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ALCYONARIAN SPICULITE: LIMESTONE OF SOFT CORALS

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ABSTRACT

Among the spiculate alcyonaceans (soft corals), the species of genus *Sinularia* are so extraordinary in that their basal stalk of the living colony becomes consolidated through submarine cementation of the densely concentrated coenenchymal spicules (=spindles) and attaches firmly on the substratum. They locally contribute lenticles uniformly composed as thick as a few tens of centimeters which encrust other reef frame-building organisms.

It is now known that this peculiar kind of autochthonous solid limestone occurs ubiquitously in the Western Indo-Pacific between the reef front edge shallower than 10 m and the reef flat in both Holocene and Pleistocene reef environments, and probably also in the older geologic columns formed under similar conditions.

This limestone, which is described by a new term, 'alcyonarian spiculite', is of sedimentologic importance for the identification and reconstruction of ancient reef structures.

INTRODUCTION

Alcyonaceans, especially their representative family Alcyonariidae, are the major reef-dwelling "soft corals" in the Indo-Pacific (Bayer 1957), as compared with Gorgonaceans in the Atlantic. Their potential role as carbonate-producer should not be underestimated, since they provide conspicuous coverage among sessile reef communities and high percentage of calcitic spicules inlaid within the soft tissues.

Examination of their thanatocoenose at some fringing reefs along the Ryukyu Islands (Japan), however, indicates that their ultimate contribution to the unconsolidated carbonate sediments is insignificant. Therefore, occurrence of the limestone exclusively composed of the alcyonariidean spicules which are subsea-cemented during the organism's lifetime should be documented (Konishi 1979). Such limestone of a specific origin is now known from both subaerial outcrops and subsurface drilled cores in the Holocene and Pleistocene reefs of the Ryukyu Islands, and may be more widespread spatiotemporarily in the Western Indo-Pacific.

ALCYONARIIDEAN SPICULES AND GENUS *SINULARIA*

Soft corals are one of the spiculate orders of Octocorallia, which embed abundant spicules (=sclerites) in both ectoderm and coenenchyme of the living soft tissues. The spicules are postmortemly freed from the decaying tissues after death as discrete fragile particles which are apt to be bioeroded with algae, fungi or other microborers and abraded through sedimentation.

The spicular calcimass in a colony ranges from 19.75 to 35.86% (weight), with an average of 27.4% for 12 species in the Caribbean gorgonaceans (Cary 1918) and from 8.73 to 35.58%, with an average of 19.1% for 4 species in the South Pacific alcyonariideans (Cary 1931). Analyses of several alcyonariideans from the Ryukyus and Micronesia revealed that the spicules' weight is over 50% of the dried colonies.

Although "five years" which was estimated by Cary (1931) as the time of turnover for the Caribbean gorgonaceans may be too short to be accepted (Milliman 1974), the large size of the fast growing Alcyonariidean colonies together with the high concentration of the spicular calcimass strongly suggests a relatively fast rate of turnover and appreciable addition of spicules into shallow-water carbonates.

Contrary to such a prediction, however, a thorough modal analysis of the dredge samples from three areas in the Ryukyus, (1) off Kabira Cove (24.5°N; 124.2°E), northwest Ishigaki-jima (2) off Minatogawa, south Okinawa (26°N; 127.8°E), and (3) around Kikai-jima (28°N; 130°E), has indicated that the alcyonacean spicules can hardly contribute one % (weight) of the unconsolidated sediments, even if those of the other spiculate orders of Octocorallia (telestaceans, gorgonaceans and pennatulaceans) are summed (Table 1).

Striking exceptions are found in massive and lobate colonies of the genus *Sinularia* May. A whole colony of *Sinularia* (Tixier-Durivault 1951) may be composed of the lower stiff cylindrical sterile stalk 10 to 20 cm in diameter and height and the upper fleshy capitulum, the latter of which consists of the discoid and branching, sometimes finger-like, lobes. The spicules vary both in form and size not only

Table 1. Abundance of alcyonarian spicules in unconsolidated sediment, at Kabira, Ishigaki-jima, southern Ryukyus.

