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Ecological Parameters of Dynamited Reefs in the Northern Red Sea and their Relevance to Reef Rehabilitation

B. RIEGL†* and K. E. LUKE‡
†*Institut für Geologie und Paläontologie der Karl-Franzens-Universität, Heinrichstrasse 26, 8020 Graz, Austria*
‡*Centre for Tropical Coastal Management Studies, Department of Marine Sciences and Coastal Management, University of Newcastle, Newcastle-upon-Tyne NEI 7RU, UK*

Dynamite damage was investigated on 60 reefs in the Egyptian Red Sea. 65% of the investigated reefs had signs of dynamite damage, mostly in leeward areas (58%). Significant changes in coral and fish community composition within dynamited sites were observed. Coral cover decreased, the amount of bare substratum and rubble increased, fish communities in dynamited areas suffered a decrease in species richness and abundance. Due to a stable pattern of coral community differentiation on northern Red Sea reefs (windward *Acropora*, leeward *Porites*) most damage is on near-climax *Porites* reef slopes or *Porites* carpets. Natural regeneration of such communities is likely to be very slow, possibly taking several hundred years. Rehabilitation would be difficult since coral transplants would have to mimic the previously existing community. © 1999 Published by Elsevier Science Ltd. All rights reserved

The condition of coral reef ecosystems is reported to be declining on a global scale (Eakin *et al.*, 1997; Jackson, 1997; McManus, 1997). Some of the identified impacts are due to natural events, such as storms, predation or disease outbreaks, while others are due to human influences. The causes of man-made impacts can be indirect, by activities happening away from the reefs that nevertheless cause, for example, increased sedimentation levels or pollutant loads. Many others are direct, resulting from activities taking place on the reefs, like overfishing or reef degradation due to destructive fishing methods.

The adverse effects of destructive fishing techniques have received considerable attention in the literature (Alcala and Gomez, 1979, 1987; Galvez and Sadorra, 1988; Pauly *et al.*, 1989; McManus, 1997; Salvat, 1987) and dynamite fishing was investigated in detail by several studies (Rubec, 1988; McAllister, 1988; Saila *et al.*, 1993, Edinger *et al.*, 1998). Most of these studies are from South-East Asia, but few exist from the Middle East. The Red Sea, with a relatively small coastal population and extensive reef systems, has so far appeared to suffer mainly from localized impacts, due to expanding coastal urban and industrial centres, ports and tourism (Hawkins and Roberts, 1994; White *et al.*, 1997). However, it appears that even outside these affected areas, otherwise healthy reefs are heavily impacted by destructive fishing methods. Reef damage due to dynamite fishing, recent and old, is frequently encountered on Egyptian Red Sea reefs. Due to the behaviour of the dynamited fish, and in order to maximize catch-per-unit-effort, fishermen target specific reef areas, like leeward slopes, with a resultant concentration of damage.

With the increase of international efforts to promote reef conservation (Dight and Scherl, 1997) and the advancement of reef rehabilitation techniques (Clark and Edwards, 1993, 1994, 1995), it is of interest to study how specific patterns of damage, or of damaged communities, affect the likelihood of natural regeneration or the possibility of artificial rehabilitation.

This paper (1) describes characteristics of unimpacted coral and fish communities, (2) investigates patterns of dynamite damage, (3) describes the effects of dynamite fishing on coral and fish community composition, (4) investigates the effects of damage patterns on natural recovery and (5) aims to assess whether reef restoration is necessary and what can be achieved.

Methods

A total of 60 reefs between the Ashrafi reef complex in the Straits of Gubal (27.46° N, 33.42° E) and Ras Banas (23.57° N, 35.47° E) were visited and sampled by two methods: rapid ecological assessment (REA, phototransects for corals, transect swims and point counts for fish; REA sites are indicated in Fig. 1 by an arrow, fully sampled sites are named), and line intercept transects.

*Corresponding author.

