and the shelf system (local reef profile, water depth, slope angle, and shelf width). A steep slope causes a seaward transport of rubble and the formation of a talus; rubble can be transported to water depths of around 500 m (Harmelin-Vivien and Laboute 1986). Gentle slopes and/or shallow waters associated with a wide reef flat result in onshore transport and formation of back-reef ramparts and reef-flat storm ridges (Woodley et al. 1981; Scoffin 1993; Hughes 1999), which can form enormous piles of coral reef rubble up to 19 km long and 4 m high (Maragos et al. 1973; Baines and McLean 1976); such ridges formed at Funafuti Atoll remained unstable for years and continuously moved onshore and longshore. In a few cases, rubble piles can also be formed in the shallower fore-reef area (Macintyre and Glynn 1976; Blanchon et al. 1997). Davies (1983) described extensive accumulations of coral rubble along exposed reef slopes of One Tree Reef, which act as a source for rubble remobilized onto the reef flat during storms. Davies called such accumulations "temporary sediment holding zones." Blanchon et al. (1997) found at Grand Cayman that the rubble formed by storm impacts is washed either seaward, aiding in the formation of pinnacles on the shelf-edge-reef, or landward, there forming a biodetrital fringing reef. Yamano et al. (2001) showed that storm-generated rubble was the main agent for framework development in the back-reef area (infilling of the moat). The quantity of rubble produced was found to be controlled by cyclone frequency and sea level – tectonic uplift raised more reef area into the area subject to strongest abrasion by cyclones and thus increased rubble production and back-reef infilling.

Even in the absence of strong storms, *permanent wave agitation* can produce remarkable amounts of reef rubble transported downslope, as reported from Lizard Island (Hughes 1999). Much of this rubble may have been loosened during former storms and by bioerosion and was only remobilized by wave action.

Plagues of predators may periodically destroy corals (e.g., Endean 1973), but also permanent *bioerosion* (e.g., Perry 1998, 2000) causes fragmentation of the reef framework. The bioeroded material can be removed by permanent wave agitation and storms. Hallock (1988) discusses the control of nutrients on the destruction of primary frameworks. Her study suggests that under conditions of increased nutrient availability, bioerosion would increase and frameworks would gradually be replaced by more detrital fabrics. It is most likely that a combination of different factors triggers rubble formation: frameworks affected by bioerosion are more easily fragmented by storm events, and fragments loosened by storms are subsequently transported by permanent wave agitation.

Sea-level changes during the Holocene led to the formation of widespread rubble deposits. They are formed by erosion of subaerially exposed reefs (Schlager 1998), are associated with storm deposits, and allow dating of the sea-level changes (Shepard et al. 1967; Curray et al. 1970; Buddemeier et al. 1975; Macintyre and Glynn 1976). Attention is drawn again to the findings of Yamano et al. (2001, see above), who were able to correlate sea-level changes with changes in rubble production due to more framework being moved within the destructive reach of wave action during cyclones.

Also *human impacts*, such as trampling on reef flats, dynamite fishery, or ship impacts (Fig. 1e–g), can produce considerable amounts of reef rubble (Cook et al. 1994; Gittings et al. 1994; Guozhong et al. 1994; Riegl and Luke 1998). According to Macintyre and Glynn (1976), the accumulation of large reef boulders on the reef slope does not necessarily indicate internal or external catastrophic events; it can also be caused by a *climax stage* of the reef causing reduced accumulation space. Finally, *earthquakes* and *volcanic activity* can cause mass disturbance of sediment and breakage of the framework (Scoffin 1992).

Rubble and reef regeneration

The formation of rubble translates to abrasion of framework builders, their mechanical destruction, and transport into unfavorable downslope positions as well as destruction and burial of other sessile organisms by the transported rubble (e.g., Woodley et al. 1981; Lirman and Fong 1997). However, rubble formation can also have positive effects. The fragmentation of living corals may increase the density of coral cover due to asexual propagation and regeneration of the fragments (Woodley et al. 1981; Highsmith 1982; Fong and Lirman 1996). Reworking of rubble towards the slope may promote reef growth by passive dispersal of live coral fragments to soft substrate, which allows larval settlement on the fragments (Woodley et al. 1981; Dollar and Tribble 1993; Cortes et al. 1994; Hughes 1999). In this respect, the transport of live rubble into downslope environments may enable progradation of reefs towards the sea (e.g., Shinn 1972; Goreau and Land 1974; Highsmith 1980; Blanchon and Jones 1997).

Further positive aspects of rubble occurrences in general are discussed by Kobluk and Lysenko (1987) and Meesters et al. (1991). Cryptic habitats below rubble allow the existence of sub-rubble communities, which can act as a recruitment pool after impacts. They also provide a shallow-water refuge for deep-water open reef organisms, a shelter against predation, and a refuge from competition for space.

Although the time and grade of reef recovery after disturbances generally depend on the type and frequency of disturbance, the recovery process depends on several subsequent elements such as environmental tolerance of the main reef builder, larval recruitment, intra- and interspecific competition, disease, predation, parasitism, and bioerosion as well as rubble stabilization, eutrophication, fresh-water runoff, and sedimentation possibly associated with the disturbance event (e.g., Andres and Rodenhouse 1993; Byron 1994; Scoffin 1994; Steneck 1994; Lirman and Fong 1997). Moreover, recovery in terms of both time scale and resultant diversity patterns is often site-specific and can vary within a single reef (Dollar and Tribble 1993; Rogers 1993).

The duration of reef regeneration after impacts is highly variable. Some reefs off Florida may start to recover from hurricane damage and ship impacts within 5 years (Shinn 1976; Gittings et al. 1994). However, because corals are relatively slow-growing and long-lived, the successional process of most reefs takes place on a scale of decades. Dollar and Tribble (1993) suggest that pre-storm conditions could be reached within 40 to 70 years in Hawaii; Blanchon et al. (1997) estimate a recovery time of 50 years for Grand Cayman; Cook et al. (1994), 100–150 years for Bermuda; and Aronson et al. (1994), 100 years for the Virgin Islands.

