PINK-TO-RED CORAL: A GUIDE TO DETERMINING ORIGIN OF COLOR

Christopher P. Smith, Shane F. McClure, Sally Eaton-Magaña, and David M. Kondo

Pink-to-red coral has a long history as an ornamental gem material in jewelry, carvings, and sculptures. However, due to a variety of environmental and legal factors, the supply of high-quality, natural-color coral in this color range has dramatically decreased in recent years—and the quantity of dyed coral on the market has increased. From a study of more than 1,000 natural- and treated-color samples, this article summarizes the procedures that are useful to identify the color origin of pink-to-red coral. A variety of techniques—including magnification, exposure to acetone, and Raman analysis—can determine if the color of a piece of such coral is dyed. Although there are limitations to the use of magnification and acetone, Raman analysis can establish conclusively that the color is natural.

Coral is an organic gem material that has been used for ornamental purposes (figure 1) for several thousand years (see, e.g., Walton, 1959). Amulets of red coral dating back to 8000 BC were uncovered in Neolithic graves in Switzerland, coral jewelry was made in Sumeria and Egypt around 3000 BC, and Chinese cultures have valued coral highly since about 1000 BC (Liverino, 1989). The material also is mentioned in the ancient writings of both Theophrastus (Greece, 4th century BC) and Pliny (Italy, 1st century AD; Caley and Richards, 1956). Due to its distinctive natural form, coral has been used not only for jewelry, but also for dramatic carvings and sculptures that highlight the natural form of the coral branch (figure 2). The region centered around Torre del Greco near Naples, Italy, has a long tradition as an important fashioning center for coral (Bauer, 1969; Pizzolato, 2005). This is largely because the Mediterranean Sea has been a major source of the world's pink-to-red ornamental coral. Today, commercial quantities of pink-to-red coral also are found off the coasts of Japan and China (Henn, 2006).

Fine specimens of attractive pink-to-red coral are the most desirable yet among the least available. This limitation has led to the practice of dyeing pale-colored and white coral into the more highly valued shades of pink to red. Commonly, the coral is bleached prior to the dyeing process so that better penetration and more homogeneous coloration may be achieved (figure 3). Additionally, polymer impregnation—with or without a coloring agent—may be used to enhance the appearance of coral and give it a smoother surface, which makes it more comfortable to wear (see, e.g., Pederson, 2004).

The present article looks at the current status of this ornamental material—its formation, supply, and the potential impact of environmental considerations—as well as the techniques used to distinguish between natural-color and dyed corals. In particular, this article will outline some of the procedures typically used by gemologists and gemological laboratories to determine the origin of color for pink-to-red coral.

See end of article for About the Authors and Acknowledgments.
GEMS & GEMOLOGY, Vol. 43, No. 1, pp. 4–15.

Figure 1. For thousands of years, coral like the branch shown here has been fashioned for use as carvings and in jewelry. Although the harvesting of gem-quality pink-to-red coral has decreased steadily in recent years because of environmental and other problems, leading to a proliferation of dyed material, fine pieces such as these beads (13–17 mm) and cabochons (24 mm) continue to enter the marketplace. Courtesy of R. H. & Co., Glendale, California; photo by Harold & Erica Van Pelt.

GENERAL BACKGROUND

Formation/Biology. Because it shows aspects of the mineral, animal, and plant kingdoms, coral was not properly classified until the 17th century (Liverino, 1989). A branch of coral is the skeletal remains of a colony of tiny animals called coral polyps (figure 4). The term *coral* can refer to both the marine animal and the material produced from its skeletal remains. Polyps are simple organisms with a mouth surrounded by tentacles and gastrovascular function. A polyp colony consists of three different parts: the sclerax, the coenosarc, and the polyps themselves. The sclerax is the hard skeleton left behind by the coral polyps, and it is this material that can be worked as a gem material. The coenosarc is the tissue that binds the polyps to the skeleton. In addition to organic macromolecules such as proteins, polysaccharides, and lipids, the coral skeleton also contains biogenic (i.e., biologically generated) carbonates ($CaCO_3$). The two major polymorphs are calcite and aragonite (see, e.g., Rolandi et al., 2005; Bocchio et al., 2006). The polyps precipitate the major components of most coral branches from sea water (Liverino, 1989): calcium carbonate (82–87%) and magnesium carbonate (~7%).

A new coral colony is originally created through sexual reproduction, but it continues to grow through gemmation, whereby a polyp separates off a portion of itself to create a new polyp. Coral requires a sturdy foundation such as rocks, other coral, or debris (e.g., a shipwreck), and it has a growth rate of a

Figure 2. Coral lends itself to extraordinary carvings, such as this Asian-inspired piece (28.6 cm tall × 30.5 cm wide) that conforms to the natural form of the coral branch. Photo © Harold & Erica Van Pelt.

few millimeters up to 1–2 cm per year (Liverino, 1989; Chadwick, 1999).

Pink-to-red coral in the Mediterranean Sea can grow at depths of 5–300 m. The red coral harvested from the waters near Japan and China is often recovered from depths down to 400 m (Liverino, 1989; O'Donoghue, 2006), but it has been discovered near Hawaii at depths down to 1,000 m (O'Donoghue, 2006). According to Rolandi et al. (2005), there are two classes of coral that have skeletons tough enough to be used as gem materials and for carvings: Hydrozoa and Anthozoa. Within these classes, there are again two orders that produce a majority of the species of pink-to-red corals used for ornamental purposes: Stylasterina and Coralliidae, respectively. However, various species of pink-to-red coral typically have not been differentiated within the jewelry industry (Pederson, 2004).