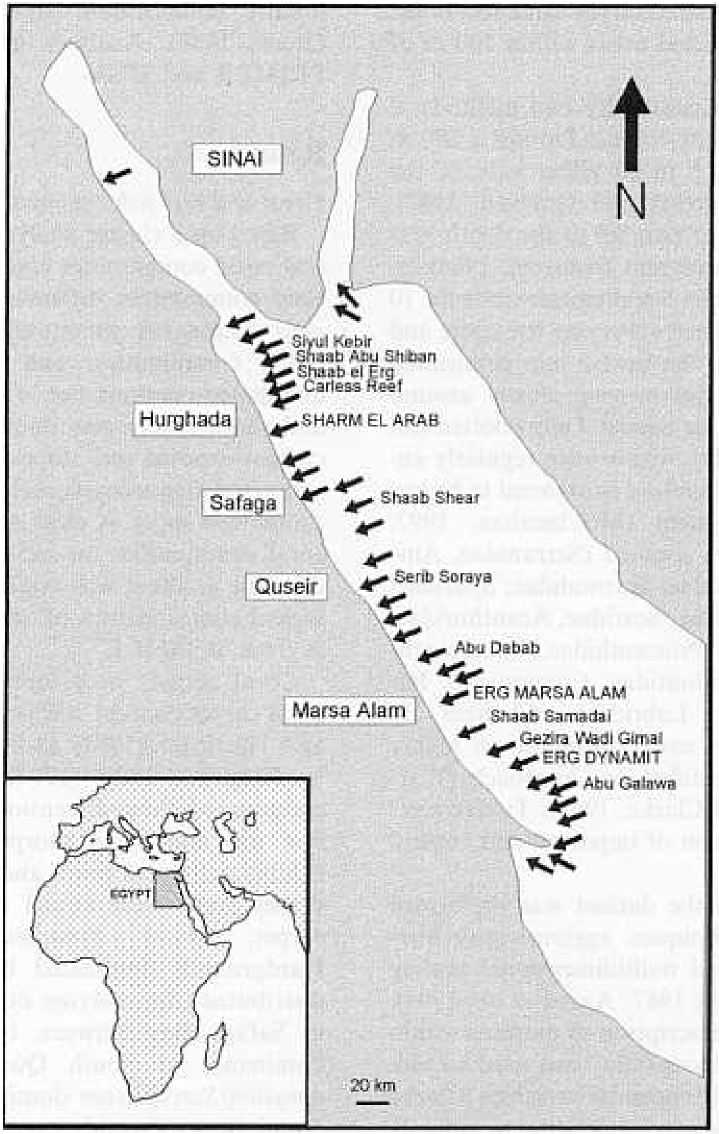

Fig. 1 Map of the northern Red Sea showing investigated reefs. Reefs visited during rapid ecological assessment are indicated by an arrow only, impact and control reefs used for the description of dynamite impacts are named (capitals for coral sites, small caps for fish sites, coral sites were fish sites as well), also sites mentioned elsewhere in the text are named. A total of 60 sites were visited and sampled, but not all could be shown for reasons of clarity on the graph.

Where dynamite damage was encountered, the position and characteristics (leeward or windward, shallow or deep, reef zone, community type) were recorded. For the basic description of coral and fish communities, random sites in areas with different levels of hydrodynamic exposure were chosen and sampled. For coral communities we used 10m line transects, or photo transects from which we later obtained the line transect information (Riegl *et al.*, 1995). The adequacy of that transect length had been previously documented for the studied area (Riegl and Velimirov, 1991, 1994). The intercepts of all coral species, benthic invertebrates and macro-algae were recorded to the nearest centimetre along each transect. Also the type of substratum, classified as sand, rock or rubble, was recorded.

For corals, 3 sites (Erg dynamite, Sharm el Arab, Erg Marsa Alam, see Fig. 1) were chosen for impact versus control sampling. The study attempted to compare damage extremes (totally undamaged, totally damaged). This was necessary, as otherwise a satisfactory description of dynamite damage can be difficult. Individual dynamite craters and spatially restricted damage can be masked by natural free space in the data-set which can mask damage patterns and confuse interpretation (Riegl and Velimirov, 1991). Within dynamited areas of sufficient size (> 100 m in length) random samples were taken. Control sites were situated on the same reef in the same depth-zone in unimpacted areas within 100 m of the impact site.

Fish communities were assessed by two methods: a 200 m transect swim or point counts. During a 200 m swim all fish encountered 5 m to either side of the transect were counted (Roberts and Ormond, 1987). These swims were performed parallel to the depth gradient. Point counts (Bohnsack and Bannerot, 1986) involved a structured search of a 5 m diameter circle for 10 min. The first 3 min were spent surveying the circle and noting the families present, the next 3 min confirming the list, and the final 4 min moving slowly around checking for individuals so far missed. Only selected fish families (plus one subfamily), which were regularly encountered on all reefs and therefore considered to be key components of the ecosystem (McClanahan, 1997; Hayward *et al.*, 1997) were counted (Serranidae, Anthiinae, Lutjanidae, Lethrinidae; Haemulidae; Sparidae, Mullidae, Mugilidae, Labridae, Scaridae, Acanthuridae, Siganidae, Pomacentridae, Priacanthidae, Pomacanthidae, Dasyatididae, Tetraodontidae, Caesionidae, Balistidae, Chaetodontidae, Labridae). Changes in communities are frequently easier to detect on higher taxonomic levels, which justified our approach (Warwick, 1988; Somerfield and Clarke, 1995). Twelve reefs were used for the comparison of impacted and control sites.

Pattern detection within the dataset was performed using two multivariate techniques: agglomerative hierarchical cluster analysis and multidimensional scaling (MDS, Digby and Kempton 1987; Agard *et al.*, 1993). MDS is not limited to the description of patterns within the community, but has successfully been used to link community structure to environmental variables (Clarke and Ainsworth, 1993; Agard *et al.*, 1993) and to estimate severity of disturbance (Warwick and Clarke, 1993). Both statistical methods have advantages for delineating very distinct groups (cluster analysis) or groups with gradations (MDS; Field *et al.*, 1982; Kenkel and Orloci, 1986; Warwick *et al.*, 1988). If both analyses provide consistent results, it is likely that they represent natural groupings. MDS was preferred over principal components analysis (PCA) which is better suited for environmental data (continuous data) than species abundances (James and McCulloch, 1990; Clarke and Warwick, 1994).

For the comparison of groups (impact versus control), community characteristics were compared using one-way analysis of similarity (Clarke and Green, 1988). This analysis is built on a non-parametric permutation procedure applied to the same rank similarity matrix underlying the classification or ordination of samples. It is more applicable to the presently used data sets than a multivariate analysis of variance as it does not assume normality of data and allows for the dominance of zero counts in the typical transect data-set. It tests against the null-hypothesis that there are no differences in community composition between samples (Clarke and Green, 1988). Analyses used the software packages PRIMER and SPSS.