Geological aspects: the reef interior

Fossil reef frameworks have most likely been affected by the same disturbances as their modern counterparts. Reef rubble means not only a change from stable to unstable substratum but also a change in lithology, such as a change from framestone to rudstone (after Dunham 1962; Embry and Klovan 1972; Insalaco 1998), and is therefore detectable in the fossil record. With stable sea level, reefs growing on the edge of shelf margins often prograde over their own talus formed largely by reef rubble (for summary see Wood 1999). The progradation of a true in-situ, organism-built framework over its talus requires preliminary stabilization of the talus debris.

However, not only the talus is largely made up of rubble. Blanchon et al. (1997), in a case study of the fringing reef of Grand Cayman, suggest that a permanent cycle of coral destruction and regeneration will produce a reef core that is built up by successive layers of coral rubble over thousands of years (Fig. 1c, d), and thus impressively point to the "framework problem". A study on the sedimentary budget of a shelf-edge reef system at St. Croix (Hubbard et al. 1990) found that accretion rates generally increased with water depth over the past 2–3 ka, which was a result of active slumping along the steepening reef face. Detrital material played a major role in the reef fabric due to secondary processes that constantly reworked the substrate. This resulted in a reef interior that was "more a garbage pile than an in-place assemblage of corals cemented together into a rigid framework" (Hubbard et al. 1990). Discussing several fossil examples, the authors came to the conclusion that the same patterns of production and degradation that can be recognized in modern reefs were important in fossil reefs. Cabioch et al. (1995) qualified the relation between framework and debris for fringing reefs of New Caledonia. They suggested that in areas exhibiting steeply dipping substrates and subject to high wave energy, fringing reefs are framework-dominated; in contrast, in sites typified by gently sloping, pre-existing surfaces and medium wave energy, the reefs are mainly made up of detritus. The authors assumed that this pattern is of general occurrence.

Not all sediment produced is retained within the reef. Even though the reef interior can be dominated by debris, coral reefs are usually sediment exporters, meaning that they produce far more sediment than they are able to retain internally (Fagerstrom 1987).

The problems of recognizing fossil reefs and differentiating them from mere rubble accumulations are discussed by Hubbard et al. (1990), who state that "geological reefs are the end-products of not only constructive processes that produce calcium carbonate, but also of destructive processes...that reduce solid substrate to sediment, and of physical processes that rework the reef fabric and transport sediment"; and "specifically, the lack of recognizable, in-place framework in many ancient deposits is contrary to our perception of the interiors of most modern reefs; true 'reefs' (e.g., boundstones, framestones) must necessarily contain a significant and recognizable element of in-place and interlocking material." The authors came to the conclusion that modern models overemphasize the importance of in-situ frameworks for the definition of a reef. Braithwaite et al. (2000) took the amount of storm-generated reef rubble specifically into account in their reef-accretion model. According to their model, the frequency of disturbance by strong storms and thus the amount of produced rubble is directly responsible for a reef's growth-fabric, reefs in high-disturbance areas being made up largely of rubble. Insalaco (1998) reviewed the framework concepts and also found that they fail to include non-intergrown or non-bound growth fabrics.

Preliminary stabilization

Preliminary stabilization implies that rubble remains stable at least during average wave conditions. Unless rigidly bound, such rubble accumulations represent "temporary sediment holding zones" (Davies 1983) acting as a source for rubble dispersal onto other reef areas. There, a rigid binding of rubble requires preliminary stabilization (e.g., Scoffin and McLean 1978). According to Wulff (1984), preliminary stabilization is most important in shallow water and where bioturbation keeps unbound rubble in motion. Very large blocks and rubble not influenced by water movement and bioturbation may become rigidly lithified without preliminary stabilization agents. The main agents are summarized in Table 1.

Decline of hydrodynamic energy

According to Scoffin and McLean (1978), a preliminary stabilization of storm-induced reef rubble on reef flats may be caused by a decline in the frequency and intensity of erosion and washover as the rubble sheets migrate across the reef flat and the distance from the reef front increases. Preliminary stabilization can also be achieved through development of another rampart in front of the older one, thus restricting wave agitation of older deposits.

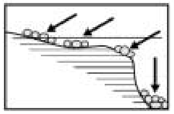
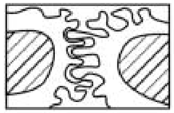
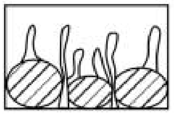
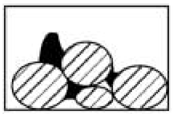
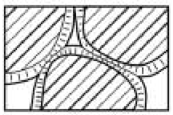
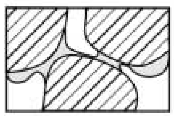
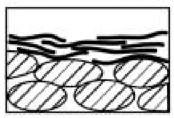
Algae and seagrass

Coralline algae are able to preliminarily stabilize rubble by forming rhodoliths (i.e., free-living nodular aggregates of coralline algae; Adey and Macintyre 1973; Bosence 1983). When rhodoliths encrust reef rubble particles, they increase the size and weight of the component, whereby the growth direction is most frequently lateral (Piller and Rasser 1996). In this way, especially when adjacent rhodoliths interlock, they are more stable than not-encrusted particles.

Rubble and rubble-nucleated rhodoliths washed to the leeward reef area are known from discharge channels or seagrass beds (Bosellini and Ginsburg 1971; Piller and Rasser 1996). Rubble and rhodoliths are preliminarily stabilized by the seagrass; however, due to seasonal growth cycles of seagrass, the likelihood of permanent stabilization is slim. Usually, rhodoliths remain unstable. Back-reef rhodoliths from Puerto Rico showed rubble nuclei formed by hurricanes and accretion rates of at least 30 mm within 19 years. Two percent of the rubble was overturned daily and thus formed an unstable substrate unsuitable for reef recovery (Ballantine et al. 2000).