Present Coral Supply and Environmental Considerations. By some estimates, coral reefs cover about 0.25% of the oceans' subsurface area and support approximately 25% of all known ocean species (Chadwick, 1999). However, beds of coral species that are large enough to support harvesting are becoming increasingly scarce. The annual harvest of red coral in the Mediterranean Sea decreased from about 100 tonnes in 1976 to about 25 tonnes in 2000 (Tsounis, 2005). To reach such coral forests, divers must now go to greater depths than in the past. As an example, along Costa Brava in the northwest Mediterranean Sea, only 10% of the dives to retrieve coral are to depths of less than 30 m, while 70% are to depths of 30–50 m (Tsounis, 2005).

A wide range of factors are responsible for depleting the world's total coral supply, including global warming, industrial pollution, oil spills, thermal stress caused by heated discharge from power plants, destructive fishing through the use of cyanide and dynamite, human overpopulation in coastal areas, and, finally, overharvesting of the coral itself. Given the depths at which most of the pink-to-red coral beds are principally found, overharvesting has had the greatest impact. Japan and other countries, such as the U.S. (Hawaiian islands), that wish to preserve a sustainable supply of coral have established strict limits on the quantities and types of coral that may be harvested (Laurs, 2000; Prost, 2001). These restrictions also limit the available areas and depths at which harvesting is permissible.

Note that the chemical bleaching performed on some harvested coral prior to dyeing is very different from the "bleaching" that other species of coral (usually not considered gem material) have experienced over the last few years. This latter bleaching, which has been the subject of much media attention (e.g., Fountain, 2004; Bierman, 2005; Doney, 2006),

is the natural response of a living coral ecosystem to environmental changes such as increases in water temperatures and differences in the acidity and salinity of the water (Chadwick, 1999). Typically, many shallow-water corals coexist in a symbiotic relationship with various colored algae, which indirectly provide the polyps' primary source of food. Environmental stressors may cause the algae to leave the coral's surface, exposing the white skeleton. The previously vibrant corals then appear quite bleak. Deprived of their major food source, they have difficulty surviving (Doney, 2006).

The reduction in supply of high-quality, natural-color coral has led to a greater amount of dyed-color, lower-quality coral in the most highly valued shades of pink to red. Some U.S. dealers report that a large portion, as high as 90–95%, of the new coral entering the market is color-enhanced (Prost, 2001).

Origin of Color. In the 1980s, carotene was established as the cause of color in pink-to-red coral (Merlin and Delé, 1983; Merlin, 1985). Carotene is one of more than 600 related natural pigments that are collectively grouped as carotenoids and are produced primarily in phytoplankton, algae, and plants (Rolandi et al., 2005). Carotenoids are responsible for a broad range of colors in both plants and animals, depending on the complex formed and its incorporation into the host. For example, carrots are a vibrant orange due to alpha- and beta-carotene, tomatoes are red due to lycopene, and flamingos are pink due to the presence of astaxanthin in their diet; all of these colorants are carotenoids. In coral skeletons, various carotenoids are also responsible for yellow, orange, brown, and blue-to-violet hues. The specific color is influenced by the carotenoid's incorporation into the skeleton (Rolandi et al., 2005). In addition, carotenoids form complexes with other materials—most notably proteins—that may significantly influence the color exhibited.

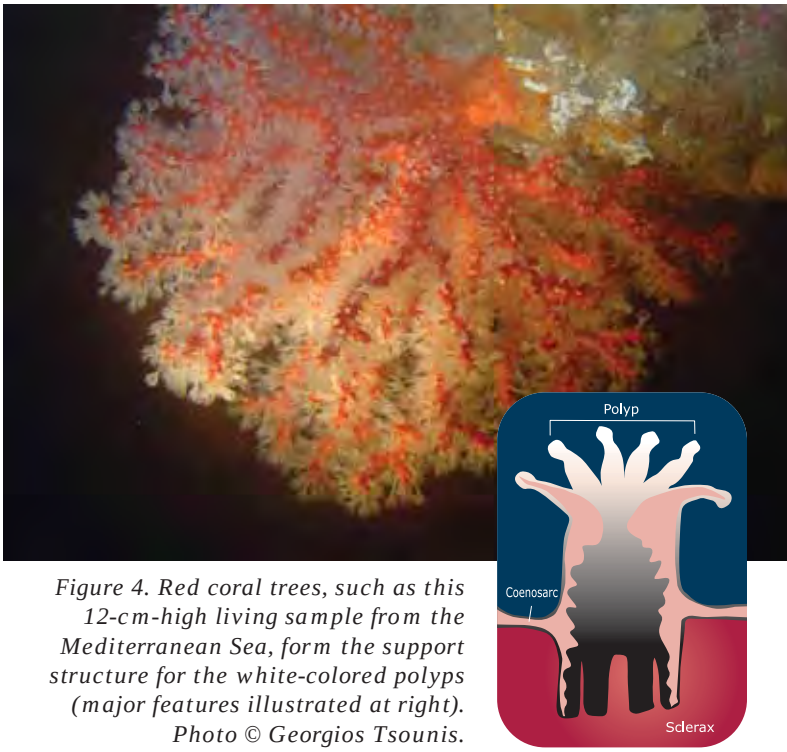


Figure 4. Red coral trees, such as this 12-cm-high living sample from the Mediterranean Sea, form the support structure for the white-colored polyps (major features illustrated at right). Photo © Georgios Tsounis.

Figure 3. The coral branch on the left (67 mm) has been bleached, which is commonly performed prior to dyeing to improve the penetration of the dye and allow for a more homogeneous coloration after dyeing. The branch on the right has been dyed red. Also clearly evident in these two samples of Corallium rubrum *are striations parallel to the length of the branches. The grooves are canals that the coral polyps used to transport nutrients and are one of the most distinguishing characteristics of the coral structure. Photo by Jessica Arditi.*

Gemological Properties. The identification of coral is made through a variety of properties. GIA's *Gem Identification Lab Manual* (2005) indicates that key tests include: refractive index (1.486–1.658), birefringence (0.172—accompanied by a birefringence blink), and magnification. The ribbed, pitted, and scalloped structures of natural coral (refer to the "Microscopic Examination and General Observations" section below) provide a readily available means of separating coral from its most commonly encountered imitators, including shell and plastic, with magnification. Reconstituted coral is produced from low-quality coral that has been pulverized, mixed with an

Figure 5. Natural-color coral can span a wide range of hues, including these examples (2.5–11.8 mm) of the most valuable shades of pink to red. These strands of coral belong to the following species: (1) Melithaea ochracaea, *(2)* Corallium elatius, *(3)* Corallium rubrum, *(4)* Corallium elatius, *(5)* Corallium *species*, *(6)* Corallium secundum, *and (7)* Corallium rubrum. *Photo by Jessica Arditi.*

epoxy, reformed into blocks, dyed, and then used to make jewelry (Weldon, 2003). It does not show a surface pattern or a ribbed structure.