Results

Coral and reef fish communities of the study area

Based on a cluster analysis of 132 line transects, several coral communities could be differentiated (Fig. 2). Reef communities differentiated into windward *Acropora* dominated communities, leeward *Porites* dominated communities, and current-exposed *Millepora* dominated communities. The inner portions of marsas and sharms were also dominated by *Millepora*. Steep, current-exposed reef slopes were characterized by high soft coral frequency (usually *Dendronephthya* spp. and *Litophyton* spp.). A clear ecological subdivision of the coral communities on reefs along a depth and hydrodynamic gradient was evident. An overview of the biological characteristics of scleractinian reef communities is given in Table 1.

Coral carpets were found in several localities. The coral carpet concept was originally formulated by Reiss and Hottinger (1984) and received detailed treatment by Riegl and Piller (1997). They do not produce an accentuated three-dimensional relief, but roughly follow the underlying morphology. Nevertheless, they exhibit rich coral cover and build a framework. Three carpet types were found in the study area (*Porites* carpet, *Porites (Synaraea)* carpet, faviid carpet). Hardgrounds dominated by soft corals were widely distributed (*Sarcophyton* dominance off Hurghada and in Safaga Bay between 10 and 30 m, *Lobophytum* dominance at South Queisum island, mixed *Lobophytum*/*Sarcophyton* dominance in Foul Bay between 1 and 10 m). Xeniids were widespread and dominated particularly in greater water depths (>20 m). Space coverage was between 10 and 20% for the *Sarcophyton* and *Lobophytum* communities and up to 60% for the xeniid community.

Based on cluster analysis of 67 fish point counts and 22 transect swims on reefs in all hydrodynamic exposure (Figs. 1 and 3), it became apparent that fish communities followed the differentiation of coral communities into windward, leeward and current exposed communities. Furthermore, the point counts and transect swims from damaged areas (dynamite and other damage) tended to form distinct clusters, which indicated differences in community structure in these sites. Exposed sites differed from sheltered sites in community composition, but not in averages of abundance and diversity (*t*-tests, $p > 0.05$). The sites with the lowest fish abundances were *Porites* carpets and damaged areas. Windward sites were characterized by a higher frequency and species richness, typical families were Pomacentridae and Serranidae (including *Anthias*). Current-exposed sites were characterized primarily by *Anthias*. Sheltered and deep sites had less fish, were also frequently domi-

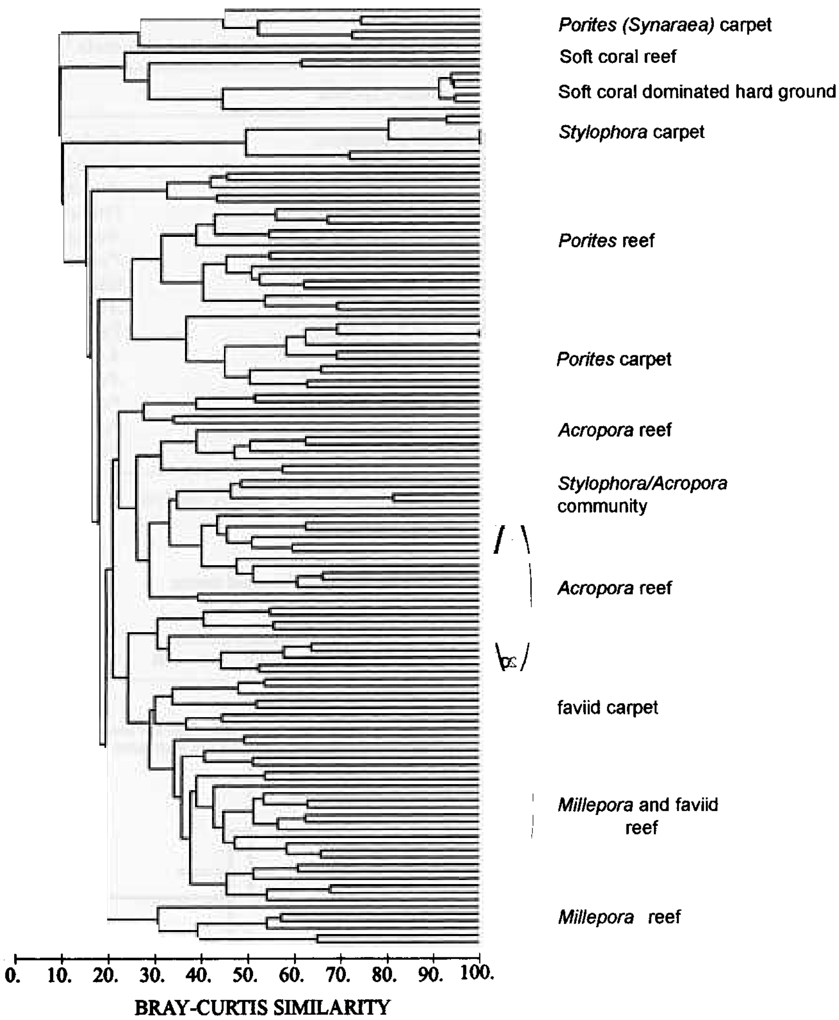

Fig. 2 Classification of coral transects. Linkage is group average, distance measure is the Bray–Curtis similarity index. The sites used for the description of dynamite impacts are not included in this analysis. Clusters are dependent on space cover of the dominant species. Further analysis of the samples contained in the clusters, which correspond to zonation patterns on the reefs, is presented in Table 1.

nated by Pomacentridae but had a higher proportion of the other families.