Algae, especially filamentous algal turfs, rapidly colonize bare substrata on coral reefs. Filamentous algae in the Caribbean are estimated to produce 700 g C m^{-2} $year^{-1}$ and macroalgae 1,170 g C m^{-2} $year^{-1}$ (Wood 1999). Preliminary stabilization by fleshy

Table 1. Main agents of preliminary coral reef rubble stabilization and rigid binding and related features

	MAIN STABILISATION/ BINDING AGENT	RESULTING STRUCTURE		IMPORTANCE FOR REEF REGENERATION	ENVIRONMENT OF STABIL./BINDING	DURATION OF STABIL./BINDING	FOSSIL PRESERV. POTENTIAL	SELECTED LITERATURE
PRELIMINARY STABILIZATION	**decline of and/or protection from hydrodynamic energy**		reef talus; back reef ramparts; reef flat storm ridges; temporary holding zones	prerequisite for the establishment of further agents	all	rapid	none, except for talus after progradation	Scoffin & McLean (1978) Davies (1983)
	interlocking of rhodolith branches		lateral interlocking of laterally growing branches	none, because of shallow water depth	reef flat	not reported; potentially within months	potentially high	Scoffin et al. (1985) Piller & Rasser (1996)
	uncalcified algae seagrass, and microbial mats		temporary inter- and overgrowing	none	backreef; other environments not reported	not reported; potentially within weeks	none	Wulff (1984) Piller & Rasser (1996)
	sponges		cryptic sponges bind the rubble interior; erect sponges bind superficially	high; act as precursors for rigid binding	above 5 m; reefal environment not reported	at least one month	none	Scoffin & Hendry (1984) Wulff (1984)
RIGID BINDING	**marine phreatic diagenetic cementation**		isopachous cement rims and peloids	high; expected to be the main rigid rubble binding agent	all shallow subtidal environments with high water flux, mainly < 5m	not reported	high	Macintyre & Glynn (1976) Montaggioni & Pirazzoli (1984) Lighty (1985) Scoffin (1993) Macintyre (1997) Bourrouilh-Le Jan (1998)
	marine vadose diagenetic cementation		gravitative and meniscus cements	none	back reef ramparts exceeding sea-level; intertidal beaches; supratidal deposits affected by spray	not reported	high	
	crustose coralline algae		superficial, lateral overgrowth; cruststones and bindstones; algal ridges	high, unless dominance of coralline algae prevents settlement of coral larvae	shallow fore-reef; shallow back reef (subtidal)	at least seven months	high	Wulff (1984) Cabioch et al. (1995) Blanchon et al. (1997) Marshall et al. (1998)

macroalgae was described from a shallow reef in Panama (Wulff 1984). Stoloniferous macroalgae (*Dictyota*, *Caulerpa*, *Halimeda*) stabilized reef rubble very rapidly and securely. This binding was, however, only temporary because the algae deteriorated rapidly during the dry season.

Interlocking

The process of interlocking by live corals can provide a substrate sufficiently stable for reef growth without further binding agents (e.g., Aronson and Precht 1997). According to Kornicker and Boyd (1962), this type of interlocking could be termed a "non-rigid frame." This process of stabilization has, however, not been described for rubble.

Interlocking rhodoliths were described from reefal environments of Muri Lagoon, Cook Islands (Scoffin et al. 1985), and the northern Red Sea (Reef Shahad Model: Piller and Rasser 1996). In the Red Sea, *Lithophyllum kotschyanum* encrusts dead parts of living scleractinian corals or reef rock substratum. Reef substratum, encrusted scleractinians, and algal branches are broken by bioerosion and/or wave agitation during storms. The multidirectional growth of coralline algae encrusting the fragments can give rise to the formation of rhodoliths on the reef flat. Both encrusted fragments and rhodoliths can be washed into reef flat depressions. Rhodoliths that are stabilized in depressions continue to grow laterally and the branches of adjacent rhodoliths interlock to form a "non-rigid" coralline algal framework.

Sponges

Although most extant species do not possess a rigid skeleton, sponges are able to form reef-like structures (e.g., Wiedenmayer 1980). Wulff (1984) and Scoffin and Hendry (1984) described rubble binding by sponges from Panama. A few days after rubble production, sponges had begun to settle and stabilized rubble piles within a month. Wulff (1984) referred to binding by sponges as temporary binding, rigid binding being performed by subsequent encrustations by coralline algae. Cryptic sponges were found to "glue together" the rubble in the interior of rubble piles down to 2 m below the rubble surface, while erect sponges bound adjacent rubble pieces through superficial overgrowth. Subsequent rigid binding by coralline algae and settlement of a coral framework was restricted to rubble piles preliminarily stabilized by sponges (Wulff 1984). These results were reported from a shallow-water reef (down to 5 m water depth) without further notes on the position within the reef, but the author suggested that also the deep talus and the fore-reef escarpments of other Caribbean reefs could be bound by sponges. This suggestion is supported by Goreau and Hartman (1963), who suggested that sponges are capable of binding rubble of the reef talus, thus providing stable substratum for settlement of corals.

Rigid binding

Requirements for rigid binding are preliminary stabilization and physical as well as biological factors favoring the occurrence of binding agents. Binding agents causing rigid binding are diagenetic cementation and organisms that are able to grow laterally. Biotic binding agents include crustose coralline algae, corals, bryozoans, bivalves, gastropods, serpulid worms, foraminifera, brachiopods, and sponges (Table 1; Fagerstrom 1987; Scoffin 1992).

Lateral growth requires free space, which is a rare commodity in reefs. As summarized by Meesters et al. (1991), the theory of "competitive networks" of Jackson and Buss (1975) indicates that this lateral expansion is usually only possible by winning a competitive overgrowth battle. Disturbance creates new space for colonization (Rogers 1993), thus supporting the occurrence of biotic binding agents.