Beach	Md (Φ)	Number of spicules in 10g of sediment (Φ =0 ~ 1)-fraction	Total weight (mg) of spicules in 5g of sediment (Φ =1~2)-fraction
supratidal (M-2)	-0.32	13	154
intertidal (M-1)	0.96	20	33
Shallow Channel in Cove			
(M-11)	1.39	18	31
Reef Flat			
" 300 m" from reef crest	-0.16	2	8
" 250 m"	1.49	15	19
" 200 m"	0.35	0	6
" 150 m"	1.30	10	14
" 100 m"	-0.26	4	17
" 50 m"	1.17	29	36
Reef Crest			
Forereef			
-10 m in water depth (M-17)	0.82	20	41
-46 m " (KT-77-17- 2)	-0.08	0	10
-46 m " (KT-77-17-22)	-0.53	5	15
-46 m " (KT-77-17-23)	-0.41	0	9
-60 m " (KT-77-17- 4)	3.50	0	4
-65 m " (KT-77-17-15)	-0.18	5	10
-67 m " (KT-77-17- 5)	3.41	3	6
-70 m " (KT-77-17-14)	3.59	0	10
-92 m " (KT-77-17- 7)	2.97	0	2
-95 m " (KT-77-17-12)	2.71	18	33
-100 m " (KT-77-17- 8)	2.48	3	3
-100 m " (KT-77-17- 9)	2.93	72	126
-100 m " (KT-77-17-11)	2.62	21	18
-102 m " (KT-77-17-16)	2.54	18	38
-156 m " (KT-77-17-17)	1.04	13	10
-200 m " (KT-77-17-20)	0.41	19	28
-212 m " (KT-77-17-18)	1.22	21	15
-215 m " (KT-77-17-19)	2.19	16	11

with species, but also within the same colony. Compared with the cortical spicules, (often called "clubs") in the surface layer of the lobes and stalk, the coenenchymal spicules, (usually termed "spindles") are more than ten times larger in size, but simpler in gross shape. They are aligned loosely within the coenenchyme more or less parallel to growing direction of the colony and, in some species, protrude from the surface of the stalk (Fig. 1; terminology after Verseveldt 1978 and earlier).

Each spindle straight or curved may be pointed or blunt-ended with or without a constriction in the middle, and is occasionally bifurcated or irregularly ramified. Its surface is densely ornamented with tiny coarse warts (=protuberances) arranged in traverse rows (Fig. 2). These spindles of *Sinularia* are so extraordinarily large, (ranging from several hundred microns to one mm in diameter and up to several mm in length,) that their generic assignment (Bayer 1956) is no doubt assured based merely on their size. Their mineralogy is magnesian calcite (high-Mg) with $MgCO_3$ ranging between 12 and 15% (mol).

The basal portion of the stalk tends to become consolidated with the substratum while the overlying parts are still living. In fact, this is the unique feature confirmed with many species of this genus in the Ryukyus, Guam, Ponape and elsewhere during the present study (Fig. 3). The consolidated base at times exceeds 10 cm in thickness, so that the colonies as high as 30 cm may encrust and strengthen the substratum and rise prominently to be water-resistant like other reef frame-builders. Cary (1931) reported that the consolidated part beneath the older colonies may reach a thickness of 45 to 60 cm (18 to 24 in).

These spindles are responsible in forming the consolidated basal unit of the *Sinularia* stalk as "a mass of spicule rock" (Cary 1931). The contact between the spicule rock and the upper stalk is gradual.