The fishery technique

Descriptions of the techniques involved in blast fishing are based on the accounts of local fishermen gathered during several months of expeditions. Although we did not directly witness the activity (except hearing and feeling the blasts under water), we were led to several sites that according to our guides had been recently dynamited. After the fishermen acquire the explosives, they are placed into a plastic or tin container of variable size which is fitted with a fuse. As water-tight fuses are generally not available, the bomb is put into a bigger tin, weighted down with stone, the wicket is lit, the tin closed, and the bomb thrown overboard. Dynamiting parties operate from small boats, usually in groups of three or four – one or two fish-bomb handlers and one or two fish retrievers. Mainly leeward shallow areas within easy free-diving range and areas with low currents, which allow easy collection of fish, are targeted. After the explosion, some fish float to the surface while others flee into crevices in the reef where they are then collected by the divers. Steep windward reefs are not well suited for dynamiting as the bombs tend to sink too deep, fish can flee into deeper water after being damaged and be irretrievable, and strong currents can wash the fish on the surface away.

Frequency of dynamite damage

Of the 60 reefs sampled, 21 (35%) showed no signs of dynamite damage. Of the remaining 39 sites, 24 reefs (40% of all 60) had damage on the leeward side only, four reefs (7%) had damaged windward sides only and a combination of damage on windward and leeward sides was found in 11 (18%) reefs. Due to the stable pattern of

TABLE 1

Ecological zonation and average coverage values on northern Red Sea reefs.[a]

	Exposed	Semi-exposed	Sheltered
Reef crest	*Pocillopora verrucosa*, *Acropora gemmifera*, *Stylophora mordax* *Average cover:* 43 ± 18%		*Stylophora pistillata*, Faviidae *Average cover:* 24 ± 17%
Reef edge	*Acropora hyacinthus* group *Average cover:* 54 ± 11%		Porites lutea *Average cover:* 68 ± 30%
Reef slope	Various *Acropora*, diverse without clear dominance *Average cover:* 59 ± 18%		*Porites lutea* and various massive species *Average cover*: 85 ± 29%
Slope base	Tabular *Acropora* (*A. clathrata*, *A. divaricata*) *Average cover:* 58 ± 25%		Tabular *Acropora* (*A. clathrata*, *A. divaricata*) *Average cover:* 26 ± 11%
Fore reef and low-relief areas	diverse carpet (faviid carpet with *Acropora*) *Average cover:* 28 ± 3%		*Porites* carpet and/or faviid carpet *Average cover*: 85 ± 15%

[a] Values are mean and S.D. for transects within each zone, which was determined by the cluster analysis in Fig. 2.

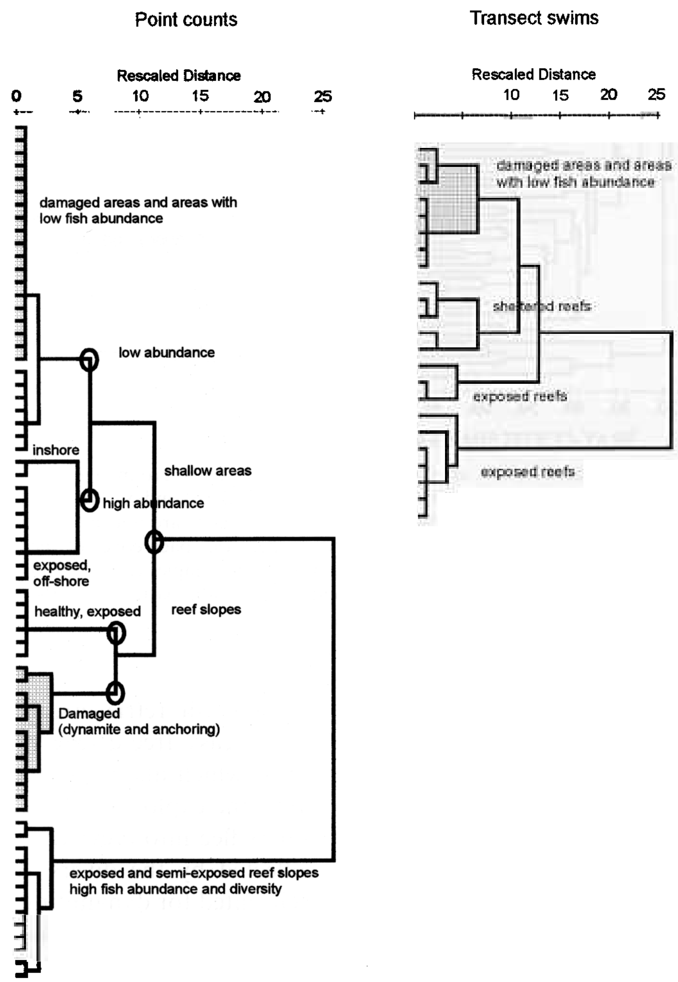

Fig. 3 Fish community structure: Classification of point counts and transect swims. Clustering algorithms is Ward's method with squared euklidian distance as measure. Damaged sites form distinct clusters, which suggests changes in community structure. The sites used for the description of dynamite impacts are not included in this analysis.

windward-leeward coral community differentiation, most damage occurs on *Porites* dominated communities (Fig. 4).

