# Mapping, habitat characterization, and fish surveys of the deep-water *Oculina* coral reef Marine Protected Area: a review of historical and current research

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**Abstract.** Deep-water *Oculina* coral reefs, which are similar in structure and development to deep-water *Lophelia* reefs, stretch 167 km (90 nm) at depths of 60-100 m along the eastern Florida shelf of the United States. These consist of numerous pinnacles and ridges, 3-35 m in height, that are capped with thickets of living and dead coral, *Oculina varicosa*. Extensive areas of dead *Oculina* rubble are due in part to human impacts (e.g., fish and shrimp trawling, scallop dredging, anchoring, bottom longlines, and depth charges) but also may be due in part to natural processes such as bioerosion, disease, or global warming. In the 1970s, the reefs were teeming with fish. By the early 1990s, both commercial and recreational fisheries had taken a toll on the reefs, especially on the coral habitat and populations of grouper and snapper. In 1984, 315 km$^2$ (92 nm$^2$) was designated the *Oculina* Habitat of Particular Concern (OHAPC), prohibiting trawling, dredging, bottom longlines and anchoring, and establishing the first deep-sea coral marine protected area in the world. In 2000, the *Oculina* Marine Protected Area (MPA) was expanded to 1029 km$^2$ (300 nm$^2$). Despite these protective measures, manned submersible and ROV observations in the *Oculina* MPA between 1995 and 2003 suggest that portions of the coral habitat have been reduced to rubble since the 1970s, grouper spawning aggregations may be absent, and illegal trawling continues. This paper

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is a review of the results of the mapping, habitat characterization, and fish surveys from the early historical studies (1960-1980s) to the more recent surveys (1995-2003).

**Keywords.** *Oculina*, *Lophelia*, deep-water, coral reef, Marine Protected Area

## Introduction

Two types of deep-water coral reefs, formed principally by the framework constructing species of scleractinian corals, *Oculina varicosa* and *Lophelia pertusa*, occur off the southeastern United States. Deep-water *Oculina* reefs grow at depths of 60-100 m and are only known off central eastern Florida, whereas *Lophelia* reefs in this region occur at depths of 490-870 m from North Carolina to Florida. Both types, however, consist primarily of a single species of azooxanthellate coral, occur in areas of strong currents or zones of upwelling, and form high-relief mounds and pinnacles. Both provide essential habitat for diverse communities of fish and invertebrates (Reed 2002a, b). Deep-water coral reefs have recently gained considerable attention as fisheries expand to deeper habitats. Unfortunately few deep-water reefs have been mapped and little is known regarding the ecology of these diverse and fragile ecosystems.

The *Oculina* reefs are the first deep-water coral reefs in the world to be designated as a marine protected area. The first management plan for these reefs, enacted in 1984 by the South Atlantic Fishery Management Council, banned bottom trawling, bottom longlines, and anchoring in a 315 $km^2$ (92 $nm^2$) portion of the *Oculina* reef system (NOAA 1982). The *Oculina* Marine Protected Area (MPA) was expanded in 2000 and now encompasses 1029 $km^2$ (300 $nm^2$; Fig. 1).

The deep-water *Oculina* reefs were first described in the 1960s (Moe 1963; Macintyre and Milliman 1970) from dredge and camera drops and from surveys of commercial fisheries. The first detailed submersible surveys describing the reefs began in the 1970s (Avent et al. 1976, 1977; Avent and Stanton 1979; Reed 1980). These were followed by a sidescan sonar survey on a small portion of the bank system (Thompson et al. 1978; Thompson and Gulliland 1980). From 1975 to 1985, various studies followed: coral growth rates, biodiversity of associated invertebrates and fish, and geology (Reed 2002a). Unfortunately over the following years, poaching by illegal shrimp trawlers and fishing pressure resulted in the collapse of the grouper and snapper fish populations as well as considerable damage to the coral habitat (G. Gilmore, J. Reed, personal observations; Koenig 2001; Koenig et al. 2004).

Recent surveys (1995 to present) of the *Oculina* MPA characterized the condition of the coral habitat and fish populations in the only MPA on the U.S. east coast. These surveys have been sponsored largely by the National Oceanic and Atmospheric Administration (NOAA). This paper reviews the results of the mapping, habitat characterization, and fish surveys from the historical studies (1960-1980s) to the more recent surveys (1995-2003).

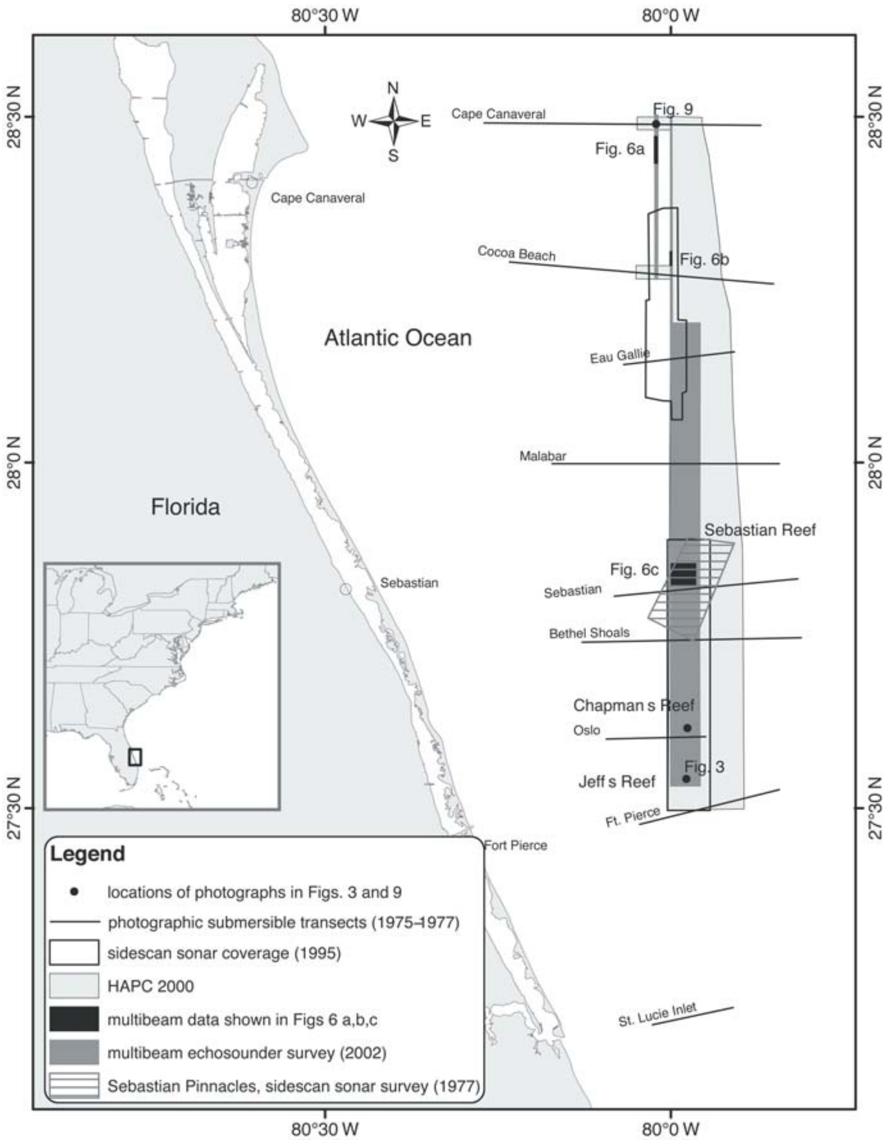



**Fig. 1** Light shaded area: 1029 $km^2$ (300 $nm^2$) deep-water *Oculina* Marine Protected Area (MPA) off eastern Florida. The original 315 $km^2$ (92 $nm^2$) *Oculina* Habitat of Particular Concern (OHAPC) that was designated in 1984 (also known as the Experimental *Oculina* Research Reserve) is indicated by the boxed area (1995 sidescan sonar coverage) that extends from the Sebastian Reef area to the south at the Ft. Pierce transect line

## Methods

### Historical surveys

#### *1960s dredge and commercial fish surveys*

Moe (1963) first described some of the shelf-edge features off eastern Florida based on interviews with commercial fishermen. Macintyre and Milliman (1970) surveyed the physiographic features of the shelf-edge break (80-110 m) from Cape Hatteras, North Carolina (35°N) to Ft. Lauderdale, Florida (26°N) using echosounder profiles, rock dredge, sediment samples, and bottom photographs. Information on coral distribution was also summarized from 57 dredge and trawl records from the R/V *Gosnold* and R/V *Aquarius* between 1973 and 1977 (Reed 1980).