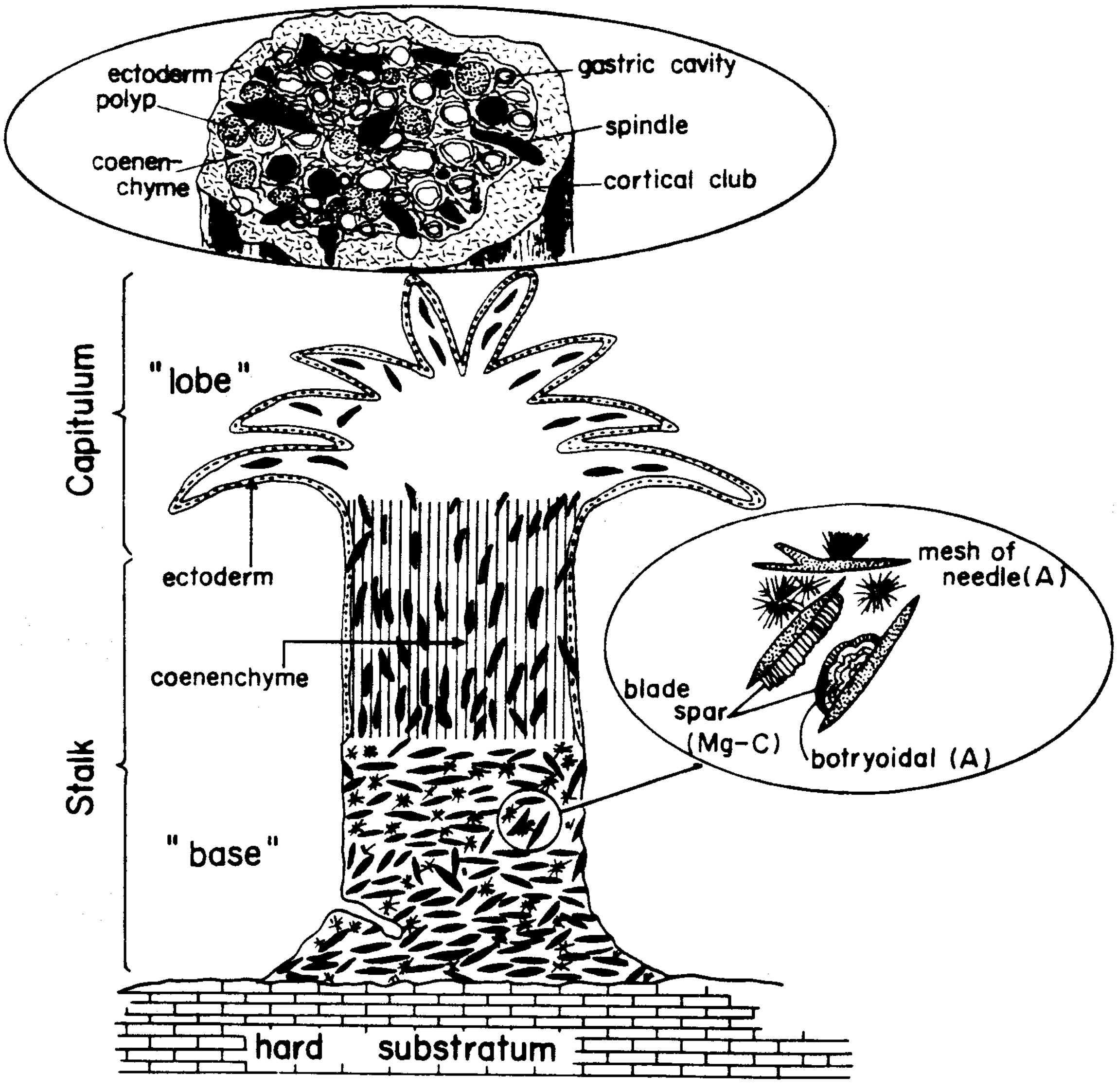


Figure 1. Schematic diagram showing anatomical characteristics of a *Sinularia* colony. Not in scale.

The concentration of the spindles appears to decrease upwards from the spicule rock to the coenenchyme of the lobe via that of the stalk, as if showing the aging effect on calcification. The spindles in the rock are oriented more or less horizontally and pushed more densely compared with the soft stalky part, and suggest their post-mortem redisposition.