Impacts on coral communities

Three sites (Erg dynamite, Sharm el Arab, Erg Wadi Gimal, see Fig. 1) were quantitatively sampled inside and

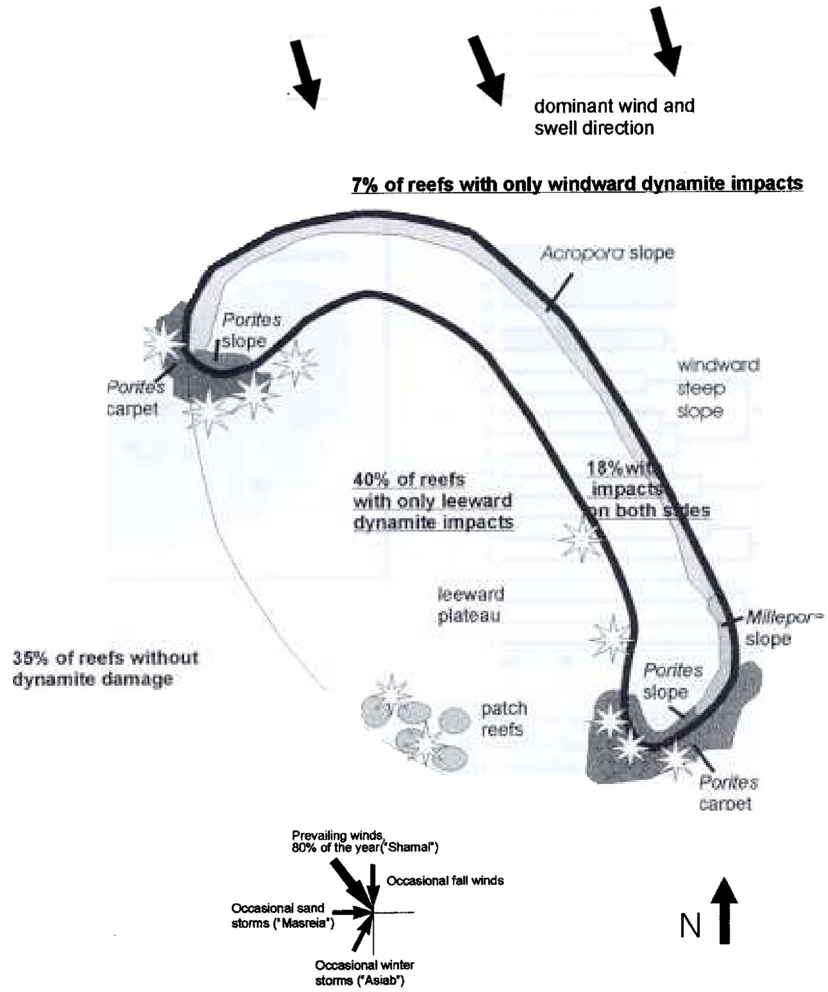

Fig. 4 Sketch of a typical northern Red Sea offshore reef with Windward–Leeward differentiation. White stars indicate the most frequent location of dynamite damage.

outside of dynamited areas. Both cluster analysis and MDS grouped transects from impact and control sites into distinct clusters, suggesting differences in community structure (Fig. 3a,b). Some degree of overlap existed in both analyses. In cluster analysis, two transects of the Sharm el Arab impact site grouped with the control transects. In the MDS, one impact transect did not fall clearly within either group. Such overlaps can be expected, as some impacted sites still retained patches of good coral cover. Overall, the separation of groups was very clear (Fig. 5). One-way ANOSIM confirmed that significant differences existed in the community structure of dynamited versus control sites (global $R = 0.626$, $p < 0.001$). Coral cover decreased significantly, as did the proportion of rock, while the proportion of rubble increased significantly (two-way ANOVA, $p < 0.01$, Table 2).

Qualitative observations

Damage varied with the intensity of blasting and ranged from individual blast craters to total community plus framework destruction. Damage was caused either by direct hits, which created craters in the cavernous coral frameworks (such as *Porites* carpets) or blasted corals off the rocky substratum (Fig. 6a). Collapse of whole reef slope sections due to the concussion caused by the explosion was frequently observed (Fig. 6b). The effects of direct hits were frequently amplified by the collapse of large sections of unstable coral framework, as frequently observed in *Porites* carpets, where parts of the framework collapsed into their own cavern system (Fig. 6c,d). Overall damage levels per reef can be hard to estimate as they range between total damage (in the immediate area of the impact, usually 2–3 m diameter, Fig. 6e), to some tissue damage (in corals immediately adjacent to the blast). On individual colonies, the positive pressure wave created by the explosion (Saila *et al.*, 1993) either fractured branches and columns, or blew the tissues off massive species (Fig. 6f). Mainly big *Porites* colonies withstood the shock-wave but suffered tissue mortality.