Diagenetic cementation

Process

Rapid diagenetic cementation in modern reefs is a common process (Scoffin 1992) and was reviewed in detail by Macintyre and Marshall (1988). Waves and currents pump seawater through the framework and sediment, causing submarine cementation by precipitating magnesium calcite (including pelleted micrite) and aragonite crystals. In high-energy platform margins, cementation is most pervasive close to the framework surfaces, while in sheltered areas, lithification takes place some centimeters below the surface (Macintyre 1985; Scoffin 1992). Additionally, interstitial sediment triggers cementation of the primary reef framework (Macintyre 1985; Cabioch et al. 1998). Submarine diagenetic cementation is generally a near-surface phenomenon most prevalent in substrates formed under conditions of high wave agitation and/or slow accumulation, although it varies according to the hydrology of the reef interior. There also seems to be a correlation between oxic pore waters (and therefore high energy and higher water flux rates) and lithification (Macintyre and Glynn 1976; Macintyre 1985; Buddemeier and Oberdorfer 1986; Macintyre and Marshall 1988; Tribble et al. 1990, 1992). Warming of cool, upwelled water can reinforce this process (Whittle et al. 1993), and Bourrouilh-Le Jan (1998) showed that a high availability of $CaCO_3$ due to solution of carbonate reef rubble causes higher rates of diagenetic cementation. Lithification of rubble requires stabilization of rubble for sufficient time and a high degree of interstitial fine sediment for retention of saturated waters at grain contacts (Scoffin and McLean 1978).

Diagenetic cementation is frequently triggered by the metabolism of reef organisms, including microbial activity, and organic compounds in solution (Buddemeier and Oberdorfer 1986; Purser and Schroeder 1986; Macintyre and Marshall 1988). For example, extraskeletal cementation triggered by coralline algae is known from large cavities of tropical reefs (Alexandersson 1977; Bosence 1985); conditions leading to the formation of these cements are availability of suitable pores continually flushed by seawater supersaturated with $CaCO_3$ and a high pH.

"Lithified crusts" were described by Marshall (1983) and Macintyre and Marshall (1988). They represent "...cemented deposits of Mg calcite pelmicrite that form coatings, usually of the order of 0.1 to 0.5 cm thick, on corals and associated encrusting organisms...or within cavities between the framework..." (Marshall 1983). They can show laminations which are considered a result of the degree of packing of the essentially peloidal infill. Additionally, Mg micrite can lead to micritization of reef rocks (Land and Moore 1980; Macintyre and Marshall 1988). As discussed by Macintyre (1997), these lithified micrite crusts resemble coralline algae and the author suggests that many crusts assigned to coralline algae may in reality be such micrite rims.

Diagenetic cementation of rubble beds, particularly on flat or only slightly inclined surfaces but also in other reef environments, may lead to the formation of "pavement limestones" sensu Macintyre and Marshall (1988). Extensive episodes of boring, sediment fill, and lithification would then replace much of the original rubble frame with the potential of turning it into a dense "marble-like" limestone (Macintyre and Marshall 1988).

Occurrences

Montaggioni and Pirazzoli (1984) described different cement generations from a 6-ka-old reef flat rampart in French Polynesia that were formed by storm events. The lower sequence showed submarine diagenetic cementation formed in pore spaces saturated with normal saline interstitial waters (marine phreatic zone). The upper sequence was characterized by microstalactitic aragonitic cements. These geopetal textures indicated lithification in the marine vadose zone and a supratidal environment. Such lithifications in supratidal environments require a high quantity of "spray" or "rising" water by capillary forces within the interparticle pores followed by evaporation (Curray et al. 1970; Montaggioni and Pirazzoli 1984; Bourrouilh-Le Jan 1998). Scoffin (1993) suggested that diagenetically cemented storm ridges are most likely to be found in areas where extreme events occur infrequently, and that the overall abundance of 3- to 4-ka-old ridges is due to their stability after a slight sea-level fall.

Hydrodynamically exposed rubble pavements at Lee Stocking Island are heavily cemented and form the substratum for patch reefs. The rubble consists of fragmented corals and is cemented largely by high-magnesium cryptocrystalline cement. Diagenetic cementation is triggered by warming of cool, upwelling water (Whittle et al. 1993).

Subfossil rubble from an algal ridge was described from Holandes Cays, Panama (Macintyre 1997), which was formed by rapid deposition of coral rubble as storm deposits. Although coralline algae encrust this rubble pile and give the appearance of an algal ridge, the main binding agent is diagenetic cementation.

Macintyre and Glynn (1976) found that extensive submarine cementation at Galeta Point is almost restricted to a shallow fore-reef pavement at a water depth of < 5 m. Although this rubble contains remarkable amounts of coralline algae, they suggest that also here the binding agent is diagenetic cementation (see also Macintyre 1997). The only occurrence of reef rubble lithification below 30 m was described by Lighty (1985) from the Florida Shelf. Coralline algal crusts occur, but they are not reported to stabilize the sediment. Coarse reef rubble is well lithified by extensive submarine diagenetic cementation and occurs intermittently as discontinuous layers (10–15 cm thick) that extend several meters in length down the talus slope.

Microbialites

Microbialites are lithified micritic crusts defined as "organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation" (Burne and Moore 1987). They can occur in a variety of fresh-water and marine environments (for review see Riding 2000). Due to their potentially high calcification rates and their ability to form laterally persistent mats, they represent possible binding agents in reefs and their metabolism supports submarine diagenetic cementation (Fagerstrom 1987; Montaggioni and Camion 1993; Reitner 1993; Zankl 1993; Camoin et al. 1999).

Although microbialites may have the potential to be important reef binders, binding of rubble has not yet, to our knowledge, been reported. For example, Camoin et al. (1999) describe thick crusts on coral rubble, but they do not report whether they bind the rubble piles. Microbialites seem to be more typical for binding and trapping fine-grained sediment than coarse reef rubble.

Coralline algae

Process

Encrusting coralline algae are well-known representatives of the binder guild in Holocene reefs (e.g., Kornicker and Boyd 1962; Marshall and Davies 1982; Montaggioni et al. 1997). Due to calcified cell walls, heavy fixation to the substrate, as well as intra- and extraskeletal cementation, coralline algae are able to withstand high wave energy (e.g., Bosence 1985). Coralline crusts are therefore well known in exposed areas (e.g., Kornicker and Boyd 1962; Marshall and Davies 1982; Adey 1986; Littler and Littler 1997; Testa 1997), where they have growth rates ranging from 0.03 to 22 mm/year, depending on environmental conditions (for review see Matsuda 1989). Although massive coralline algal crusts in coral reefs are well documented, it is unclear whether the algae truly bind the primary reef framework (e.g., Cabioch et al. 1999).