ALCYONARIAN SPICULITE

The spicule rock forming the basal stalk of *Sinularia* colonies is what is hereafter termed "alcyonarian spiculite" (Fig. 4). This is a new type of autochthonous limestone built from a local, in situ, concentration of the alcyonariidean spicules. It is composed of exclusively unispecific, yet variable, spindles randomly oriented and subsea-cemented. Two minerals, aragonite and magnesian calcite, are accountable for the submarine cementation, although aragonite overwhelms magnesian calcite.

The most common type of the aragonite cement is the "mesh of needles" (James and Ginsburg 1979), which ranges in form from an irregularly chaotic arrangement of randomly oriented crystallites (150-250 μm long and 5-15 μm wide) to interlocking

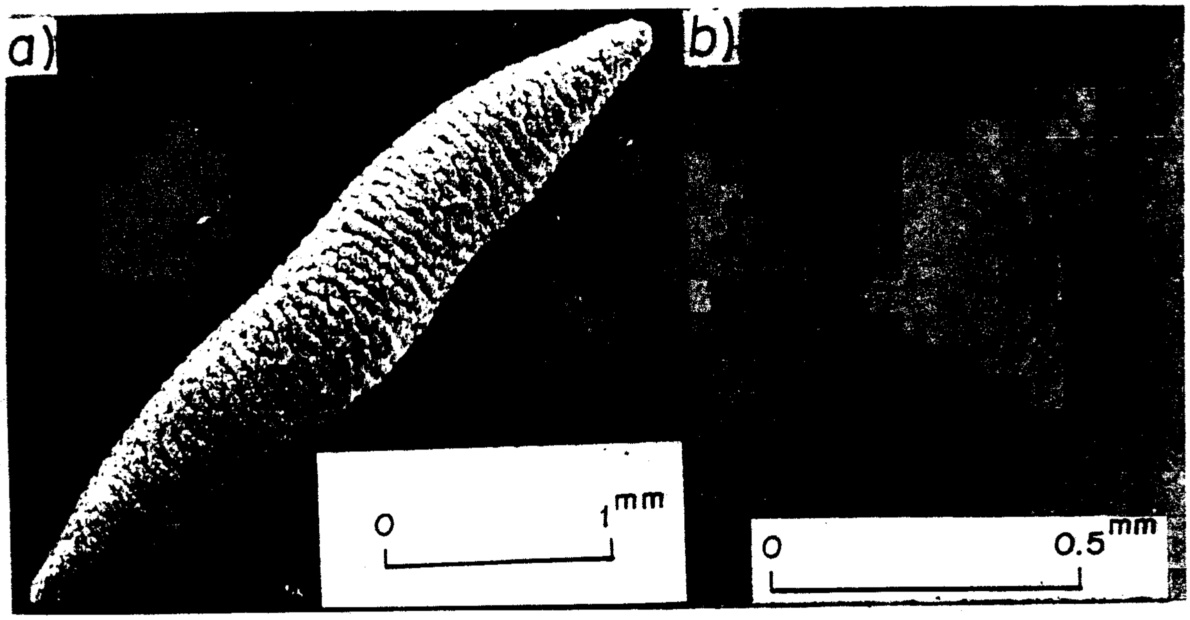
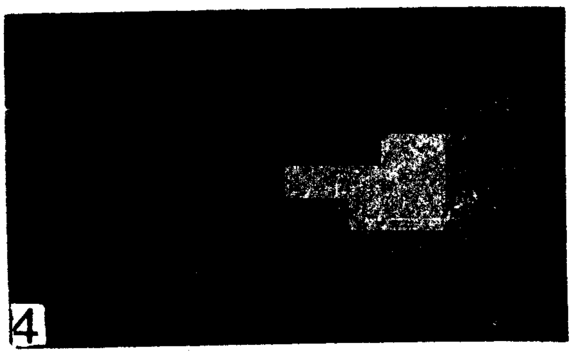


Figure 2. Spindle-like spicule of *Sinularia*. a. Surface view (SEM). b. cross section.