A careful R.I. reading, S.G. determination, and infrared spectroscopy—combined with observation of specific growth-structures—may provide clues to the particular species of the coral. Such tests may also help determine if the coral species is predominantly composed of calcite or aragonite (Kaczorowska et al., 2003; Pederson, 2004; Rolandi et al., 2005); however, these topics are outside the scope of this article. Because so little has been published in the recent gemological literature on the identification of dye in coral, especially given the analytical techniques that are now available, we conducted numerous tests—standard gemological exams and more sophisticated spectroscopic analyses—on known treated and untreated samples to determine which methods were most effective.

MATERIALS AND METHODS

One of the authors (CPS) acquired seven strands of coral beads covering four species of the Coralliidae order—*Corallium elatius*, *Corallium rubrum*, *Corallium secundum*, and *Melithaea ochracaea*—as well as samples of unknown species (figure 5), all of which were represented as natural color. They ranged from pinkish orange to pink and red. In addition, 11 strands of coral—all represented as dyed—were obtained (see, e.g., figure 6). Most of these belonged to the *Corallium rubrum* species, with the dyed colors ranging from pink-orange and various shades of light pink to red. Included in this group were two strands of *Melithaea ochracaea* that had been treated with a colored polymer. We also analyzed 10 known natural-color and dyed coral specimens from the GIA reference collection and 24 dyed samples from the collection of one of the authors (SFM). In all, well over 1,000 pieces of natural-color and dyed coral were included in this study.

All of the samples were examined using a standard GIA Gemolite binocular microscope with

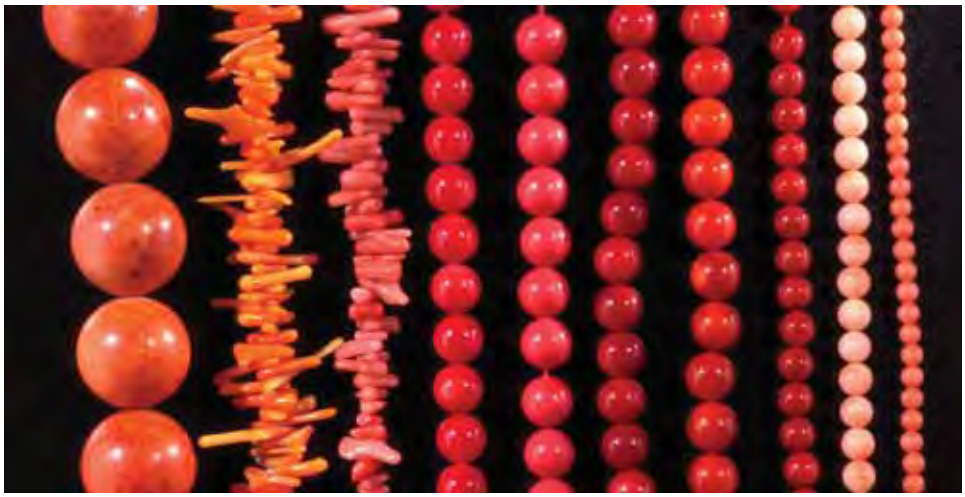


Figure 6. Coral (here, 3.5–18.0 mm) can be dyed almost any color, but it is seen most commonly in the gem trade as pink to red. Photo by Jessica Arditi.

fiber-optic illumination. Acetone and a cotton swab, such as a Q-tip, were used to test inconspicuous areas of the coral on a random sample of approximately 50 pieces of each group (natural-color and treated) for the presence of dye.

A Renishaw System 1000 Raman micro-spectrometer with an argon-ion laser (514 nm excitation) was used to analyze 40 natural-color and 40 dyed samples (including approximately 10 with a colored polymer), covering the complete color range. For the Raman analysis, we used a variety of magnifying lenses, from 5× to 50×. The integration times varied from 3 to 20 seconds per grating sequence. The spectra were taken over two different ranges. The first extended from 2000 to 100 cm^{-1} and covered the standard range used to identify the key Raman bands of a material. The second extended from 517 to 1000 nm, with the intent of measuring Raman bands outside of the previous range as well as any photoluminescence bands that might be present (refer to Raman Spectroscopy below).

Reflectance spectra of 10 natural-color and 14 dyed coral samples that varied from pink to red were acquired for the 200–850 nm range with a Perkin Elmer Lambda 950 ultraviolet/visible/near-infrared (UV-Vis-NIR) spectrometer utilizing an integrating sphere, with a 1.0 nm scan interval and 141 nm per minute scan speed. Although reflectance spectra are typically shown as % reflectance (%R), the authors have elected to portray the spectra in absorbance, as the negative log of %R divided by 100 (i.e., $-\log[\frac{\%R}{100}]$), since most spectra in gemological publications are shown using absorbance. To confirm the validity of this approach, we performed absorption spectroscopy on thin slices made from seven of the samples (four pink-to-red natural-color and three dyed) using the same spectrometer and measuring conditions. The two types of spectra, reflectance (converted to absorbance) and absorbance, were virtually identical.