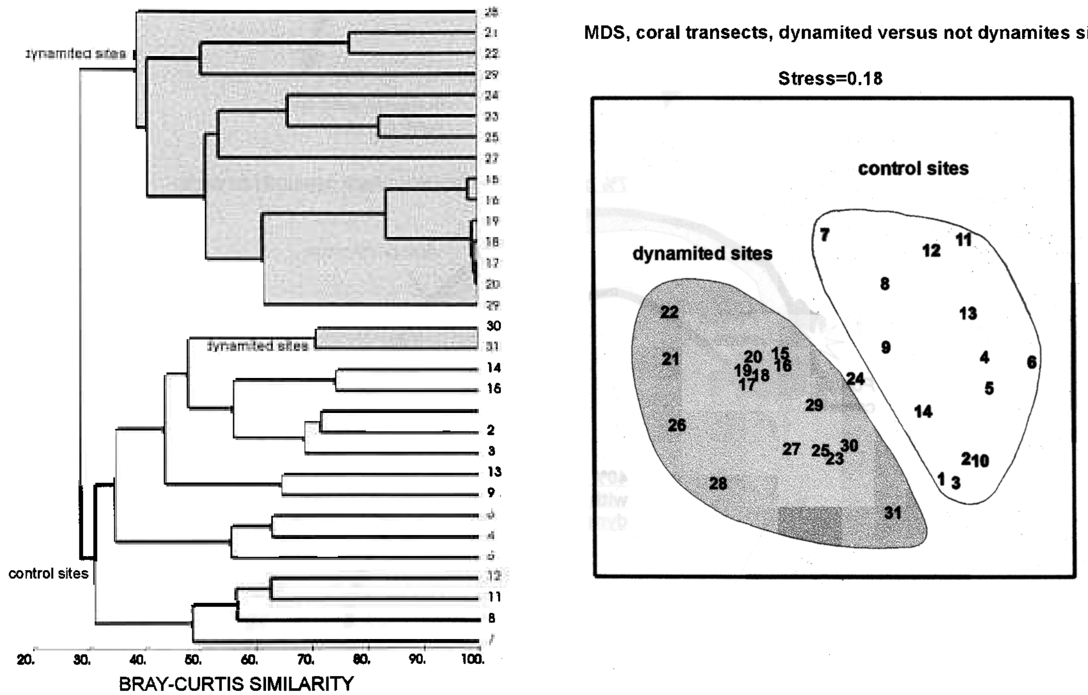

Fig. 5 Differences in community structure between dynamite impacted and control reefs. Both analyses use the same distance matrix but different grouping algorithms. The differences in community structure between impact and control sites are very clear. The low number of outliers supports the significance of the separation. Classification uses group average as linkage, distance measure is the Bray–Curtis similarity index.

TABLE 2

Percent cover values of corals and substratum in the northern Red Sea dynamite impact and control sites.[a]

Sample site	Control			Impact		
	Coral cover	Rock	Rubble	Coral cover	Rock	Rubble
Erg Dynamite	65 ± 9	29 ± 10	4 ± 5	2 ± 3	23 ± 18	75 ± 16
Sharm el Arab	45 ± 7	55 ± 7	0	13 ± 4	40 ± 39	46 ± 39
Erg Marsa Alam	43 ± 9	56 ± 9	0	15 ± 3	31 ± 26	54 ± 23

[a] Differences are significant in all cases. Values are mean and standard deviation.

Impacts on fish communities

For the comparison between impact and control sites, different localities were used than for the description of community patterns. Classification of fish counts from 12 dynamited versus non-dynamited sites did not clearly separate dynamited and non-dynamited reefs into two clusters, but dynamited sites did form separate groupings within each of the major clusters (Fig. 7). MDS failed to clearly separate the impact from the control samples and is not illustrated. However, one-way ANOSIM showed that significant differences existed when pooled data from impact and control sites were tested against each other (global $R = 0.138$, $p < 0.001$), indicating a change in community structure. In dynamited sites, there was an overall reduction in fish abundance ($t = 2.36$, df: 24, $p < 0.027$).

Discussion

The results for coral communities show clearly that due to the marked windward-leeward community differentiation, the effects of dynamite impacts vary in respect to their position on the reef. The taxonomic composition and different life history strategies of constituent species suggests differences in responses to impacts by windward and leeward communities. Windward sides harbor the higher abundance and diversity of coral and fish and are populated by faster-growing, *r*-selected communities, while leeward sides are near-climax, *k*-selected communities (Riegl and Velimirov, 1994; Riegl and Piller, 1997).

Most impacts are on leeward sides (Fig. 4), resulting in several important implications for regeneration. In-