Figures 3 and 4. 3. Partial longitudinal section of a *Sinularia* colony. Arrow points at the contact between the basal, consolidated spiculite and the upper stalk. 4. Outcrop surface view of 'alcyonarian spiculite'.

and overlapping crystallites forming felt or a fan-shape to fill extensively the interspicular pores (Fig. 5). The second, less common type of the aragonite cement, forms botryoids (Ginsburg and James 1976) grown from the points of the spicular surface. These are characteristically outlined with pale brown color under plane polarized light, concentrically multi-layered and composed of radiating needles.

Magnesian calcite cement occurs as an isopachous band composed of bladed spar crystals rimming the surface of the botryoidal aragonite. Some large crystallites apparently forming bladed spars perpendicular to the surface of spicules may also be magnesian calcite. Micrite cement of magnesian calcite supposedly common in submarine cement has not been identified in the alcyonarian spiculite from living stalk. The fossil spiculite from both the subsurface and surface samples of the Late Holocene indicates that the intergranular pores left after the initial submarine cementation are later (probably after the death of colony) infilled with carbonate mud of silt-sized peloids composed of micritic magnesian calcite, together with accidental contaminants of intraclast and terrigenous grains.

The cementation plays the major role in protecting the spindles from the post-mortem dispersion and in preserving them as a solid limestone of the unmixed origin. Otherwise, the separate spindles would be scattered, eroded and mixed with other allochem grains, and never localized to become spiculite. Lowenstam (1964) reported that, while the spicules of a gorgonacean (suborder Holaxonia) are

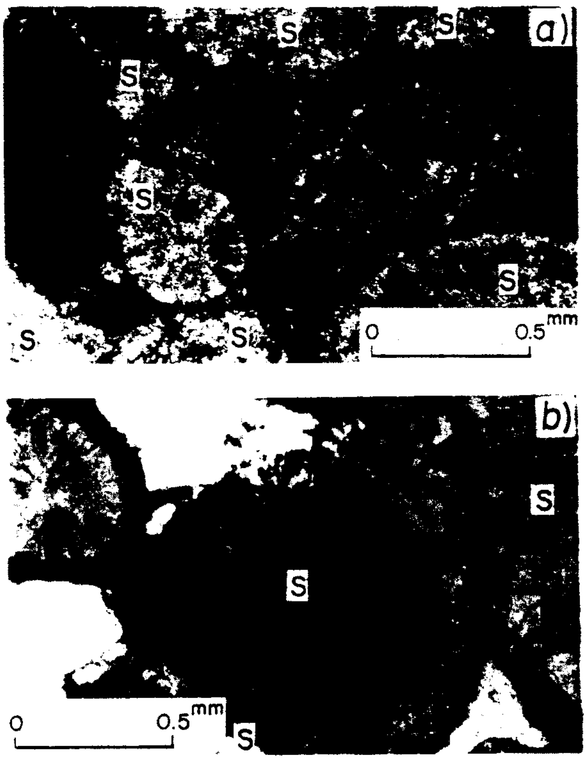


Figure 5. Types of submarine carbonate cements in alcyonarian spiculite. a. mesh of needles. b. botryoid. *s*, spicule.

calcitic, the carbonate in its basal part cemented with substratum consists of varying ratios of aragonite to calcite as a function of water temperature in the habitat. As pointed out by Bathurst (1975), these mineralogical data are for bulk samples and their anatomical distribution is unknown. If this aragonite precipitates inorganically as interspicular cement, the circumstance resembles the case of the *Sinularia* spiculite. As far as the *Sinularia* spicules on hand are concerned, aragonite decreases from the basal spiculite to the coenenchyme of the stalk within the same colony, but does not vary in the basal spiculite regionally between the subtropical Ryukyus and tropical Micronesia.