#### *1977 sidescan sonar survey*

The Sebastian Pinnacle site (110 $km^2$), within the region now designated as the *Oculina* MPA, was mapped in 1977-78 using a Klein Series 400 sidescan sonar and echosounder (fathometer) tracings (Fig. 1; Thompson et al. 1978; Thompson and Gulliland 1980). LORAN C was used for positioning which had navigational accuracy in this region of ±36 m in the east-west direction and ±850 m north-south. The fathometer had a vertical resolution of 0.25-1.0 m. Bathymetric maps were plotted with 1 m isobath contours.

#### *1975-1983 submersible and ROV surveys*

Between 1975 and 1983, data were compiled in the region of the deep-water *Oculina* banks using Harbor Branch Oceanographic Institution's (HBOI, Harbor Branch Foundation) *Johnson-Sea-Link* (*JSL*) I and II submersibles and *CORD* Remotely Operated Vehicle (ROV). These data included photographs, videotapes, cruise reports, logs, dive transcripts, hydrographic data, and collections by lockout dives from the submersibles.

From 1975 to 1977, a benthic survey consisting of 12 east-west photographic transects was made with the *JSL* submersibles at the shelf-edge break within the region that is now designated as the *Oculina* MPA (Fig. 1; Avent et al. 1976; Avent and Stanton 1979). The transects were spaced approximately 19 km apart, extended to 300 m depth, and consisted of 55 submersible dives covering 298 km. It was during this survey that the live deep-water *Oculina* banks were first observed and described in detail (Avent et al. 1977). Navigation used LORAN-A which in this region had an accuracy of ±150-300 m. Photographs were taken every 1-2 minutes during each transect and analyzed using a microfilm reader with a grid overlay for estimating percent cover. Photographic data along with hydrographic and navigation information were entered into a computer database (unfortunately the computer tapes are obsolete, but hard copies and photos are archived at HBOI).

*JSL* dives and echosounder recordings were also conducted from 1979 to 1983 for biological and geological studies within the area of the *Oculina* MPA (C. Hoskin, J. Reed pers. observations; see Reed 2002a). In addition, a time-lapse camera was deployed to document the reef community over several 48-hour periods. Extensive surveys of the fish populations and fish behavior were made concurrently between 1975 and 1983 (G. Gilmore pers. comm.; Gilmore and Jones 1992).

Tethered, mixed-gas dives (lockout) were made with the *JSL* submersibles from 1976 to 1983 on the deep-water *Oculina* banks for studies on biodiversity of animals associated with the coral, coral growth rates, and geology (Fig. 2; Reed 2002a). The scientist-lockout diver used a Kirby-Morgan band mask attached to a 30 m umbilical hose which supplied the gas mix (10 % oxygen / 90 % helium) and voice communications from the submersible.

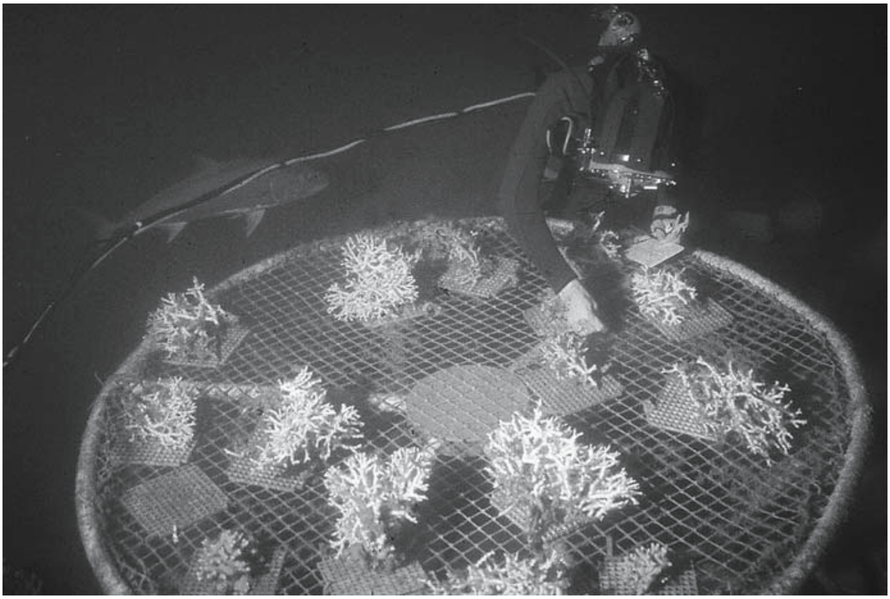


**Fig. 2** Tethered, mixed-gas dives (lockout) were made with the *Johnson-Sea-Link* submersibles from 1976 to 1983 on the deep-water *Oculina* reefs for studies on biodiversity of animals associated with the coral, coral growth rates, and geology (Jeff's Reef, 80 m depth)

## Videotape and photographic archives

Some of the original videotapes (3/4" and 1/2" open reel) and 30 m rolls of 35 mm Ektachrome film are currently in the process of being restored and archived. Unfortunately videotapes of that age are prone to hydrolysis problems. The restoration process stabilizes the polymers of the tape coating. Once stabilized the tapes will be restored and archived onto Beta SP videotapes and copied to digital video disk (DVD) for analyses. The 35 mm photographs will be digitized with a Nikon LS-2000 scanner and copied to DVD. Plans are to analyze these historical tapes and images for comparison with recent mapping and habitat characterization surveys.

## Recent surveys

Most of the recent surveys (1995 to present) of the *Oculina* MPA are a series of continuing research projects to characterize the condition of the coral habitat and fish populations. These surveys have been sponsored largely by NOAA's National Marine Fisheries Service (NMFS), NOAA's National Undersea Research Center at the University of North Carolina at Wilmington (NURC/UNCW), and NOAA's Ocean Service (NOS).

### *1995 sidescan sonar survey*

In 1995, the U.S. Geological Survey, using the NOAA ship *R/V Chapman,* conducted a 100-kHz sidescan sonar survey covering 206 $km^2$, and approximately 20 % of the *Oculina* MPA (Fig. 1; Scanlon et al. 1999). The goal was to provide reconnaissance geologic maps of the Experimental *Oculina* Research Reserve (EORR; equivalent to the original 315 $km^2$ *Oculina* MPA) and an unprotected Control Area north of the reserve (now part of the current 1029 $km^2$ *Oculina* MPA) to support NMFS studies of grouper populations.

### *2002 multi-beam echosounder survey*

In 2002, a multi-beam echosounder survey from NASA's *M/V Liberty Star*, provided the first high-resolution (1.5-3.0 m) bathymetric map of the coral habitat in the *Oculina* MPA and covered 295 $km^2$, approximately 29 % of the MPA (Fig. 1). Seafloor Systems Inc., Oregon, performed the survey using a 240-kHz RESON 8101 multi-beam echosounder system integrated with the ship's Differential Global Positioning System (GPS) unit, a DMSO 5 TSS motion sensor (quantifies heave, pitch, and roll), a SG Brown gyrocompass (yaw), and HYPACK navigation. All data were compiled in real-time using an ISIS Shipboard Data Acquisition and Image Processing System. Conductivity, temperature and density (CTD) casts were made every six hours. Raw data were post-processed in CARIS software to remove outliers and correct for sound velocity and tidal stage.

### *1995-2003 ROV and submersible surveys*

NOAA/NURC's *Phantom S4* ROV and *Spectrum II* ROV, and HBOI's *Clelia* submersible were used for habitat and fish surveys in 1995, 2001, and 2003. These surveys covered approximately 1.13 $km^2$, or 0.11 % of the *Oculina* MPA. The ROVs and submersible were equipped with digital still cameras and color video cameras with parallel lasers to indicate scale in the images. Objectives included: (1) survey high-, moderate- and low-relief areas to document the various habitats including live coral thickets, dead coral rubble, and hard bottom, and (2) revisit historical sites identified in the 1970s to document any changes in habitat. In 2003, the position of the ship and ROV were overlaid on the 2002 multi-beam map which allowed precise targeting of specific features for exploration during the dives.