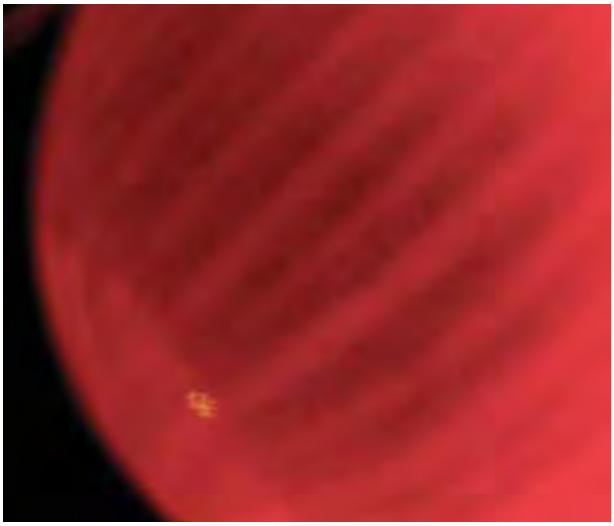


Figure 7. The parallel striations that are obvious in "rough" coral are also clearly evident after the material has been fashioned, so they readily separate coral from its simulants. Note, however, that this structure is visible in both natural-color and dyed coral. Photomicrograph by C. P. Smith; fiber-optic illumination, magnified 18×.

RESULTS AND DISCUSSION

Microscopic Examination and General Observations. The structures of the most common ornamental corals—*Corallium elatius*, *Corallium rubrum*, and *Corallium secundum*—typically consist of two patterns. The first is a ribbed or striated pattern that extends roughly parallel to the length of the coral branch (figure 7). The other is a concentric, scalloped structure (figure 8). Natural features

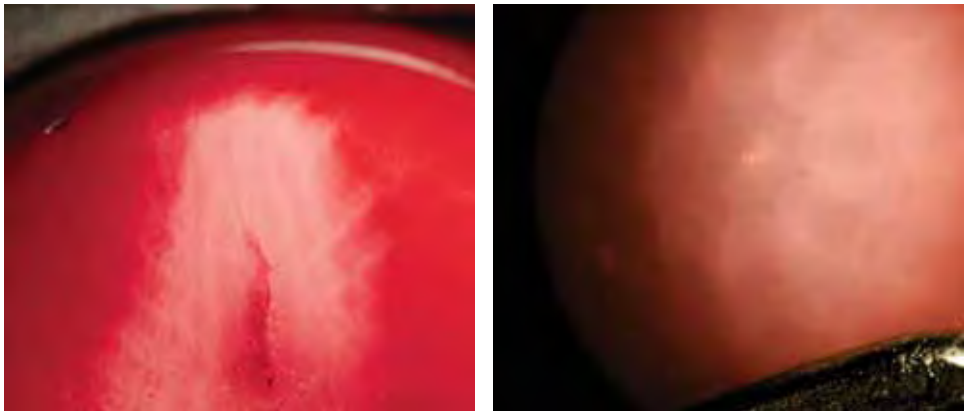


Figure 8. A concentric scalloped pattern is also characteristic of natural coral and will readily distinguish it from its most common imitators shell and plastic. Photomicrographs by C. P. Smith; fiber-optic illumination, magnified 15× (left, dyed coral) and 25× (right, natural-color coral).

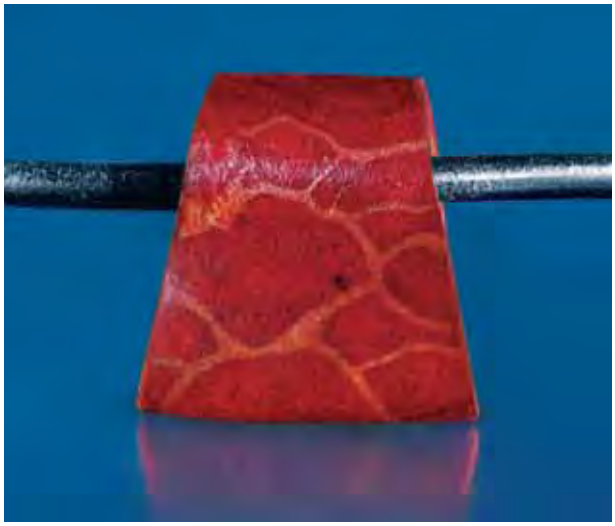


Figure 9. The red coral species Melithaea ochracaea *(sometimes referred to as "red king coral") is notable for its distinctive patterning. This piece measures 2.8 cm at the base. Courtesy of Holly Smith; photo by Elizabeth Schrader.*

dotting the coral surface, which may be described as pits and pock marks, also are common and characteristic of many *Corallium* species. The unusual patterns (figure 9) and the open and porous structure (figure 10) of the red coral species *Melithaea ochracaea* are particularly distinctive. Such features were observed in all the coral beads examined in this study, both natural-color and dyed, depending on their species.

Coral occurs naturally in a broad range of attractive pinkish orange to pink and red colors (again, see figure 5). Similarly, coral may be dyed to virtually any color; however, only results for coral that has been dyed pale pink to deep red and pink-orange are reported in this study (again, see figure 6). In some instances, the colors achieved by dyeing appear very similar to those seen in natural-color coral. Commonly, though, the dyed coral is very different in appearance from its natural-color counterpart (see, e.g., figure 11). Therefore, visual observation of color may provide an important clue to the presence of dye. In addition, the surface pits and cavities common to coral readily act as receptacles for dye concentrations (figure 12), as do fractures or separations in the concentric growth pattern. In such instances—where visual observation is insufficient—the use of acetone and a cotton swab may be effective to identify the presence of dye (figure 13). This reaction was observed in many of the dyed samples we tested; however, it was very faint in several samples and not evident at all in a few. A piece of coral may also be immersed in acetone to see if any dye leaves the coral structure and turns the acetone pink (although we did not conduct this test on our samples). However, both of these techniques are somewhat destructive, as a positive test removes some of the color imparted by the dye. For this reason—and because, as our testing with a cotton swab showed, the results are not always conclusive—we also investigated two nondestructive analytical techniques.