The fossil alcyonarian spiculite occurs commonly in the Quaternary reef limestones of the Ryukyu Islands. In Kikai-jima, the rock appears to be confined to the Upper Reefoid Member (younger than 4000 y B.P. in ^{14}C age) of the Holocene Raised Coral Reef, as observed at seven horizons in the multi-hole drilling (Fig. 6). The maximum thickness here was 22 cm (between 2.09 m and 2.31 m in depth) in the borehole No. 10. An identical spiculite was found in the Iribishi Limestone (Late Holocene) of Kume-jima (Oshiro, pers. comm.). The older examples have been found from Hateruma-jima; they are of Late Pleistocene (120 ky. in $^{226}RA/^{238}U$ age) and of Middle Pleistocene (220 ky. in $^{226}Ra/^{238}U$ age).

A short borehole drilled through the present-day reef-flat at the Eastern Agana Bay, Guam also has recovered a 25 cm-thick layer (3470±100 y.B.P. in

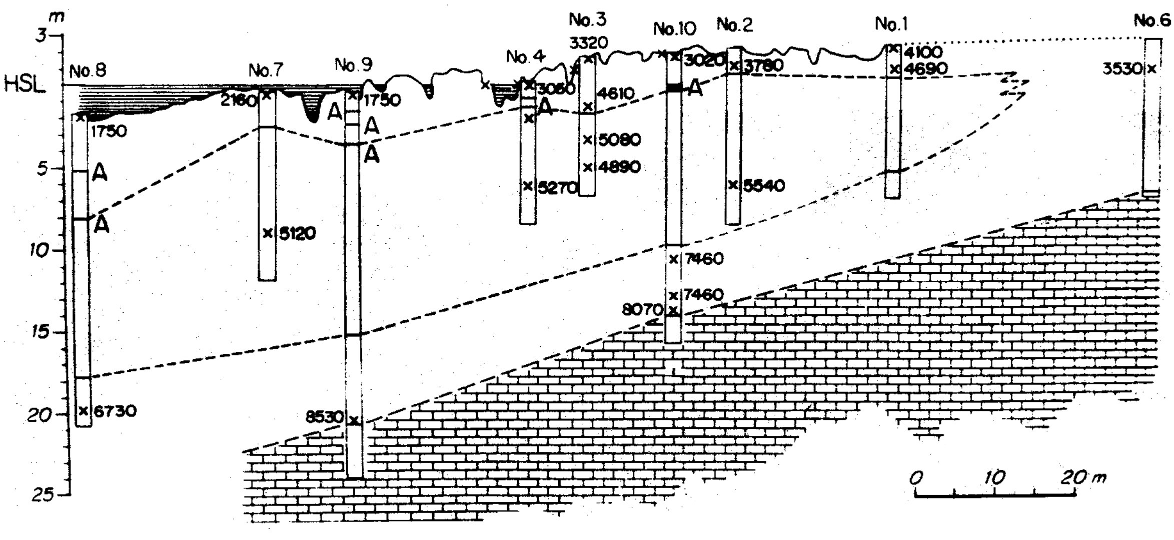


Figure 6. Borehole stratigraphic cross section showing seven horizons (marked with A) of alcyonarian spiculite in the Upper Reefoid Member of the Holocene Raised Reef Limestone of northwestern Kikai-jima; number of four figures next to X marks represent radiocarbon date (yrs B.P.).

^{14}C age) of the alcyonarian spiculite at the interval between 2.82 m and 3.07 m in depth. In addition to the classic locality at the Utelei fringing reef of Tutuila (American Samoa) (Cary 1931), these Ryukyuan and Micronesian records of the alcyonarian spiculite from the Holocene borehole stratigraphy may imply not only its ubiquitous distribution, but also its importance as a reef-forming limestone in the Indo West-Pacific.

PALEOENVIRONMENTAL IMPLICATION

The living species of the zooxanthellae-bearing *Sinularia* have been known only from the tropical and subtropical reefs realm of the Indo-Pacific Province (Fig. 7). Of the 87 species described, 11 species and 1 subspecies have been described from the Ryukyu Islands (Utinomi 1977). Species of the reef-dwelling *Sinularia* appear to thrive on the very shallow subtidal bottom (less than several meters below low tide) both in front of the reef crest and along the boat channels or grooves in the Ryukyus and Micronesia. Certain species are also not uncommon in tidal ponds on the reef flat as well as in moats behind the reef flat. Because of the ubiquitous distribution in the subtropical and tropical of the Indo-west-Pacific and their depth of occurrence from intertidal to very shallow reef front edge (less than 10 m in depth), the recognition of the *Sinularia* or similar alcyonariidean spiculite facies in a given shallow carbonate build-up of the geologic column may be useful location of ancient reef structure.