Several studies emphasize the role of coralline algae as binders (Howe 1912; Tracey et al. 1948; Womersley and Bailey 1969; Littler and Dotty 1975; Tucker and Wright 1990; Blanchon et al. 1997; Littler and Littler 1997; Perry 1999). However, according to Adey (1986) there is little real evidence of coralline algae as important binding agents in coral reefs – suggesting that they simply coat the basal coral structures. Also Macintyre (1997) came to the conclusion that coralline algae are generally not important in reefs and that the main binding agent is diagenetic cementation.

Stabilization of rubble by coralline algae may or may not be important for regeneration of coral reefs. Done et al. (1991) pointed out that encrustations of destroyed reef substrates by coralline algae also can provide negative feedback for recovery, since larval recruitment of corals may be inhibited as a result of space preemption by the algae. However, Wulff (1984) showed that coral growth on rubble piles bound by coralline algae is indeed possible.

Coralline algae by themselves can form algal ridges and algal cup reefs. Algal ridges "represent a late successional stage of coral reef development forming a constructional cap over corals as the reef approaches sea level" (Steneck et al. 1997), but they are frequently storm-rubble ridges capped by coralline algae in the Indo-Pacific, the Bahamas, and the Caribbean (Adey and Burke 1976; Adey 1978; Bosence 1984; Steneck et al. 1997). Algal cup reefs, which are also called boilers or breakers, are intertidal cup-shaped algal bioherms, mostly arising from Pleistocene rocks (Ginsburg and Schroeder 1973), and are known from Bermuda and the Caribbean (Ginsburg and Schroeder 1973; Dean and Eggleston 1975). Other algal buildups are reported by Kikuchi and Leao (1997), Testa (1997), and Gherardi and Bosence (1999).

Occurrences

Stabilization of impact-related rubble by coralline algae is described from a fringing reef at Grand Cayman (Blanchon et al. 1997). Coralline algal crusts overgrowing and binding hurricane-produced coral rubble on the shallow fore reef result in different horizons of reef rubble, each bound by a layer of encrusting coralline algae. Coralline crusts at the surface may even withstand further hurricanes and give rise to reef regeneration within 50 years. It was not reported whether the rubble is additionally bound by diagenetic cementation. The importance of coralline algae as binding agents of storm-generated *Acropora cervicornis* rubble was also reported by Perry (1999) from Jamaica.

Rigid rubble binding by coralline algae was described by Wulff (1984) in a long-term study from Panama. In shallow-water reef environments coralline algae had begun to encrust rubble piles by 7 weeks, and by 7 months the rubble was rigidly bound with a thick coralline algal crust. Rigid binding was preceded by preliminary stabilization by sponges (Wulff 1984). Cabioch et al. (1995) described several-meters-thick Holocene successions from coral rubble to coral frameworks from New Caledonia, whereby a part of the coral rubble was bound by thick coralline algal crusts. These crusts were, however, absent on much of the rubble. The authors suggested that the crusts are restricted to high wave energy conditions.

Binding of bioclastic detritus by coralline algal crusts combined with a particular absence of diagenetic cementation was described from a subtropical reef of southern Queensland, Australia (Marshall et al. 1998). This binding was described from a Quaternary occurrence of unknown age, and the paleoenvironmental position during deposition was not mentioned. Sorokin (1995) mentions geniculate (flexible branching) coralline algae growing on pieces of coral rubble and binding them to form solid rock. Unfortunately, the author gave no further information or citations.

Coralline algae versus diagenetic cementation

There are some descriptions of rigid binding by both coralline algae and diagenetic cementation that do not differentiate between the processes causing the binding. Gischler and Lomando (1999) reported a rubble pavement from Belize bound by both crustose coralline algae and cementation on the windward reef rim, which is several tens of meters wide and characterized by an almost continuous surface-breaking reef. However, they did not discuss the main binding agent. Buddemeier et al. (1975) describe 15-cm-thick coralline algal crusts on coral rubble. The rubble, however, was several thousand years older than the crusts. Therefore the rubble could have been already lithified before encrustation took place. Marshall and Davies (1982) describe bound gravel accumulations composed of branching corals and molluscs on the leeward rim of One Tree Reef (Great Barrier Reef). Coralline algae were associated with encrusting corals, homotrematid foraminifera, vermitid gastropods, and bryozoans. The deposit was interpreted as a shallow and very high-energy facies, affected by a high degree of cementation represented by "lithified crusts." The authors pointed out that diagenetic cementation was highest when extensive coralline algal encrustations were present, but Macintyre (1997) suggested that the rubble described by Marshall and Davies (1982) was bound by diagenetic cementation and not by coralline algae.

Other biota

Although the habit of encrusting corals suggests that they are potentially able to bind reef rubble, reports are scarce. Marshall and Davies (1982) described rigid binding of reef rubble by encrusting corals on the leeward rim of One Tree Reef (Great Barrier Reef) affecting gravel accumulations composed of branching corals and molluscs in a shallow and very high-energy environment.

Serpulid worms are capable of forming heavily calcified worm tubes which are attached to hard substratum. Although they are part of the binder guild, they have not yet been reported to bind reef rubble. However, Chisholm and Kelley (2001) described a formerly unknown type of binding by worms from a marine aquarium. They showed that vagile eunicid worms are able to move centimeter-sized coral heads together and bind them with a ''glue-like substance'' within one night (Chisholm and Kelley 2001). In this way they create patches of stable habitat on fine-grained soft bottoms, which provide them with food and shelter and thus potentially provide a stable substrate for reef growth. However, it is not clear whether this process represents preliminary stabilization or rigid binding, and in our opinion the interpretation that this type of binding initiates reef growth is highly speculative.