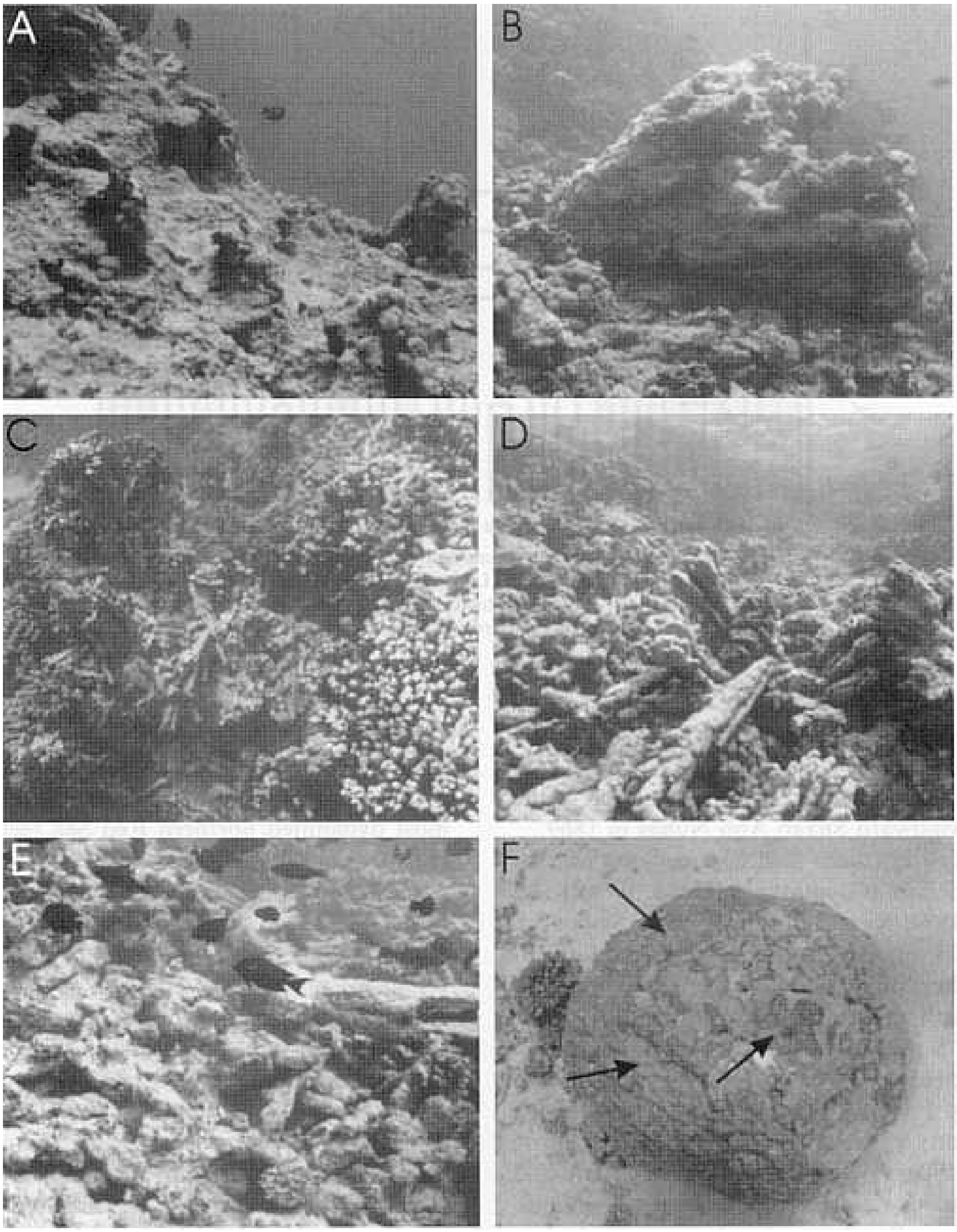

Fig. 6 Illustration of the most frequent types of dynamite damage. (A) Shaab Shear, a reef slope at 4 m depth with virtually no coral cover left. (B) Abu Dabab, 5 m depth, part of the reef slope collapsed and tumbled further down the slope. Length of the structure is approximately 2 m. (C) Shaab Samadai, 8 m depth, partial framework collapse after dynamite blast in leeward *Porites lutea*/*Porites columnaris* frame. (D) Serib Soraya, typical coral rubble produced by explosions in areas of columnar *Porites* growth. (E) Erg Dynamit, 3 m depth, Possible shift in fish communities in dynamited areas. Pomacentrids decline in frequency, the areas are mainly frequented by acanthurids and scarids (here *Acanthurus nigrofuscus*, *Scarus niger*). (F) Abu Galawa Saghir, 5 m depth, a *Porites solida* colony was stripped of most its tissues by the shock wave created by a blast occurring about a metre away to its left. The light parts of the colony are living tissues. The dead parts are indicated by arrows.

tergranular cementation, which is necessary for sediment lithification and, in this case, the re-establishment of firm substratum from impact-generated rubble is highest in areas of high water flux at the sediment-water interface (Scoffin, 1992), and is therefore likely to be higher in windward areas but slow in leeward settings. In the study area, no cemented rubble was found. It can be expected that unstable substratum, with all its nega-

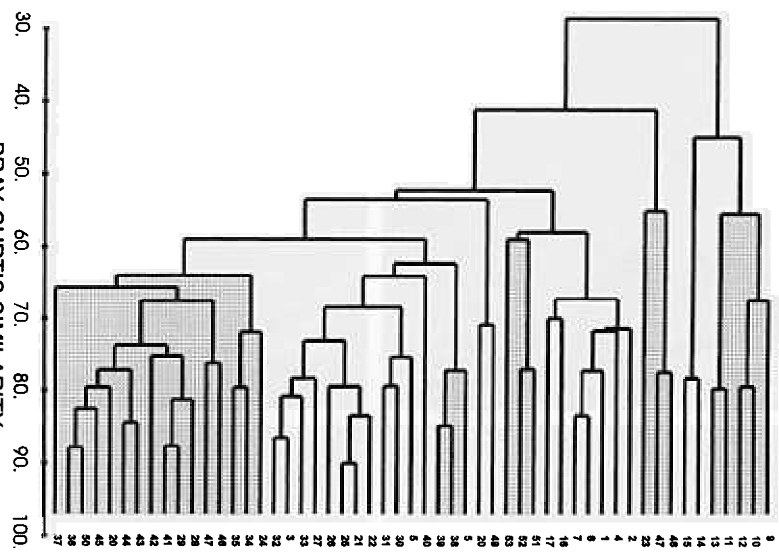

Fig. 7 Cluster analysis of fish counts in dynamited (grey) and adjacent undamaged sites (white). Linkage is group average, distance [illegible] the Bray–Curtis similarity index. Differences between dynamited and control sites are less pronounced than in corals.

tive implications for coral re-establishment will persist for long periods of time. The oldest investigated, and still uncemented, rubble was from the grounding of the "Carnatic" on windward Shaab Abu Nuhas in 1869.