### *Oculina geographic information system (OGIS)*

A multi-media geographic information system (GIS) has been developed to allow access and comparison of past and present data in the *Oculina* MPA. Portions of

OGIS are available *via* the Internet for use by resource managers and stakeholders (http://www.uncw.edu/oculina). Georeferenced digital photographs and logs from submersible dives complete the multi-media component of OGIS.

## Results and discussion

### Historical surveys

#### *1960s dredge and commercial fish surveys*

Moe (1963) first described the shelf-edge region of Cape Canaveral to Fort Pierce, Florida from interviews with commercial fishermen. “The Peaks” at depths of 35 to 65 fathoms (64-119 m) were described as highly irregular coral rock with many peaks and ledges up to 50 fathoms (91 m) high in places and a fishery composed of red and vermilion snapper, red grouper, and trigger fish.

Macintyre and Milliman (1970) described the shelf-edge features from north Florida to north Palm Beach as relict oolitic ridges or dunes formed during the Holocene transgression and covered by modern *Oculina* sp. coral debris. Radiocarbon ages of two samples of oolitic limestone were 13,730 years and 9,620 years B.P. Macintyre and Milliman (1970) stated that the oolitic sediments were apparently deposited and built into mounds during the Holocene transgression and that the 80 m deep oolitic ridge corresponded to the depth of submerged terraces elsewhere in the Caribbean and may indicate a still stand in the rising post-Pleistocene sea level (Fairbanks 1989).

#### *1977 sidescan sonar survey*

Sidescan sonar surveys from 1977 to 1978 produced three high-definition contour maps of a 110 km$^2$ portion of the Sebastian Pinnacles which is a small subset of the region now designated as the *Oculina* MPA (Fig. 1; Thompson et al. 1978; Thompson and Gulliland 1980). They described the region as topographically consisting of bifurcating ridge complexes, irregular knolls, cones, multi-peaked hills, and crater-like depressions. The maps also showed a series of 15 prominences along the 79°59'W meridian from 27°32'N to 28°02'N; many had ridges oriented E-W to SE-NW.

#### *1975-1983 submersible surveys*

Reed (1980) described the *Oculina* banks from a compilation of a total of 157 submersible dives (including the Avent dives) and 57 dredge and trawl records. This study described the extensive area of unique deep-water *Oculina* coral reefs which stretches over 167 km (90 nm) along the shelf edge off eastern Florida, at depths of 60-100 m, and ranges from 32 to 68 km offshore (Reed 1980; Thompson and Gilliland 1980). These extend from 27°32'N to 28°59'N latitude, along the western edge of the Gulf Stream (Florida Current).

Deep-water *Oculina* banks are found exclusively here and are not known to exist anywhere else on earth. A single species of azooxanthellate scleractinian coral, *Oculina varicosa* Lesueur, 1820, forms these reefs. Individual colonies, up to 2 m in diameter, grow as discrete, branched, spherical heads that coalesce into thickets. The reef system consists of numerous individual coral pinnacles, mounds, and ridges that are low- to high-relief structures, ranging from 3 to 35 m in height and 100-300 m in width (Reed 1980).

### High-relief Oculina banks and thickets

In general, the high-relief banks and larger thickets of *Oculina* coral occur in a zone ~6 km wide, paralleling the 80° meridian. In addition to the high-relief pinnacles, coral thickets which consist of 3-4 m linear colonies or groups of 1-2 m diameter colonies are also common on flat sandy bottom or on low-relief limestone outcrops (Reed 1980).

Reed (1980) described the southernmost *Oculina* bank discovered to date at 27°32'N, known as Jeff's Reef and named after the *JSL* submersible pilot Jeff Prentice (Fig. 1). This is an isolated *Oculina* bank, ~300 m in width and somewhat rectangular in shape, that consists of three parallel ridges running approximately E-W, with a minimum depth of 64 m at the crest and 81 m at the base. The south face generally has a steep 30-45° slope and is covered with massive contiguous *Oculina* 1-2 m in height (Fig. 3). In places, the coral colonies form linear E-W oriented rows, 2-3 m in width, that form step-like terraces up the slope. The three ridge crests are covered with live coral 1-2 m in height. The north slope is less steep (<25°) and

**Fig. 3** South slope of Jeff's Reef, a 17 m high *Oculina* coral reef (80 m depth)

has scattered 0.5-2.0 m diameter colonies and more extensive coral rubble. This site appears relatively intact in recent surveys. In 1982, Reed discovered 14-20 m high pinnacles as far north as 28°59.2'N, 80°06.6'W at depths of 79-84 m. These are the northernmost *Oculina* pinnacles discovered to date, and appear to have more exposed rock than the pinnacles south of Cape Canaveral, but also have scattered thickets of live *Oculina*.

During a lockout dive from the *Johnson-Sea-Link* submersible, a 22-cm long, 6-cm diameter core taken from about half way up the flank of the bank sampled a piece of coral rubble with a radiocarbon age of 480 ±70 yr B.P. (Reed 1981; Hoskin et al. 1987). The age of the mound, extrapolated from this and from coral growth rates (1.6 cm $yr^{-1}$; Reed 1981), was estimated to be 1000 to 1500 years old. It is postulated that the base of these reefs would have been exposed ~18,000 years ago during the last glacial maximum when sea level was 100-125 m below present (Fairbanks 1989).

### *Isolated colonies and rubble areas*

In addition to the high-relief *Oculina* banks and low-relief coral thickets, Reed (1980) further described over 50 sites within the area now designated as the *Oculina* MPA that had sparsely scattered live *Oculina varicosa* colonies from 0.25 to 2.0 m diameter. These were found in areas ranging from low to high relief, including flat sand bottom, limestone pavement, and limestone knolls with 1-2 m relief. Some of the high-relief *Oculina* banks that were mostly dead coral rubble also contained sparse live coral.

Between 27°45'N and 27°52'N, the majority of coral banks in the zone of dense high-relief pinnacles were covered with dead *Oculina* rubble (Fig. 4). This Sebastian Pinnacle site is the same area mapped in part by the 1977 sidescan sonar survey (Thompson et al. 1978). The submersible surveys found that some of these prominences had scattered, live coral colonies, less than 1 m diameter, covering up to 10 % of the bottom while other banks in this region appeared to be 100 % dead coral rubble. The dead coral fragments were less than 10 cm in length, but in some places standing dead colonies less than 0.5 m in diameter were present (Reed 1980; Hoskin et al. 1987).

### *Fish populations*

Surveys of fish populations and grouper behavior were conducted concurrently with the above submersible habitat and coral studies from 1976 to 1983 (G. Gilmore, R. Jones pers. observations). The deep-water *Oculina* reefs formed impressive breeding grounds for commercially important populations of snapper (*Lutjanus* spp.) and grouper (Serranidae), and dense populations of gag (*Mycteroperca microlepis*) and scamp (*M. phenax*) grouper were common (Fig. 5A; G. Gilmore pers. observations; NOAA 1982; Reed 1985; Reed and Hoskin 1987; Gilmore and Jones 1992; Reed 2002a). Scamp were seasonally abundant, forming dense spawning aggregations of several hundred individuals per hectare (Gilmore and Jones 1992).

**Fig. 4** Peak of *Oculina* reef covered with dead coral rubble (Sebastian Pinnacles, 60 m depth)

## Recent surveys

### *1995 sidescan sonar survey*

A sidescan sonar survey by Scanlon et al. (1999) characterized habitat for portions of the *Oculina* MPA into three principal types. 1) High-relief/high-backscatter (HR/HB) areas constitute very rough terrain that is concentrated along the 80 meter isobath and comprises about 3 % of the total area enclosed in the EORR (the original 315 $km^2$ *Oculina* HAPC). Portions are isolated peaks with relief up to 30 m. Two large, elongate areas of multiple peaks, ledges, and outcrops occur in the northern portion of the EORR and the northern portion of the Control Area. 2) Low-relief/high-backscatter (LR/HB) areas generally surround HR/HB areas, in 70-90 m depth, but with less than 1 m relief. 3) Low-relief/low-backscatter (LR/LB) areas are generally seaward and landward of the high-relief areas and between the isolated peaks where the seafloor appears to be smooth and is covered by sand and muddy sand. The habitat map derived from these data is included in OGIS.