Also, reports on rigid rubble binding by bryozoans are rare. Wulff (1984) showed that encrusting bryozoans in Panama bind reef rubble from within, a process, however, restricted to rubble piles that had been preliminarily stabilized by sponges.

Absence of rigid binding

Binding does not occur in all environments that appear suitable for binding. Studies from Hawaii (Dollar and Tribble 1993) revealed that rubble aggregates on the reef slope may extend the shallow platform seaward, but remain unconsolidated and subject to continual addition and movement by high wave activity. The framework did not regenerate during the observation period, because binding of rubble was absent. The authors suggested that this was caused by continuous, episodic destruction of rudimentary frameworks, and transport into the deep rubble slope.

Early submarine diagenetic cementation does not occur in all environments with highly active water circulation. For example, Hubbard et al. (1990) reported that cements are conspicuously absent in St. Croix, and Macintyre and Glynn (1976) found that diagenetic cementation at the reef of Galeta Point, Panama, is almost absent in the deeper fore-reef talus as well as in protected reef-flat rubble and back-reef sediments.

Although the talus is most frequently neither rigidly lithified nor bound by organisms, it has a greater likelihood of being preserved in the fossil record, because shallower reef portions are more affected by sea-level changes and erosion than the reef talus (Schlager 1998; Hughes 1999). The scarcity of lithification of deep fore-reef rubble may correspond to the fact that diagenetic cementation is most abundant in shallow-water areas.

Macintyre et al. (1977) described a 33.5-m-thick Holocene reef succession from the Alacran Reef complex (Mexico) that contained about 5.5-ka-old coral rubble with only partly lithification. Also coralline algae were unimportant as binding agents (Macintyre 1997). Therefore, Macintyre et al. (1977) suggested that recovery of the coral framework above the weakly stabilized rubble occurred in a water depth of 15 m, under conditions of reduced water agitation.

Synthesis

Reef disturbances causing rubble formation are frequent natural events. Most important events are strong storms, sea-level changes, earthquakes, as well as human impacts such as ship impacts and dynamite fishery. In a next step, permanent wave agitation, for example, can remove the rubble. However, the downslope accumulation of rubble or large boulders can also be caused by reduced accumulation space due to a climax stage of the reef.

Places of rubble formation and deposition

Among the events causing reef destruction, the fate of reef rubble formed by hurricanes is best studied. The deeper limit of mechanical erosion by storm waves is about 20 m, but the downslope transport of rubble can cause damage at much greater depths. Deposition of reef rubble formed by hurricanes is reported from depths to 500 m. The overall damage pattern after hurricanes depends on the local reef profile, water depth, slope angle, and shelf width. A steep slope causes downslope transport and formation of a reef talus. Gentle slopes and/or shallow waters in combination with a wide reef flat result in onshore transport and formation of bio-detrital reefs (Fig. 1d), back-reef ramparts, and reef-flat storm ridges (Fig. 2).

Consequences of rubble formation

Apparently negative aspects of reef rubble formation to reef building are (1) mechanical destruction of the main framework builder; (2) their transport into unfavorable downslope and inter-/supratidal positions; (3) abrasion, destruction, and burial of other sessile organisms by the transported rubble; and (4) very strong impacts can cause ''phase shifts'' away from dominance of one group of benthos (e.g., corals) to another (e.g., macroalgae).

However, there are various positive aspects of rubble formation: (1) passive dispersal of coral fragments to allow asexual propagation; (2) dispersal of these fragments into peripheral, soft sediment habitats allows

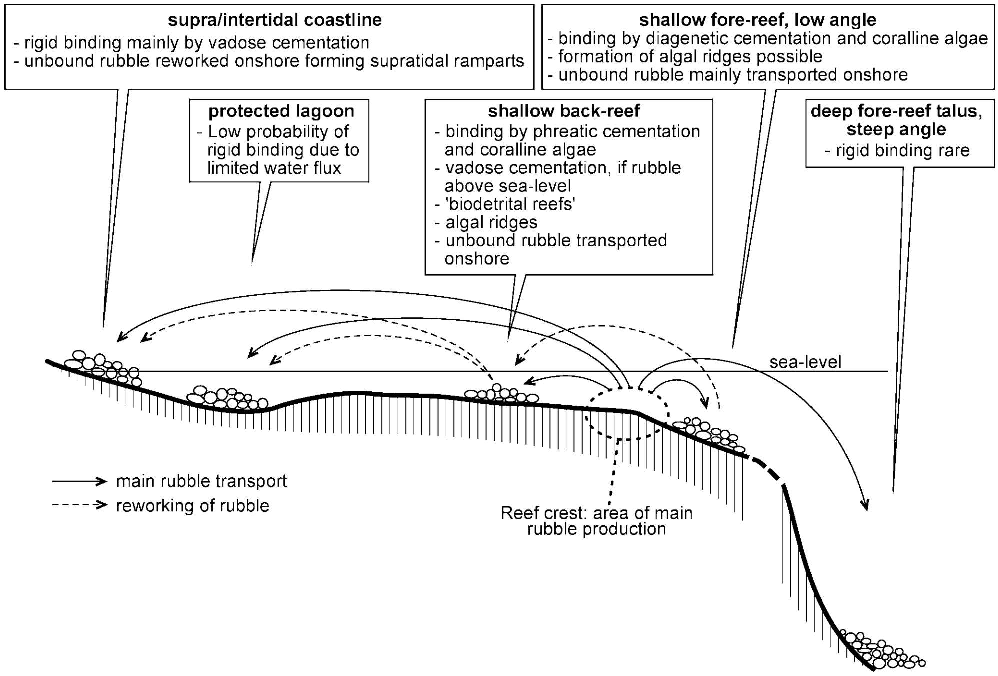


Fig. 2. A generalized model of rubble deposition, reworking, and binding along a hypothetical reef profile (not to scale). *Dotted line* in the fore-reef area indicates that the presented combination of different reef environments is artificial to allow summarization of rubble-related features: steep fore-reef slopes are characterized by both onshore and downslope (talus) transport, whereby downslope transport prevails; shallow-reef profiles are dominated by onshore transport, although the rubble can accumulate in very low-angle fore-reef areas

asexual propagation even in habitats that are otherwise unsuitable for coral settlement and growth; (3) in the case of dead rubble transported onto finer sediments, generation of secondary hard substrate for subsequent settlement of coral larvae within a fine-grained, soft-bottom surrounding; (4) formation of a talus that enables offshore progradation of reefs; and (5) filling of the cavities between the primary framework builders favors cementation of framework.