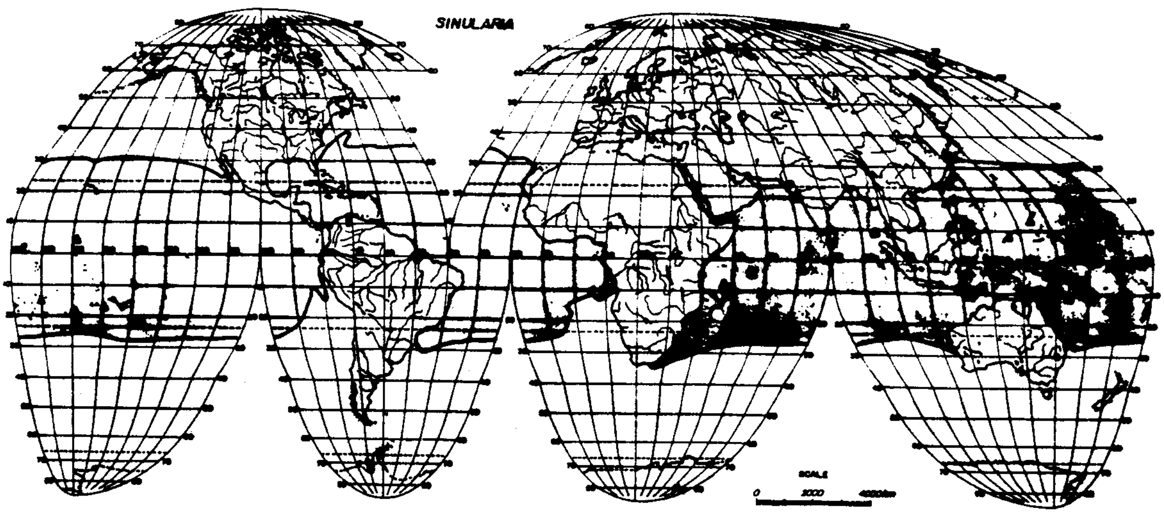


Figure 7. Map showing the reported localities of present-day *Sinularia* species in the Indo-Pacific Province; the shaded area is defined by the 25°C isotherm. Modified from Tixier-Durivault (1951) with later data (Tixier-Durivault 1953, 1966, 1969, 1970; Utinomi 1956, 1977; Verseveldt 1970, 1971, 1972, 1974, 1977, 1978, 1979).

CONCLUSIONS

1. In general, soft coral spicules freed post-mortemly from decaying tissues contribute no more than one % of the unconsolidated carbonate sediments.
2. Unique exceptions are rocks forming the basal stalk of *Sinularia* (Alcyonariidae) and exclusively composed of spicules; they are "alcyonarian spiculite".
3. They become consolidated through in situ submarine cementation, while the upper soft parts are still living. This cementation plays the prime role of protecting the spicules from dispersion and concentrating them for lithification into rocks of uniform origin.
4. Fossil equivalents occur commonly in the Quaternary reefs of the Indo-west-Pacific (American Samoa, Ryukyus, and Micronesia) and locally build reef-forming limestone.'
5. Their distribution is ubiquitous in the subtropical and tropical regions but is limited to very shallow depth which indicates their usefulness for identification and reconstruction of ancient reef environments.

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Postscript: After this manuscript was submitted, the author received the following two papers related to the alcyonarian spiculite:

Bengtson, S. 1981. *Astractosella*, a Silurian alcyonacean octocoral. J. Paleont. 55: 281-294.

Montaggioni, L. 1980. Alcyonarian spiculite in coral reefs. Résumes. 26e Congr. Geol. Intern. (Paris) 11 Sec. 6á12: 521.