### *2001 ROV and submersible-habitat surveys*

Seven ROV line transects were made over 7.6 km of high-relief pinnacles and ridges (habitat types 1 and 2, described above) in the EORR. Koenig et al. (2004) reported that 464 m (6 %) of the transects contained dense coral cover, 302 m (4 %)

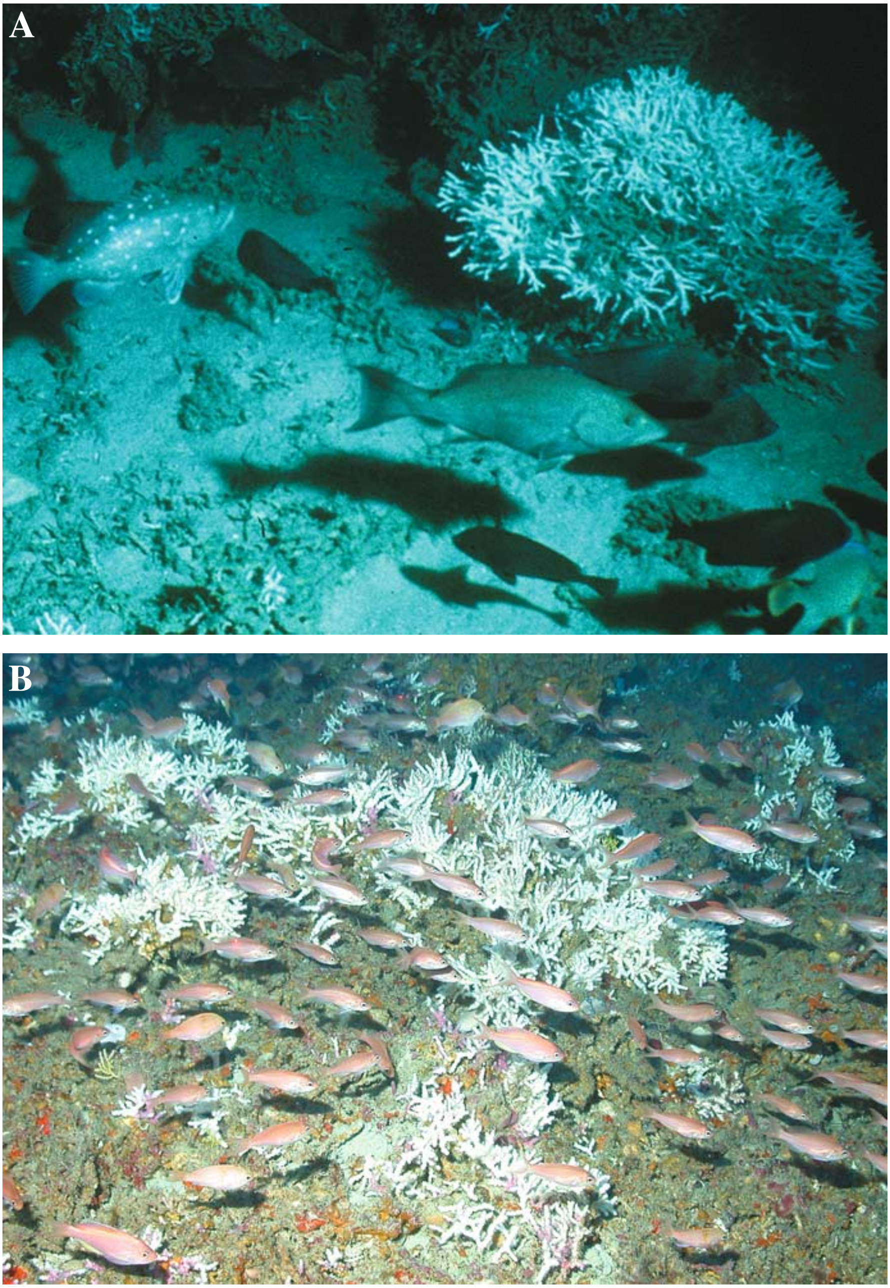



**Fig. 5 A** Schools of scamp and gag grouper were abundant on deep-water *Oculina* reefs in 1970s and 1980s (Jeff's Reef, 70 m depth); **B** Healthy *Oculina varicosa* coral colony with associated schools of anthiid fish in 2003 (Sebastian Pinnacles, 80 m depth)

contained sparse cover, and 6,877 m (90 %) contained primarily rubble which provides little to no fish habitat.

Koenig et al. (2004) also conducted 16 submersible transects within the EORR at three high-relief *Oculina* coral bank sites (Jeff's Reef, Chapman's Reef West, and Sebastian Reef), and described four habitat types: intact live coral, intact dead coral, coral rubble, and bare rock and sand. Intact live coral thickets occurred on Jeff's Reef and Chapman's Reef West within this survey. Mean live coral coverage ranged from 7 % to 22 %. Coral colony diameter ranged from 8 to 143 cm, with a mean of 47.4 cm (SE = 4.75 cm, n = 43).

Results from the 2001 expedition suggest that within the limited area surveyed (about 0.002 % of the *Oculina* MPA) considerable portions of the *Oculina* habitat consist of unconsolidated coral rubble. Only about 8 hectares (20 acres) of fully intact *Oculina* thicket habitat were documented within this survey. Unconsolidated rubble is the major habitat type on the high-relief features within the Sebastian Pinnacle region.

### 2002 multi-beam echosounder survey

During eight survey days in 2002, approximately 1704 km of multi-beam echosounder system (MBES) surveys were completed, covering 295 $km^2$ (~29 % of the total *Oculina* MPA; Fig. 6). The resulting bathymetric map, included in OGIS, was instrumental in dive site selection and in directing the ROV tracks during the 2003 ROV mission described below.

### 2003 ROV-habitat survey

During this survey, ROV dives were conducted throughout the *Oculina* MPA (Shepard and Reed 2003). Prior to the mission, 30 dive areas were overlaid on the 2002 multi-beam chart targeting the following sites: 1) new sites within and outside the *Oculina* MPA that were never explored previously; 2) sites that had not been explored since submersible dives from 1975-1983; 3) artificial reef and restoration experiments; and 4) a variety of habitats and features based on the multi-beam chart, e.g., high-relief pinnacles and associated scours, moderate-relief ledges and plateaus, and low-relief bottom.

Overall, 23 ROV transects at 20 dive stations produced 40 hr of videotape, 2200 digital still photos (Fig. 5B), and covered approximately 65 km (35 nm) of bottom. Areal coverage was ~0.194 $km^2$ (65 km x 3 m width transects), or ~0.02 % of the entire 1029 $km^2$ *Oculina* MPA. The videotapes and still photographs will be analyzed for habitat type and condition, and fish populations; these data will be added to OGIS. Dive results support conclusions from the 2001 expedition that much has changed during the past two decades, including habitat destruction and significantly reduced populations of commercially and recreationally important fish since the 1970s.

Qualitative observations of note from this survey include:

- Several isolated live *Oculina* thickets within the newly expanded *Oculina* MPA were discovered in previously unexplored regions of low to moderate relief (<2-3 m).