Necessity of rubble binding and binding agents

Rubble stabilization is important for the following reasons: (1) non-stabilized rubble accumulations represent “temporary holding zones”; the rubble can be reworked (Fig. 2) during normal wave agitation and subsequent storms, leading to destruction and burial of the framework builders; (2) stabilization in the active reef area is required in order to allow settlement of framework builders; otherwise, the organisms growing on the rubble are destroyed by reworking and abrasion; and (3) progradation of the reef requires rigid binding for the same reason. However, a few studies have shown that rigid rubble stabilization is not always necessary. If water depth and/or protection from wave agitation are sufficient, coral reef growth is possible without rigid binding, which most probably takes place by interlocking of corals (see also Braithwaite et al. 2000).

Preliminary stabilization implies that rubble remains stable at least during normal wave agitation. This can be brought about by (1) an accumulation of rubble in depressions; (2) a decline of hydrodynamic energy after storm events forming rubble piles; (3) hydrodynamic protection by seaward rubble piles formed during subsequent storms; (4) fleshy macroalgae and seagrass, although binding suffers from seasonal disappearance; these agents are not known as a precursor for rigid binding; (5) increased size and weight due to encrustation of the single rubble pieces by coralline algae; (6) interlocking of adjacent, branching rhodoliths forming a “non-rigid framework”; and (7) cryptic and erect sponges.

Rigid binding requires preliminary stabilization and physical and biological factors favoring the occurrence of binding agents. Even though a wide spectrum of binding agents are known to bind coral frameworks, only a few are reported to rigidly bind reef rubble:

1. The main binding agent for reef rubble is diagenetic cementation. Diagenetic cementation is triggered by metabolism, organic compounds in solution, hydrodynamic energy, low accumulation rates, occurrence of interstitial sediment, supersaturation with $CaCO_3$, a high pH, and warming of cool upwelling water.
2. The presented analysis of literature data supports former findings for reef frameworks which suggest that crustose coralline algae are less important binding agents than diagenetic cementation, although long-term studies have shown that they can be locally significant. There are some indications that binding by coralline algae prevents reef regeneration by preventing settlement of coral larvae; other studies indicate, however, that this is not a general rule. Age determinations showed that many encrustations by coralline algae took place after diagenetic rubble-cementation. This indicates that literature data presenting rubble binding by coralline algae must be treated with caution.

3. Even geniculate coralline algae seem to be able to bind rubble rigidly; however, the documentation of this process is insufficient.
4. Reports on rubble stabilization by encrusting corals are surprisingly rare but prove their ability to do so.
5. Bryozoans can bind the rubble from within the accumulation, but they are not abundant and are accompanied by heavy coralline algal crusts.
6. Vagile worms are potentially able to move and ‘‘glue’’ centimeter-sized coral heads together to form stable patches.

Duration of binding depends on several factors and few data are available. Preliminary stabilization by seagrass or uncalcified algae may be rapid due to their fast growth; preliminary stabilization by sponges only lasts one to a few months; rigid binding by encrusting coralline algae can take place within 7 months; and preliminary stabilization by interlocking of branched coralline algal crusts may take place within a few years, or probably within 1 year, depending on the growth rates of the particular species.

Places of rubble binding and reef regeneration

Regeneration of reefs is estimated to take place within 5 to 150 years after impacts. Factors that generally influence the regeneration of reef communities are: (1) environmental tolerance of the main framework builder and its ability to regenerate; (2) a healthy population of herbivores which prevents algal blooms; (3) larval recruitment and high survival rate of larvae; and (4) other biological factors such as predation, disease, parasitism, and bioerosion which may increase in ‘‘unhealthy’’ communities.

Factors that are especially important for reef regeneration after rubble-forming impacts are summarized in Fig. 3: (1) frequency of high impacts should allow regeneration within two events; (2) the disturbance should be intermediate, otherwise the community may be reset to a ‘‘pioneer stage’’; (3) availability of stable substrate to allow coral settlement; (4) in most cases rigid binding of the produced rubble is necessary; (5) high fresh-water runoff and eutrophication after storms may cause algal blooms; and (6) high sediment input from the hinterland after storms leads to burial of framework builder.

Rubble binding is known from most reef areas, although many authors did not define the exact position of rubble binding within the reef structure.

1. Inter- and supratidal rubble piles up on the shoreline, back-reef, and reef-flat environments are rigidly bound by submarine cementation below sea level and marine vadose cementation above sea level. Due to their position close to sea level, reef regeneration on these piles cannot be expected without a sea-level rise.
2. Rubble-nucleated rhodoliths can form laterally extensive back-reef rhodolith pavements and are caught in reef-flat depressions or in the deep fore-reef. They only reveal preliminary stabilization by interlocking – rigid coral frameworks over rhodoliths are not known.
3. Rubble binding on the reef crest has not yet been described. Larger rubble accumulations in high-energy environments cannot be expected, although sediment resulting from fragmented corals can be caught within the reef cavities. Since this is the zone of highest diagenetic cementation and it shows one of the highest growth rates of calcareous organisms, a high rigid binding potential can be expected.
4. Tropical algal ridges frequently represent storm-ridge deposits composed of reef rubble. The main binding agent is diagenetic cementation and the coralline