Figure 10. The characteristic "open" structure of Melithaea ochracaea *is evident whether the coral is fashioned with the channels open (left, magnified 15×) or if it has been impregnated with a polymer (right, magnified 25×). Today it is common to treat this species of coral with a polymer to reduce its rough texture and allow it to take a better polish. The polymer has a yellow-orange color, as may be seen in the open pores of the treated sample. Photomicrographs by C. P. Smith.*

Figure 11. Often the dyes used to treat coral will impart a vivid red hue, as in this 14 mm bead, that is not found in nature. Photo by Jessica Arditi.

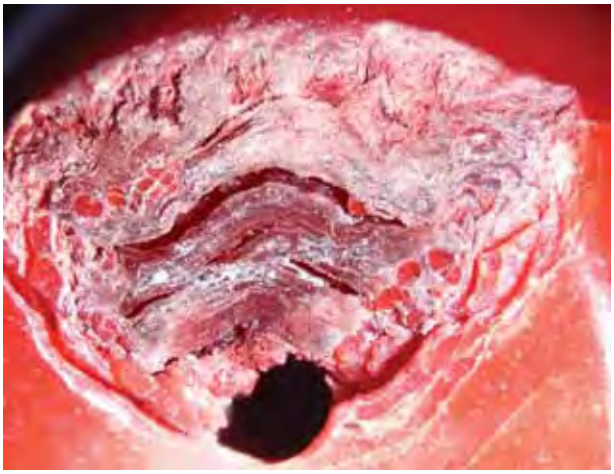


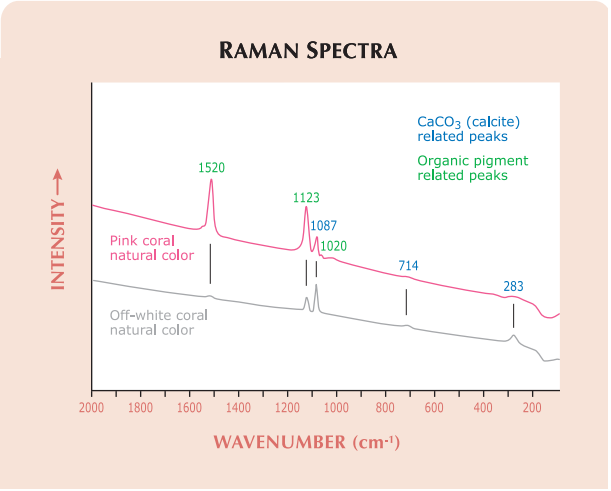
Figure 12. Coral can be a brittle material, as well as somewhat porous. Breaks or cavities at the surface commonly contain concentrated remnants of the dye that was used to color it. The very dark red masses obvious near the drill hole in this sample readily identified this bead as dyed, even without magnification. Photomicrograph by C. P. Smith; magnified 13×.

Raman and Photoluminescence Spectroscopy. The Raman spectra of these four species of coral typically exhibit a combination of bands associated with both the coral matrix ($CaCO_3$) and the compounds responsible for the color (figure 14). A distinct band positioned at approximately 1087 cm^{-1}, with subordinate peaks at approximately 714 and 283 cm^{-1}, is indicative of the calcium carbonate phase forming the skeleton of the coral. All of the samples we tested with Raman spectroscopy, both natural-color and dyed, showed this feature.

Figure 13. Acetone has traditionally been used to confirm the presence of dye in coral. Commonly this test involves dipping a cotton swab in acetone and then rubbing the cotton on an inconspicuous area of the sample to see if any of the color rubs off. Occasionally, the item is immersed in acetone to see if the liquid will discolor slightly. In both cases, this test may be destructive to the color of the sample. Photo by Jessica Arditi.

Natural color in pink-to-red coral may be readily identified by the presence of certain organic pigments incorporated into the coral skeleton. A pair of distinct Raman peaks positioned at approximately 1520 and 1123 cm^{-1}, with subordinate peaks at approximately 1297 and 1020 cm^{-1}, identify carotene

Figure 14. The Raman spectrum of coral identifies the biogenic calcium carbonate phase of the skeleton ($CaCO_3$), with peaks positioned at approximately 1087, 714, and 283 cm^{-1}. The Raman spectrum of natural-color coral typically reveals additional peaks related to organic pigments, such as those positioned here at 1520, 1123, and 1020 cm^{-1}.



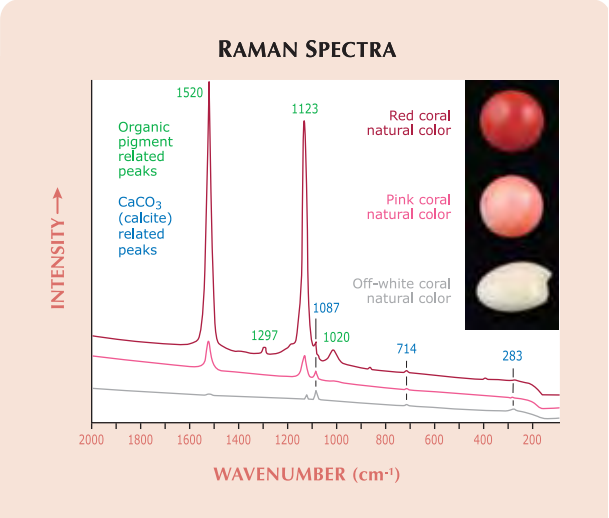


Figure 15. Carotene is the organic pigment responsible for the pink-to-red shades of natural-color coral. In the Raman spectra of these three natural-color corals, the intensity of the carotene peaks (with two dominant peaks at approximately 1520 and 1123 cm^{-1} and minor peaks at approximately 1297 and 1020 cm^{-1}) correlates directly with the saturation of color. The bands marked in blue, with the main peak positioned at ~1087 cm^{-1}, identify the calcium carbonate phase ($CaCO_3$) of the coral.