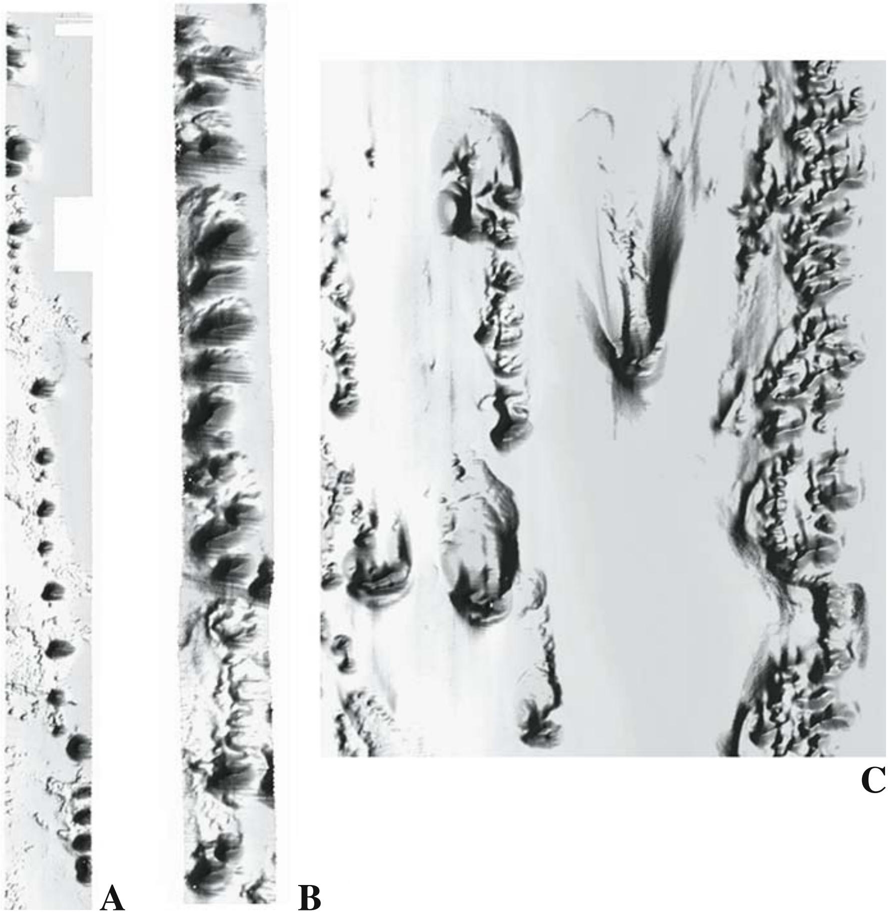



**Fig. 6** Multi-beam images of deep-water *Oculina* reefs from 2002 survey: **A, B** series of high-relief pinnacles recently discovered outside the *Oculina* MPA; **C** high-relief pinnacles within the MPA. Scale- length of maps N-S, **A** = 4.3 km (28°28.32'N to 28°25.95'N and 80°01.46'W to 80°01.15'W), **B** = 2.3 km (28°18.33'N to 28°17.08'N and 80°00.10'W to 79°59.92'W), **C** = 3.5 km (27°51.24'N to 27°49.28'N and 80°00'W to 79°57.83'W)

- Extensive live-bottom areas (primarily hard-bottom, limestone pavement and ledges with live benthos and fish) were documented, including considerable portions of the *Oculina* MPA that appeared relatively flat in the multi-beam survey. This supports the need to combine depth and backscatter data not completed in the 2002 multi-beam survey due to technical issues.
- Twenty-three high-relief *Oculina* pinnacles were discovered adjacent to but outside of the current boundaries of the *Oculina* MPA (Figs. 6A, B).
- Evidence during both the 2002 and 2003 surveys indicate that rock-shrimp fishers continue to trawl illegally within the *Oculina* MPA and some bottom fishing continues. This included visual sightings of trawlers during the

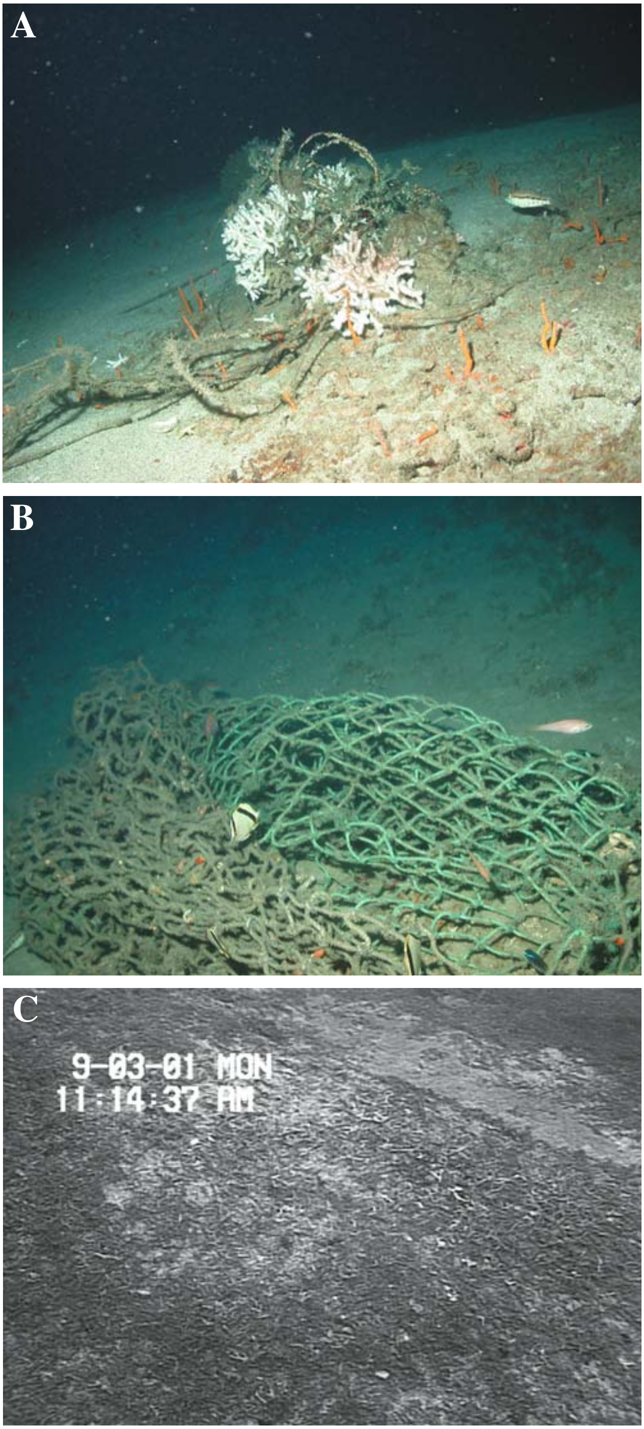
surveys; evidence of recent fishing lines and bottom longlines wrapped around coral colonies and remnants of bottom trawl nets; damaged artificial reef modules; and apparent trawl tracks in the rubble noted near the damaged modules (Figs. 7A-C).

- Many of the high-relief pinnacles are primarily coral rubble of unknown age, but many have small (10-50 cm) colonies of live *Oculina* on their slopes. Many also have live bottom at the base of their flanks where rock pavement, boulders and ledges also provide habitat for fish and epifauna.
- Areas of standing dead coral colonies (10-50 cm diameter) are fairly common on high-relief pinnacles, on low- and moderate-relief pavement and rubble areas, and along the rims of depressions that are probable scour areas at the northern bases of the high pinnacles (Fig. 6C). Historical data from the 1970s and 1980s suggest that many of these corals were alive then, but are now dead from unknown cause(s). Since these corals are standing, the cause of death may be other than trawl-related. However, continued trawling in the area may cause resuspension of sediments and smothering of coral polyps.
- Two types of coral rubble habitat are evident: 1) extensive areas of coral rubble/sediment matrix that provide little apparent habitat for epifaunal growth, relative to standing live or dead coral; 2) structured coral rubble habitat, but without the sediment matrix, which provides some habitat *lebensraum* for epifauna, and is often associated with the flanks and peaks of the high-relief pinnacles.
- Most of the pinnacles that have been explored to date, including the newly discovered pinnacles outside the *Oculina* MPA, are *Oculina* bioherms or mud mounds that may be made entirely of unconsolidated coral rubble and sediment, with varying amounts of live coral capping the slopes and peaks. In general, no rock is observed on the upper slopes or peaks on most of these bioherms; but rock pavement and ledges are present near the bases of some of these pinnacles. This suggests the presence of an underlying rock structure on which these bioherms developed several thousands of years ago.