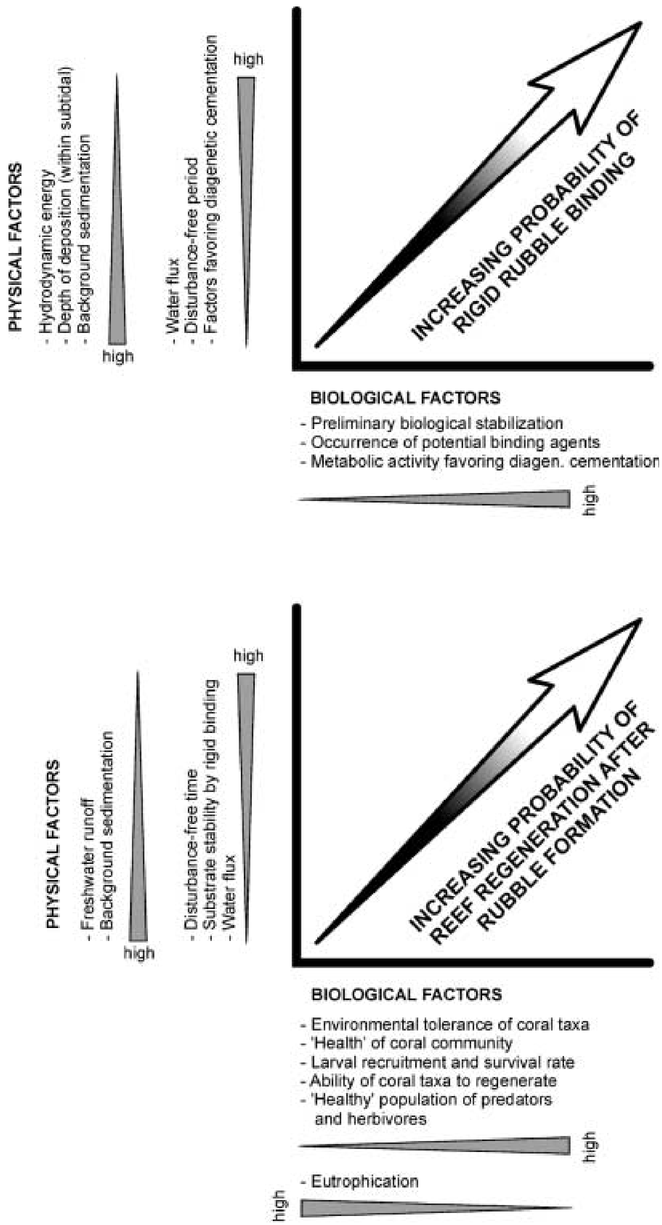


Fig. 3. Synthesis of factors involved in the rigid binding of reef rubble (*above*) and reef regeneration (*below*) after rubble formation

algal crusts only cap the ridges. These ridges occur most frequently in very shallow fore-reef and back-reef environments and the low water depths prevent settlement of corals.

5. High rates of rubble binding are reported from the shallow fore-reef area, within the upper fair-weather wave base. They are usually reported from reef profiles with low angles which allow deposition of rubble. Rigid binding is mainly by diagenetic cementation, but also binding by coralline algae is more frequent than in other environments. The distribution of coralline algal binding is typically very patchy and laterally inconsistent. A combination of binding by diagenetic cementation and coralline algae can occur. Reef regeneration occurs in most of the reported cases.
6. Diagenetic cementation of reef rubble in the relatively deeper fore-reef below 30 m is only reported for one occurrence. Coral frameworks are not formed in this environment, but the reason for this is not clear.
7. Rigid binding of reef rubble is particularly rare on the deep fore-reef talus, although preliminary stabilization by sponges is speculated to be important. The absence of coralline algal binding may be caused by low light conditions preventing the algae's extensive growth. The low abundance of diagenetic cementation could be caused by a low water flux, an interpretation that coincides with its relative scarcity in some protected reef-flat and back-reef sediments.

Geological implications

Growth of coral reefs is not simply a biological accretion process. It also includes geological processes such as destruction and loss of carbonate as well as formation and stabilization of reef rubble, whereby the amount of carbonate export tends to be higher than the import. Geological processes stabilize and shape the predominantly biologically produced reef carbonate. Binding of reef rubble is dominated overall by the geological – even though biologically induced – process of diagenetic cementation.

Studies on fossil coral reef environments should consider the following:

1. The finding that many coral reefs primarily consist of rubble and that the reef interior may specifically lack a recognizable, in-place framework makes identification of fossil reefs difficult. Holocene reef accretion models should take into account that the amount of rubble produced by storms and other disturbances is directly responsible for a reef's growth fabric; whether this is also true for fossil coral reefs needs to be tested in further studies.
2. A change in lithology such as a change from framestone to coral-rudstone reflects a disturbance of the in-situ organismic reef framework. We can suppose that the disturbances affecting modern reefs, for example storms, wave agitation, sea-level changes, bioerosion, and diseases, affected fossil reefs in a comparable manner. It is important to note, however, that massive rubble occurrences in coral reef environments (i.e., changes in lithology) do not necessarily reflect unique events, since strong impacts occur repeatedly and periodically. Moreover, also average wave agitation combined with other disturbances can create considerable amounts of rubble.
3. Rubble deposited on the deeper fore-reef talus has better chance of being preserved in the fossil record than the shallow-water reef core, although the talus is usually not rigidly bound. This seems to be caused by a higher degree of erosion by storms, wave agitation, sea-level changes, and destructive biotic activities in shallow-water environments. Furthermore, the talus may accumulate vertically until it reaches a depth suitable for rigid binding and subsequent reef growth.
4. Construction of a coral reef framework over shallow-water rubble usually requires previous rigid binding of the rubble preceded by preliminary stabilization, whereby the agent of preliminary stabilization is usually not preserved. However, progradation over the deeper reef talus may take place without rigid binding (see above).
5. A coverstone or bindstone (Cuffey 1985), for example formed by coralline algae, does not necessarily imply that the coralline algae overgrowing a rubble accumulation represent the binding agent. In fact, the presented literature data suggest that diagenetic cementation is the more probable agent and that encrustations by algae took place after lithification.
6. High rates of submarine diagenetic cementation of rubble in fossil reefs may be indicative of shallow-water areas of high wave agitation and water flux. Associated biota and organic compounds in solution can trigger diagenetic cementation, but they are frequently not preserved.

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