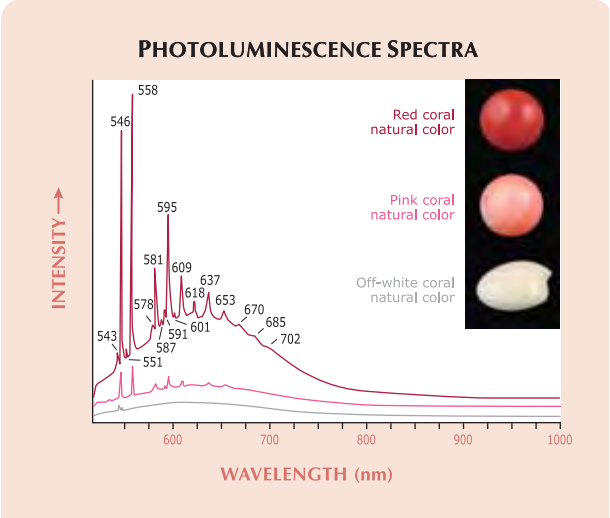


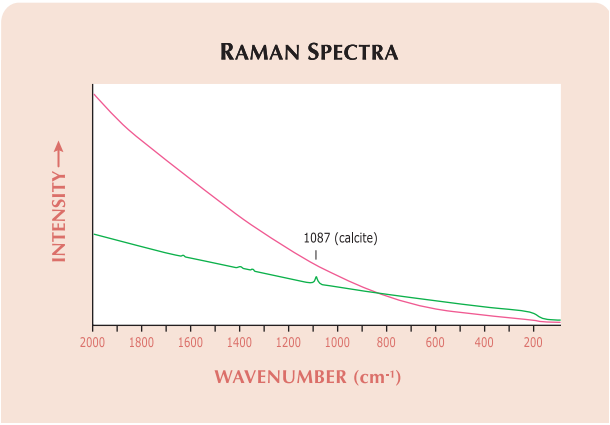
Figure 16. By scanning the full Raman spectral range capable with a 514 nm excitation Ar-ion laser (517–1000 nm), carotene pigments are seen to be responsible for a range of peaks in the same samples as illustrated in figure 15.

(Urmos et al., 1991; Kaczorowska et al., 2003; Rolandi et al., 2005). In our experience, the intensity of these carotene peaks directly correlates to the saturation of the pink-to-red color, as was the case with the natural-color samples we tested (figure 15).

Using the full spectral range of the 514 nm Ar-ion laser (517–1000 nm; figure 16), we observed a series of peaks positioned at approximately 543 (1020 cm^{-1}), 546 (1123 cm^{-1}), 551 (1297 cm^{-1}), 558 (1520 cm^{-1}), 578, 581, 587, 591, 595, 601, 607, 609, 618, 637, 653, 670, 685, and 702 nm, as well as other subordinate peaks, all of which are due to carotene pigments. In contrast, the dyed pink-to-red coral samples did not exhibit the Raman spectrum associated with carotene. Instead, they typically showed an increase in underlying photoluminescence in the standard Raman spectral range of 2000–100 cm^{-1}, in addition to a series of very weak peaks positioned at approximately 1608, 1492, 1482, 1455, 1378, 1353, 1327, 1290, 1032, 906, 817, and 701 cm^{-1} (figure 17; details of many of these peaks cannot be observed at the scale shown). With the extended spectral range (517–1000 nm), we observed that the dominant photoluminescence of the dye was centered between approximately 630 and 665 nm, the asymmetry of this photoluminescence structure indicating that it likely consists of multiple bands (figure 18). In the *Melithaea ochracaea* samples that had been treated with a colored polymer, we noted a compound spectrum of carotene peaks and a dominant broad luminescence band.

Since the dye or colored polymer may be incor-

Figure 17. The Raman spectra of dyed pink-to-red coral are identified by the increasing photoluminescence extending beyond 2000 cm^{-1}, as well as the absence of peaks associated with carotene. Often a series of very weak peaks attributed to dye may also be evident, such as the structure seen here between 1700 and 1300 cm^{-1} in the green spectrum. The red spectrum illustrates a common occurrence, where the luminescence of the dye is so strong that no other structure or Raman peaks are evident.



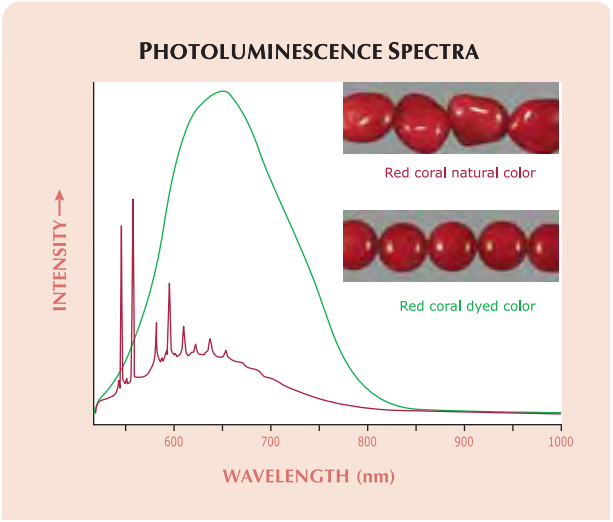


Figure 18. Photoluminescence in the 517–1000 nm spectral range clearly illustrates the differences between the series of very strong carotene peaks in the area of ~540–700 nm in natural-color coral and the dominant photoluminescence band structure centered at ~630–665 nm in dyed red coral.