### *1995-2003 ROV and submersible-fish surveys*

Population densities for the dominant fish species correlated highly with habitat type (Koenig et al. 2000; Koenig 2001; Shepard and Reed 2003; Koenig et al. 2004). Gag (*Mycteroperca microlepis*) and scamp (*M. phenax*), grouper and juvenile speckled hind (*Epinephelus drummondhayi*) were predominately associated with the intact coral habitat. In 1994, a 10-year moratorium on bottom hook-and-line fishing was enacted within the *Oculina* MPA. Although fish populations observed in 2001 and 2003 were not directly comparable to previous surveys in 1995 or 1970s,

**Fig. 7** Damage from fishing gear within *Oculina* MPA: **A** longline fishing gear wrapped around colony of *Oculina varicosa* (Sebastian Pinnacles, 80 m depth); **B** discarded shrimp trawl net (Sebastian Pinnacles, 80 m depth); **C** apparent trawl track at Cape Canaveral Pinnacle site (67 m depth)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there was a noted increase in grouper numbers and size. There was also an increase in the abundance of males of gag and scamp since the 1995 survey, suggesting the possible reoccurrence of spawning aggregations of both species.

Still, very few commercial reef fish (snapper and grouper) were observed in 2003, even after a 10-year moratorium on bottom fishing. The most common fish encountered included: tattler (*Serranus phoebe*), yellow-tail reef fish (*Chromis enchrysurus*), bigeye (*Priacanthus arenatus*), short-bigeye (*Pristigenys alta*), flounder (*Paralichthys* sp.), bank butterfly fish (*Chaetodon aya*), blue angelfish (*Holocanthus bermudensis*), red barbier (*Hemanthias vivanus*), roughtongue bass (*Holanthias martinicensis*), and greater amberjack (*Seriola dumerili*) (Shepard and Reed 2003). The most common larger grouper observed were red grouper (*Epinephelus morio*) and scamp, although a few snowy (*E. niveatus*) and gag grouper were also present. In the 1970s and 1980s, red grouper were not common on the reefs whereas black sea bass (*Centropristis striata*) were abundant and large (50-100 kg) warsaw grouper (*Epinephelus nigritus*) were common (G. Gilmore, J. Reed pers. observations; Reed 2002a). However, neither black sea bass nor warsaw grouper were observed on any of the recent ROV or submersible dives.

### *Artificial reef restoration experiments*

Surveys also included artificial reef restoration experiments that consist of clusters of 1 m diameter, hollow, concrete domes which were placed in rubble areas of the *Oculina* MPA in 2000 and 2001 (Figs. 8A, B; Koenig 2001; Koenig et al. 2004). The reefballs were constructed to simulate the size and aspect of *Oculina* coral colonies and serve as coral larval recruitment surfaces and structure for reef fish. Gag, scamp and snowy grouper were observed to associate with the reefball clusters. Several artificial reef blocks (~1 m x 1 m aggregates of concrete blocks) that were deployed in 1998 were also revisited in 2003 (Shepard and Reed 2003). Numerous small colonies (1-10 cm) of *Oculina* were photographed growing on the blocks providing additional data on growth rates and evidence of settlement by planula larvae (Brooke and Young 2003). Estimates of the minimum growth rate for the larger corals on the reef blocks was 1.6 to 2.0 cm $yr^{-1}$, which is similar to previous studies by Reed (1981, 2002a).

## Summary and conclusions

Since these deep-water *Oculina* reefs were first discovered and described, irreparable habitat damage and decimated fish populations have occurred (Koenig 2001; Koenig et al. 2004). Recent ROV and submersible surveys have confirmed the evidence of continued poaching by shrimp trawlers and fishers within the *Oculina* MPA. Bottom trawl nets, bottom longlines, and fishing lines are evident on the bottom.

Although the *Oculina* reefs were the first deep-water coral reefs in the world to be designated as a marine protected area, the protection given in 1984 only extended to <30 % of the reef system. Since then, shrimp bottom trawlers were allowed to continue trawling in the northern sector of the reefs until 2000 when the boundary

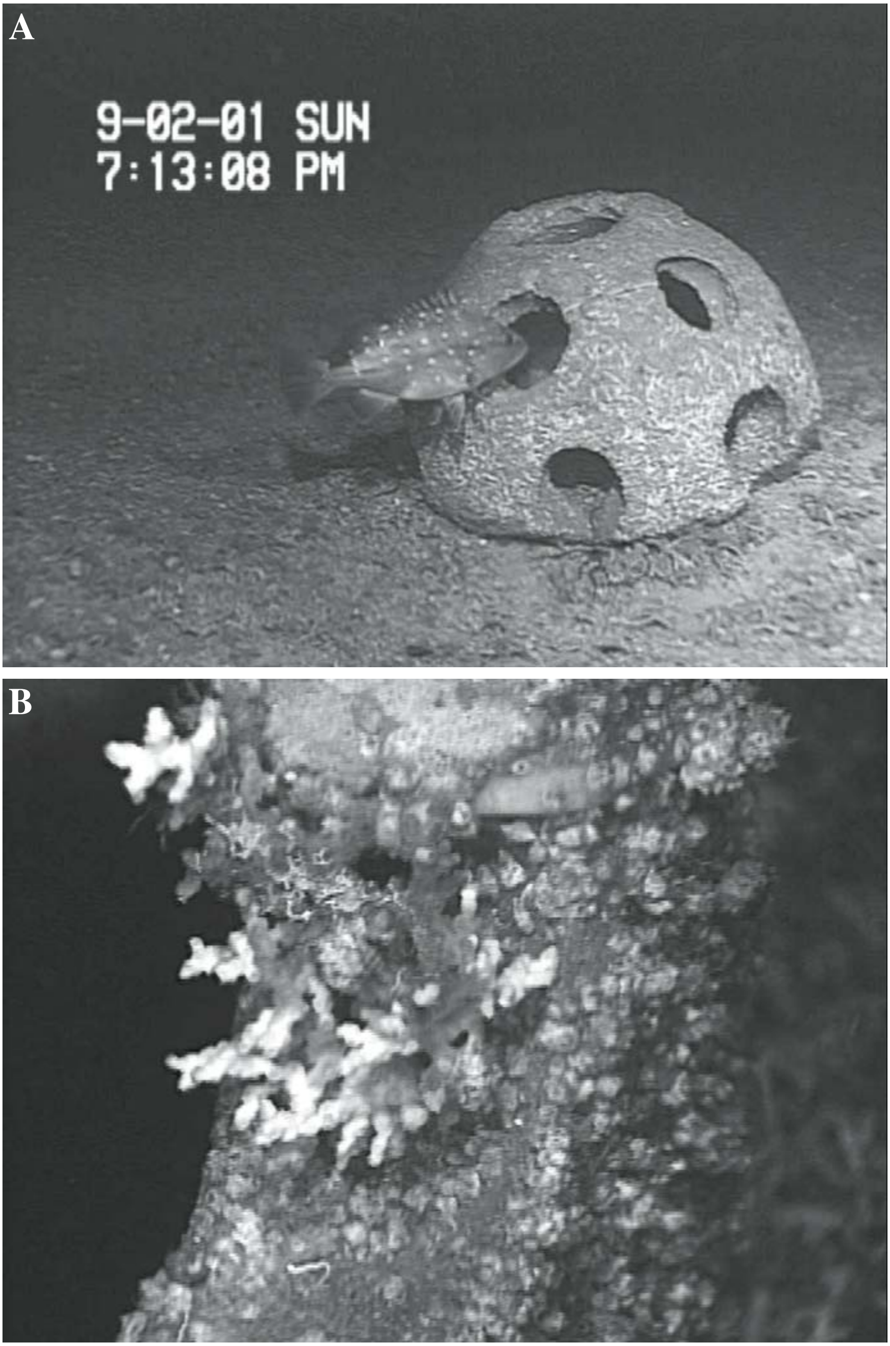


**Fig. 8** Reefballs deployed within Sebastian Pinnacles of *Oculina* MPA: **A** reefball with snowy grouper (80 m depth); **B** close-up of *Oculina varicosa* coral growing on reefball (80 m depth)

of the *Oculina* MPA was extended to Cape Canaveral. Even this does not cover the extent of the known deep-water *Oculina* habitat. The 2002 multi-beam survey and the 2003 ROV video transects revealed a series of high-relief *Oculina* bioherms that extend over a linear distance of 22 km just outside the western boundary of the current *Oculina* MPA. Over 23 high-relief *Oculina* mounds were mapped with the multi-beam echosounder outside the reserve, and it is estimated that over 100 bioherms may exist in this unprotected zone. In addition, based on a few submersible dives in 1982, *Oculina* pinnacles extend at least 55 km north of the current *Oculina* MPA, but no recent studies have been made in this region.