Leeward shallow northern Red Sea reefs are characterized by a high *Porites* dominance (Head, 1984; Riegl and Velimirov, 1994; Riegl and Piller, 1997). Slopes are usually on a mild angle, what allows bombs to hit directly among the corals. *Porites* are relatively slow growing corals with a mean linear skeletal extension rate of 6.17 mm yr^{-1} (Gulf of Aqaba) to 6.42 mm yr^{-1} (southern Egypt; Heiss, 1994). They are *k*-strategists and the low-diversity *Porites* communities are near-climax communities (Potts *et al.*, 1985; Riegl and Velimirov, 1994; Riegl and Piller, 1997). From the growth rate and the sizes of massive *P. lutea* colonies and the column lengths of columnar *P. columnaris* colonies, we calculate in some areas an age of several centuries of continuous coral growth (*P. columnaris* framework of 7 m thickness at Abu Dabab, in which individual columns could be traced over the entire growth period, similar frameworks exist in other localities). These age estimations compare well to those of Potts *et al.* (1985) from the Great Barrier Reef. From this, and from records of Red Sea reef accretion in the literature (Braithwaite, 1982; Dullo *et al.*, 1996), we infer that on leeward sides (a) accretion is slower, (b) regeneration of suitable settlement substratum is slower due to slower cementation rates, (c) regeneration of the coral community is slower due to the constituent coral's slower growth rates, and (d) regeneration of the original fish and other associated faunal communities may also be slower.

Recovery periods are difficult to estimate and depend on the definition of recovery. If Pearson's (1981) definition of "restoration of a coral assemblage to a degree comparable to its original state" is used, dynamited *Porites* reefs may stand a low chance of natural recovery. Due to the special ecological parameters of most dynamited northern Red Sea reefs, differences in regeneration characteristics are likely to exist in comparison with other areas. The recovery model of Saila *et al.* (1993) from the Philippines calculates, according to model parameters, a recovery period for original diversity of up to 100 yr in a highly diverse system of 300–500 coral species. In leeward northern Red Sea reefs, the impacts are primarily on near-climax, low diversity, *k*-dominated systems. The question therefore is not only how soon the system's total diversity (slightly over 200 species, Veron pers. comm.) is regenerated, but also how soon a similar successional stage can be reached again (Pearson, 1981). It could happen that this will never be the case, particularly if the reef framework was damaged. In the Maldives, Brown and Dunne (1988) found virtually no recovery 16 yr after coral mining had ceased. Also in our study, remarkably little regeneration of dynamited sites was observed during the present study. This may, however, be partly the result of emphasis being put on detecting impact versus control patterns, rather than making assumptions about regeneration. The likelihood and speed of regeneration is probably a function of scale. While small scale impacts (individual blasts) are on the scale of a localized episodic event that does not alter the system (or the community), large scale impacts (several densely spaced blasts over large portions of a reef) can totally alter ecological and even environmental parameters and thereby make natural regeneration almost impossible. It is therefore possible that if something reminiscent to the original Red Sea *Porites* community were to be re-established, it would have to be by artificial means, like transplantation (Clark and Edwards, 1993, 1994, 1995).

Rehabilitation efforts should respect the original zonation patterns. If leeward sides were artificially recolonized primarily by rapidly growing, aggressive corals, such as *Acropora* (Thomason and Brown 1986), the slow growing, competitively weak *Porites* would be disadvantaged from the beginning and recreation or regeneration of the original community could be difficult. Clark and Edwards (1995) showed that *Porites* exhibit high survival rates after transplantation into damaged sites. This result indicates that there may be a hope of at least partly restoring even late-successional stage communities. Transplantation of a sufficient number of sufficiently large specimens may, coupled with the high survival rate (Clark and Edwards, 1995) and capabilities of asexual reproduction (Highsmith, 1980, 1982), significantly speed up the artificial re-installation of a *Porites* dominated reef.

The observed decrease in fish abundance is in agreement with reports from the literature that dynamited reefs have lower fisheries yield than undisturbed reefs (McAllister, 1988; Rubec, 1988). Herbivore loss can be critical for reef health (Steneck, 1993). Indeed, in some impacted sites strong algal growth was observed (growth of *Laurencia* sp., several cm thick). The absence of enough herbivores and the concomitant increase of algal abundance leads both to a reduction of coral settlement (Bohnsack, 1993) and suppressed growth of coralline algae, which can act as important binders in some reef zones (Blanchon *et al.*, 1997). The return of territorial damselfish and other territorial grazers could possibly be aided by transplanting corals or any structure which can serve as refuge or territory into the denuded areas (Sano *et al.*, 1984, 1987). In order to achieve near natural coral larvae settlement rates, it may be necessary to first re-establish all components of the fish community, the activities of which may play an important role in priming the damaged reef for re-settlement.

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