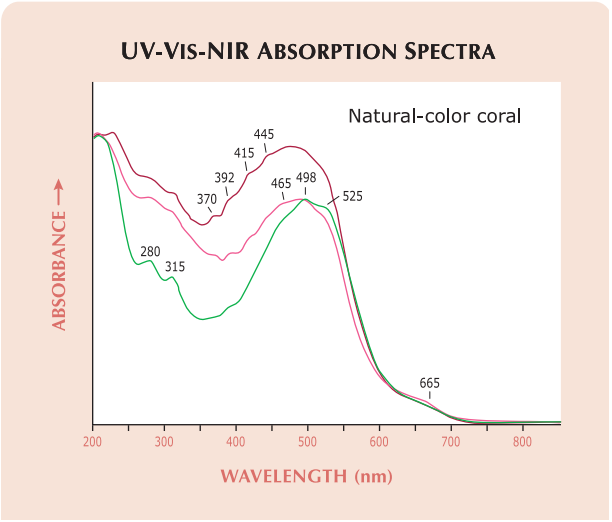


Figure 19. As these three representative spectra indicate, natural-color pink-to-red coral has a series of broad absorption bands in the UV-Vis-NIR region. The predominant absorption consists of a multiple-band structure with individual positions located at ~465, 498, and 525 nm. The same general combination of absorptions was recorded in all the natural-color coral tested during this study.

porated unevenly, our samples also confirmed the wisdom of analyzing several areas on the piece in question. In some areas with a partial natural coloration, we noted a combination of spectral features: the presence of carotene-related peaks indicating natural color, together with the significantly increased broad luminescence indicating dyed color. In such instances, the intensity of the carotene-related peaks was not consistent with the saturation of color in the area analyzed.

Reflectance Spectroscopy. The UV-Vis-NIR spectra of the pink-to-red coral samples were dominated by a series of broad absorption bands. In the natural-color samples, the primary absorption responsible for the color consisted of a multiple-band structure composed of at least three independent bands located at approximately 465, 498, and 525 nm (figure 19). At the tail of this absorption on the high-wavelength side, most of the natural-color samples showed another broad absorption feature positioned at ~665 nm. Also seen in most of the samples were absorptions positioned at approximately 370, 392, 415, and 445 nm, as well as other broad bands deeper in the UV region at approximately 280 and 315 nm.

In the dyed samples, the spectra were dominated by an absorption feature that saturated the detector in the spectral range between approximately 400 and 550 nm (figure 20). The 465, 498, and 525 nm bands noted in the natural-color corals were not evident. We also did not record the weak broad bands at approximately 315, 370, 392, 415, and 445 nm that are present in natural-color coral. However, the

Figure 20. The absorption spectra of these three samples of dyed coral have a predominant absorption in the 400–550 nm range, similar to that seen in the natural-color coral shown in figure 19. However, several of the associated, subordinate broad absorption bands present in natural-color coral are not seen. In addition, there is a slightly modified absorption trend in the deep UV region.

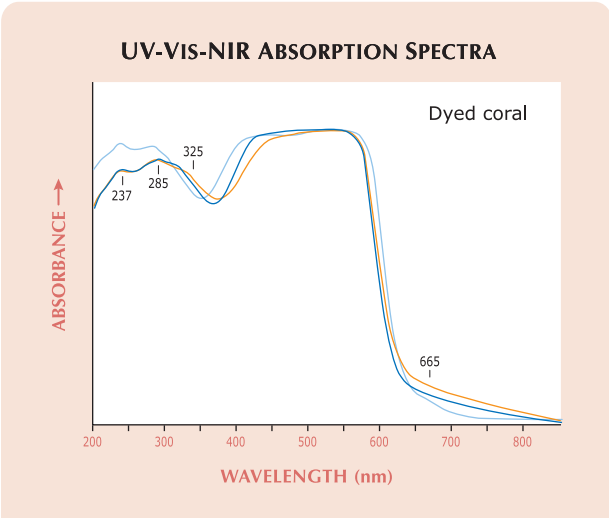


Figure 21. Pink-to-red coral, with its natural variations in color, can be carved to create unique pieces of jewelry such as this image of a woman's face (56 mm high). Courtesy of Castelnuovo d'Aiassa Designs, Mount Hamilton, California; photo by Harold & Erica Van Pelt.

broad feature at 665 nm was weakly present in a few of the dyed specimens. In addition, we also noted three weak bands in the UV region of the spectrum positioned at approximately 237, 285, and 325 nm.

IDENTIFICATION

Once it has been established that an item is coral, several tests may be conducted to determine if its pink-to-red color is natural or dyed. The visual appearance of the coral may provide an indication of the origin of color, but such observations should not be considered conclusive. Additionally, although microscopic examination alone can prove the presence of dye in color-treated coral (through concentrations of color in surface pits, cavities, or fractures), the lack of such features is insufficient to prove that the color of a specimen is natural. Historically, gemologists have used acetone to confirm the presence of dye, but as our experiments showed, not all dyed coral will respond to acetone. In those cases where acetone is inconclusive or the use of this potentially destructive test is not advisable, the coloring agent may be conclusively and nondestructively identified with Raman spectroscopy. By establishing the presence of carotene in the Raman spectrum—with its two dominant peaks located at approximately 1520 and 1123 cm^{-1}—and correlating it to the intensity of color, it is possible to confirm the natural color of pink-to-red coral. In contrast, dyed pink-to-red coral is characterized by a dominant underlying photoluminescence band centered between approximately 630 and 665 nm, usually without specific carotene-related peaks (again, see figure 18). Because dye may be unevenly distributed, it is important to analyze several areas on the sample. In areas that contain a partial natural coloration, the spectra will show a combination of carotene-related peaks (that will not correspond to the intensity of color, as would be the case with untreated pink-to-red coral) and significantly increased broad photoluminescence centered at approximately 630–665 nm.

The study revealed some potentially interesting trends in the UV-Vis-NIR spectra of the natural-color and dyed samples. However, more testing is needed to establish the consistency of these findings and their usefulness in making this distinction.