Since 1995, surveys have only covered a portion of the *Oculina* MPA and very little of the potential *Oculina* habitat outside the reserve. Areal coverage of all surveys since 1995 (excluding the new sites discovered outside the MPA), includes:

- Submersible dives, 0.45 $km^2$ (0.13 $nm^2$) (0.04 % of MPA);
- ROV dives, 0.69 $km^2$ (0.2 $nm^2$) (0.07 % of MPA);
- Sidescan sonar survey, 206 $km^2$ (60 $nm^2$) (20 % of MPA);
- Multi-beam survey, 295 $km^2$ (86 $nm^2$) (29 % of MPA).

Therefore, all ROV and submersible dives combined since 1995 cover less than 0.11 % of the *Oculina* MPA. Only a few of the sites that were described from the surveys of the 1970s have been directly compared to the present. This is, in part, due to the difficulty of precisely pinpointing sites recorded historically with LORAN-A or -C relative to modern GPS as well as due to the limited areal coverage of the recent submersible surveys.

The sidescan and multi-beam maps have been especially helpful in providing high precision details of the bottom topography. Even with these, however, it is not possible to determine the bottom habitat without video or direct visual observation. From the remote geophysical surveys, for example, it is impossible to differentiate intact live coral from standing dead coral, or coral rubble fields from coarse shell hash bottom. From the current multi-beam map, one can only differentiate features of 2-3 m, therefore low- to moderate-relief features can not be ascertained. The recent ROV ground-truthing of the multi-beam map provided new information, including: 1) discoveries of isolated thickets of live *Oculina* that exist within the newly expanded *Oculina* MPA; 2) numerous high-relief *Oculina* bioherms that were previously unknown exist outside the *Oculina* MPA; and 3) extensive areas of live-bottom habitat (primarily hard-bottom, rock pavement and ledges) and *Oculina* thickets occur within the low-relief areas. However, ROV surveys are extremely difficult to conduct on these high-current, high-relief reefs and are limited to drifting with the current in most cases. Human-occupied submersibles have consistently proved to be of greater value in surveying the fish populations and mapping the deep-water *Oculina* reefs.

Recent surveys (1995 to present) documented that the *Oculina* coral habitat on some of the reefs initially described in the 1970s is still thriving and apparently healthy. Most of these healthy reefs that we have surveyed recently occur within the southern portion of the *Oculina* MPA where trawl damage is apparently less than the northern portion.

Evidence of habitat damage, during the interval between the discovery of the *Oculina* reefs and the present, was especially evident from a submersible dive made in 2001 on a 20 m high *Oculina* pinnacle off Cape Canaveral. In 1976, this reef had been described from a submersible dive (*JSL* II-63) as having an estimated 25 to 100 % cover of live *Oculina* coral thickets on the slopes and crest of the reef (Fig. 9A; J. Reed, unpub. dive notes). This region, however, had been open to trawling until 2000 when the *Oculina* MPA was expanded. The 2001 submersible survey (*Clelia* 616), however, found that the coral thickets on the mound had been reduced to rubble (Fig. 9B). Except for a few scattered intact coral colonies at the base, all the coral on the crest and the flanks of the reef had been demolished.

Fish populations have yet to recover from overfishing in the 1980s and 1990s. Population densities of the dominant fish species correlate highly with habitat type (Koenig 2001; Koenig et al. 2004). Speckled hind, which may be designated in the near future as a threatened species, and gag and scamp grouper are predominately associated with the intact coral habitat. Twenty years ago the deep-water *Oculina* reefs formed impressive breeding and feeding grounds for commercially important populations of grouper and snapper. Large spawning aggregations of scamp and gag grouper commonly schooled above individual *Oculina* reefs. Unfortunately these large aggregations made perfect targets for both commercial and recreational fishermen and were decimated by the early 1990s (G. Gilmore pers. observations; Koenig et al. 2000). Even after a 10-year moratorium on hook-and-line fishing for grouper and snapper, which was extended indefinitely in 2003 by the South Atlantic Fishery Management Council, our recent ROV and submersible surveys show limited improvement in fish stocks.

## Protection and management

In 1984, the uniqueness, productivity, and vulnerability of the *Oculina* habitat prompted the South Atlantic Fishery Management Council (SAFMC) to declare a 315 $km^2$ (92 $nm^2$) portion of the banks a Habitat Area of Particular Concern (HAPC), in order to protect the coral from bottom trawling, dredging, and other mechanically disruptive activities. Impacts of overfishing on grouper spawning aggregations further stimulated the SAFMC in 1994 to close the original HAPC for a period of 10 years to bottom hook-and-line fishing as a test of the effectiveness of a fishery reserve in protecting the reproductive capacity of groupers. The area was called the Experimental *Oculina* Research Reserve (EORR; Fig. 1). In 2000, the *Oculina* HAPC was further expanded to 1029 $km^2$ (300 $nm^2$). In 2003, the EORR closure to bottom fishing was extended indefinitely to protect the overfished deep-water species of grouper and snapper. In addition, the SAFMC has mandated that the rock shrimp industry develop and implement a vessel monitoring system (VMS) for the fishery to aid in enforcement of the closed *Oculina* MPA areas. Bottom trawling for rock shrimp and brown shrimp has been the primary threat to these reefs.

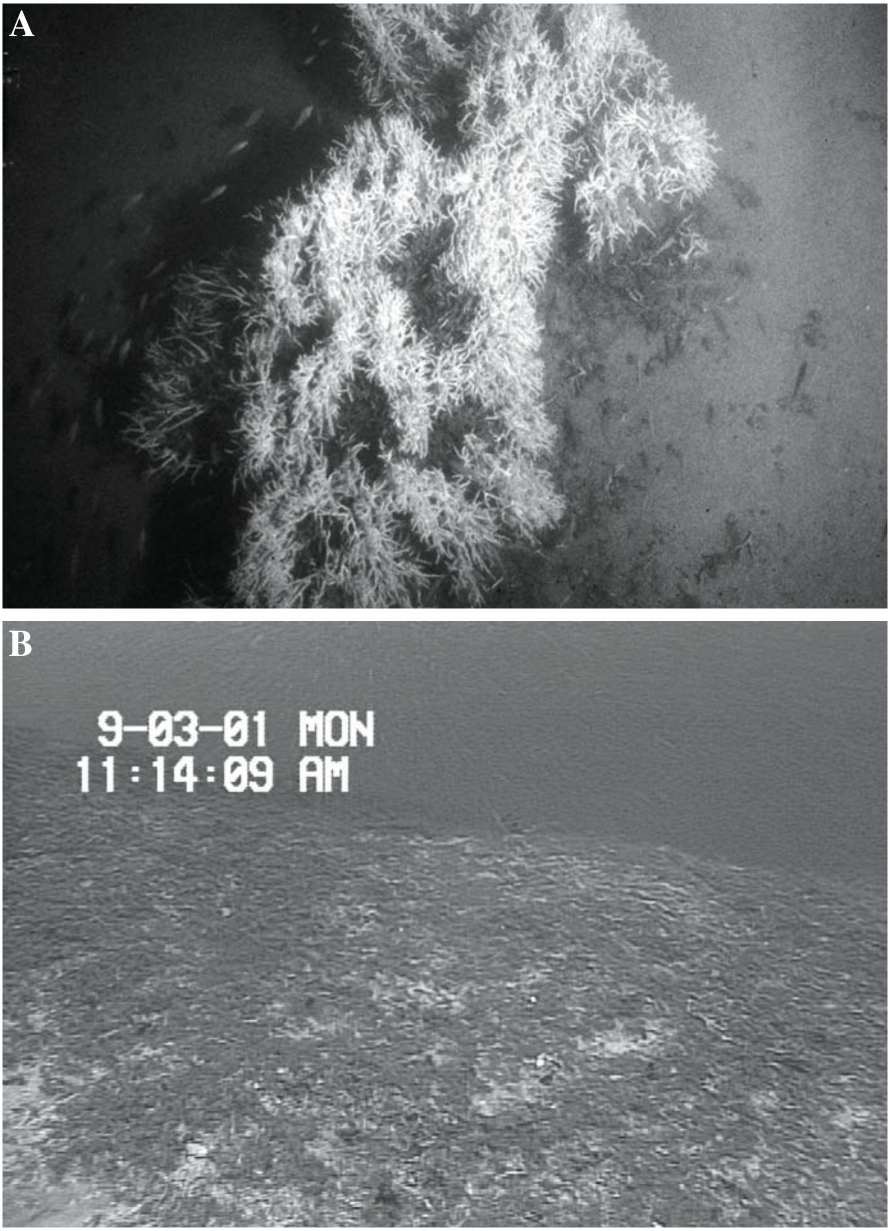


**Fig. 9** Peak of 20 m high *Oculina* reef at Cape Canaveral Pinnacle site (67 m depth; 28°29.8'N, 80°01.27'W): **A** historical photo (*JSL* II-63) from June 8, 1976; **B** same site (*Clelia* 616) on Sept. 3, 2001, reduced to rubble from apparent trawling