SUMMARY AND CONCLUSION

Coral has been used in jewelry and *objets d'art* for thousands of years, and it continues to be very popular in many markets today (figure 21). Attractive

shades of pink to red are typically considered the most valuable. Unfortunately, the global supply of gem-quality coral is diminishing, as overharvesting and other factors have had a detrimental effect on existing coral beds. This has led to an increased use of dyes to expand the availability of the most sought-after colors. In some cases, microscopy or testing with acetone is sufficient to identify the presence of a dye. However, the use of acetone to remove color may be somewhat destructive, and the results are not always conclusive. UV-Vis-NIR reflectance spectroscopy may provide clues to the natural or dyed condition of a piece of coral, but further work is necessary to confirm the applicability of this testing procedure. However, Raman analysis is a nondestructive method that can conclusively determine the natural origin of such colors, as well as the presence of dye. Carotene, the natural coloring agent for pink-to-red coral, may be readily identified by its signature Raman spectrum.

ABOUT THE AUTHORS

Mr. Smith (chsmith@aglgemlab.com) is vice president and chief gemologist at American Gemological Laboratories (AGL), New York City; at the time the article was originally written, he was director of Identification Services at the GIA Laboratory in New York. Mr. McClure is director of Identification Services at the GIA Laboratory in Carlsbad, California. Dr. Eaton-Magaña is technical editor of Gems & Gemology*, and Mr. Kondo is a research technician at the GIA Laboratory, New York.*

ACKNOWLEDGMENTS

The authors thank Peter Rohm of Rohm GesmbH & Co. KG, Linz, Germany, for supplying both natural-color and dyed samples of known coral species. They also thank the following for helpful discussions on the origin of color in coral: Dr. Carolyn Van der Bogert, former research scientist at the GIA Laboratory, New York; Wendi Mayerson, former senior staff gemologist in the Identification Department, GIA Laboratory, New York; and Shane Elen, analytical equipment supervisor at GIA Research, Carlsbad.

REFERENCES

Bauer M. (1969) *Precious Stones*. Charles E. Tuttle & Co., Rutland, VT.

Bierman F. (2005) Coral reefs in peril, report says. *New York Times*, March 13, http://query.nytimes.com/gst/fullpage.html?sec=travel&res=9801E4D61E3DF930A25750C0A9639C8B63.

Bocchio R., Bracco S., Brajkovic A., Comotti A., Rolandi V. (2006) Gem corals: X-ray diffraction, solid state NMR, elemental analysis. *Australian Gemmologist*, Vol. 22, pp. 524–532.

Caley E.R., Richards J.C. (1956) *Theophrastus on Stones*. Ohio State University Press, Columbus, Ohio.

Chadwick D.H. (1999) Coral in peril. *National Geographic*, Vol. 195, No. 1, pp. 30–37.

Doney S.C. (2006) The dangers of ocean acidification. *Scientific American*, Vol. 294, No. 3, pp. 58–65.

Fountain H. (2004) When coral turns white. *New York Times*, June 15, http://www.nytimes.com/2004/06/15/science/15obse.html?ex=1402632000&en=a14415ae73ca3ef4&ei=5007&partner=USERLAND#.

Henn U. (2006) Corals in the gem and jewellery trade. *Gemmologie: Zeitschrift der Deutshen Gemmologischen Gesellschaft*, Vol. 55, No. 3/4, pp. 77–104 (in German with English abstract).

Gemological Institute of America (2005) *Gem Identification Lab Manual*, 5th ed. Gemological Institute of America, Carlsbad, CA.

Kaczorowska B., Hacura A., Kupka T., Wrzalik R., Talik E., Pasterny G., Matuszewska A. (2003) Spectroscopic characterization of natural corals. *Analytical and Bioanalytical Chemistry*, Vol. 377, No. 6, pp. 1032–1037.

Laurs B. (2000) Gem News: Coral exploration resumes in Hawaii. *Gems & Gemology*, Vol. 36, No. 3, pp. 263–264.

Liverino B. (1989) *Red Coral*. Transl. by J. H. Johnson, Analisi-Trend s.c.r.l., Bologna, Italy.

Merlin J.C. (1985) Resonance Raman spectroscopy of carotenoids and carotenoid-containing systems. *Pure and Applied Chemistry*, Vol. 57, pp. 758–792.

Merlin J.C., Delé M.L. (1983) Étude par spectroscopie Raman de résonance de la pigmentation des sequelettes calcaires de certains coreaux. *Bulletin de la Société Zoologique de France*, Vol. 108, pp. 289–301.

O'Donoghue M. (2006) *Gems: Their Sources, Descriptions and Identification*, 6th ed. Butterworth-Heinemann, Oxford, U.K.

Pederson M.C. (2004) *Gem and Ornamental Materials of Organic Origin*. Elsevier Butterworth-Heinemann, Oxford, U.K.

Pizzolato V. (2005) Coral and Torre del Greco. http://www.gimav.it/glassinstyle/giugno/coral.pdf.

Prost M.A. (2001) In the red. *Colored Stone*, Vol. 14, No. 4, pp. 32–33.

Rolandi V., Brajkovic A., Adamo I., Bocchio R., Landonio M. (2005) Gem corals: Classification and spectroscopic features. *Australian Gemmologist*, Vol. 22, No. 7, pp. 285–297.

Tsounis G. (2005) Demography, reproductive biology and trophic ecology of red coral (*Corallium rubrum* L.) at the Costa Brava (NW Mediterranean): Ecological data as a tool for management. Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, http://web.awi.de/Publications/Tso2005d.pdf.

Urmos J., Sharma S.K., Mackenzie F.T. (1991) Characterization of some biogenic carbonates with Raman spectroscopy. *American Mineralogist*, Vol. 76, No. 3–4, pp. 641–646.

Walton J. (1959) Coral: Classification of species, method of formation and characteristics. *Gemmologist*, Vol. 28, No. 335, pp. 105–116.

Weldon R. (2003) The sea's vanishing gift. *Professional Jeweler*, Vol. 16, No. 8, pp. 35–36.