## Future of the *Oculina* MPA

Large gaps still exist in our knowledge of these deep-water *Oculina* reefs. Priorities for habitat mapping and characterization include: 1) complete multi-beam maps of the *Oculina* MPA and adjacent areas that may contain *Oculina* bioherms; 2) ground-truth these maps with submersible and ROV dives to characterize and document the extent and distribution of the *Oculina* reefs and other habitats; 3) document the extent of damage from recent trawling, both by direct mechanical damage and by indirect damage from resuspension of sediments and smothering of coral; 4) document other potential causes of coral death such as possible temperature changes from global warming, increased nutrient loading, or disease; 5) document the recovery of the fish populations and relationships with artificial reefball structures.

We have little data on when or how the coral rubble was formed, especially the vast areas that were rubble in the 1970s. It is important to know how much of this is from natural causes and how much is man-made. For example, during World War II the Sebastian Pinnacle and Bethel Shoals region (Fig. 1) was bombed extensively with depth charges by the U.S. military in search of German U-boat submarines (Cremer 1986). However, the age of dead coral, whether due to trawling *versus* depth charges, is too young for radiocarbon dating. Also little is known about the rubble ecosystem. For example, what role does it play as habitat for shrimp and other benthic fauna? Characterization should continue and experimental research is needed to quantify the value of coral thicket habitat (live and dead of various sizes) *versus* the alternate rubble state.

Certainly, trawling continues to be the primary threat to the ecosystem as evident from recent photographs of trawl nets found on the bottom (Fig. 7), destroyed reefball modules, and the documented destruction of the Cape Canaveral Pinnacle reef in the past 25 years (Fig. 9). Since 2000, illegal trawling has been documented within the *Oculina* MPA, and several poachers have been intercepted by the U.S. Coast Guard. Surveillance and enforcement remain the greatest tasks in protecting the *Oculina* MPA, as well as any deep-water coral reserve. We remain hopeful that the recently mandated use of a vessel monitoring system for the shrimp fishery in this region along with additional enforcement vessels will aid in the long-term protection of the *Oculina* MPA. In addition, proposed projects are envisioned to use surface buoys with satellite relay to monitor the reefs with acoustic devices which could relay real-time data on sounds of boat traffic and illegal trawlers. These could also be used by scientists studying the fish population patterns, and perhaps include arrays of thermographs, current meters, cameras, and other equipment to help understand this remote yet valuable resource.

## Acknowledgments

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## References

Avent RM, King ME, Gore RH (1977) Topographic and faunal studies of shelf-edge prominences off the central eastern Florida coast. Int Rev Ges Hydrobiol 62: 185-208

Avent RM, Stanton FG (1979) Observations from research submersible of megafaunal distribution on the continental margin off central eastern Florida. Harbor Branch Found Tech Rep 25, 40 pp

Avent RM, Stanton FG, Reed JK (1976) Submersible reconnaissance and research program. Harbor Branch Found, Inc, Fort Pierce, Florida, Annu Rep, 52 pp

Brooke S, Young CM (2003) Reproductive ecology of a deep-water scleractinian coral, *Oculina varicosa*, from the southeast Florida shelf. Cont Shelf Res 23: 847-858

Cremer P (1986) U-boat commander. Berkley Books, New York, 244 pp

Gilmore RG, Jones RS (1992) Color variation and associated behavior in the epinepheline groupers, *Mycteroperca microlepis* (Goode and Bean) and *M. phenax* Jordan and Swain. Bull Mar Sci 51: 83-103

Fairbanks RG (1989) A 17,000 year glacialeustatic sea level record: influence of glacial melting rates on younger Dryas event and deep-ocean circulation. Nature 342: 637-642

Hoskin CM, Reed JK, Mook DH (1987) Sediments from a living shelf-edge reef and adjacent area off central eastern Florida. In: Maurrasse F (ed) Symposium on South Florida Geology. Miami Geol Soc Mem 3: 42-57

Koenig CC (2001) *Oculina* banks: habitat, fish populations, restoration, and enforcement. Rep South Atlantic Fish Managem Counc, Charleston, South Carolina, December 1, 2001, 24 pp

Koenig CC, Coleman FC, Grimes C, Fitzhugh G, Scanlon K, Gledhill C, Grace M (2000) Protection of fish spawning habitat for the conservation of warm-temperate reef-fish fisheries of shelf-edge reefs of Florida. Bull Mar Sci 66: 593-616

Koenig CC, Shepard AN, Reed JK, Coleman FC, Brooke SD, Brusher J, Scanlon K (2004, in press) Habitat and fish populations in the deep-sea *Oculina* coral ecosystem of the Western Atlantic. Proc Benthic Habitat Meet, Amer Fish Soc, Spec Publ, Tampa, Florida

Macintyre IG, Milliman GD (1970) Physiographic features on the outer shelf and upper continental slope, Atlantic continental margin, southeastern United States. Bull Amer Geol Soc 81: 2577-2598

Moe MA (1963) A survey of offshore fishing in Florida. Prof Pap Ser 4, Florida State Bd Conserv Marine Lab, St. Petersburg, Florida

National Oceanic and Atmospheric Administration (1982) Fishery Management Plan for Coral and Coral Reefs of the Gulf of Mexico and South Atlantic. Gulf Mexico and South Atlantic Fish Managem Counc, Tampa, Florida, 342 pp

Reed JK (1980) Distribution and structure of deep-water *Oculina varicosa* coral reefs off central eastern Florida. Bull Mar Sci 30: 667-677

Reed JK (1981) *In situ* growth rates of the scleractinian coral *Oculina varicosa* occurring with zooxanthellae on 6-m reefs and without on 80-m banks. Proc 4th Int Coral Reef Symp, Manila 2, pp 201-206

Reed JK (1985) Shelf edge *Oculina* reefs. In: Seaman W (ed) Florida Aquatic Habitat and Fishery Resources. Florida Chapter Amer Fish Soc, Kissimmee, Florida, pp 466-468

Reed JK (2002a) Deep-water *Oculina* coral reefs of Florida: biology, impacts, and management. Hydrobiologia 471: 43-55

Reed JK (2002b) Comparison of deep-water coral reefs and lithoherms off southeastern U.S.A. Hydrobiologia 471: 57-69

Reed JK, Hoskin CM (1987) Biological and geological processes at the shelf edge investigated with submersibles. In: Scientific Applications of Current Diving Technology on the U.S. Continental Shelf. NOAA Symp Ser Undersea Res 2: 191-199

Scanlon KM, Briere P, Koenig C (1999) *Oculina* Bank: sidescan sonar and sediment data from a deep-water coral reef habitat off east-central Florida. U.S. Geol Surv Open File Rep 99-10, CD ROM

Shepard A., Reed JK (2003) *Oculina* Banks 2003: characterization of benthic habitat and fish populations in the *Oculina* Habitat Area of Particular Concern (OHAPC), Mission Summary Report. NOAA/ NURC and South Atlantic Fish Managem Counc, 14 pp

Thompson MJ, Gulliland LE (1980) Topographic mapping of shelf edge prominences off southeastern Florida. Southeast Geol 21: 155-164

Thompson MJ, Gulliland LE, Mendlein GE (1978) Bathymetric mapping of three selected areas on the southeastern Florida continental shelf. Harbor Branch Found, Inc, Fort Pierce, Florida, Tech Rep 27, 54 pp