

X-RAY COMPUTED MICROTOMOGRAPHY: DISTINGUISHING NATURAL PEARLS FROM BEADED AND NON-BEADED CULTURED PEARLS

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The distinction of natural from cultured pearls traditionally has been based on X-radiography. X-ray computed microtomography (μ -CT) has recently been applied to gain more insight into pearl structures. Using this technique, this article presents features observed in a selection of natural pearls and beaded and non-beaded cultured pearls. Based on these observations, μ -CT is shown to be a powerful tool for pearl identification.

In recent years, we have seen more interest in natural pearls, especially in the high-end jewelry trade (figure 1). A number of important historic natural pearls have been sold at auction in New York, Geneva, Hong Kong, and Dubai. However, the supply of newly harvested natural pearls is very small, and is restricted to only a few local sources, mainly in the Middle East and Southeast Asia. Therefore, most natural pearls in the market today are from old stocks and historical collections, accumulated over many years. They may be found in estate jewelry or restrung into contemporary necklaces.

Cultured pearls are far more abundant than natural pearls in today's market. They mainly consist of Chinese freshwater cultured pearls from *Hyriopsis* spp. (Akamatsu et al., 2001) and saltwater cultured pearls from several mollusks, including *Pinctada maxima* oysters in Australia and along the coast of Southeast Asia, *P. margaritifera* in the Pacific and the Red Sea, *P. martensii* in Japan, *P.*

chemnitzii in China, and *Pteria sterna* in Mexico. As cultivation techniques have improved (Hänni, 2007), the distinction between natural and cultured pearls has become more difficult (see, e.g., Scarratt et al., 2000; Akamatsu et al., 2001; Hänni, 2006; Sturman and Al-Attawi, 2006; Sturman, 2009), and we predict it will be even more challenging in the future.

For decades now, gemologists have relied primarily on X-radiographs for the separation of natural from cultured pearls (Webster, 1994; Sturman, 2009; and references therein). Only recently has X-ray computed microtomography (μ -CT) been applied to pearls (Strack, 2006; Soldati et al., 2008; Wehrmeister et al., 2008; Krzemnicki et al., 2009; Kawano, 2009) and gemstone analysis (Hänni, 2009). This article focuses on the features observed with μ -CT in natural and cultured pearls (non-beaded and beaded). For background on the technique, the reader is referred to Karampelas et al. (2010).

MATERIALS AND METHODS

From over 50 pearls analyzed with μ -CT, we selected 11 natural and 19 cultured pearls for this study, from both freshwater and saltwater mollusks (see table 1). The samples are from the SSEF reference collection, and from reputable sources consisting of pearl farms and collectors of natural pearls (see Acknowledgments).

Imaging was performed on a SkyScan 1172 high-resolution μ -CT scanner (SkyScan NV, Kontich, Belgium), equipped with a 100 kV / 100 μ A X-ray source and a 10 megapixel (4000 \times 2000) X-ray sensitive CCD camera. The system allows for a flexible geometry along the sample path (i.e., objects can be magnified until the boundaries of the field-of-view of the camera are reached). The sample chamber is roughly 30 \times 40 \times 15 cm, but the largest sample that can be imaged is 50 mm in diameter. The scanner allows for image formats up to 8000 \times 8000 pixels. The best achievable pixel size is 600 nm (isotropic), thus allowing a detail detectability below 1 μ m. Reconstruction by means

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Figure 1. X-ray computed microtomography may be an important tool in the analysis of single pearls. This exceptional five-strand natural pearl necklace (4.45–12.20 mm) from the collection of Gourdj des Perles Fines, France, was certified recently at the SSEF Swiss Gemmological Institute. Photo by Luc Phan, © SSEF.

of a modified Feldkamp algorithm was performed on a four-PC 64-bit reconstruction cluster using SkyScan's NRecon platform.

Samples were scanned using an 88 kV accelerating voltage and a target current of 100 μ A, with a full 360° sample rotation (0.30 increment) and an exposure time of 2356 milliseconds per frame. For a voxel size of 2–8 μ m (a voxel is a three-dimensional [3D] pixel), the scan time was less than two hours. A full dataset typically was 30 GB per pearl, and reconstructions took about six hours each. The resulting cross sections were resolved at 2.97 μ m pixel size (4000 \times 4000), and were converted into black-and-white binary bitmap images to model the pearls' internal structures. Additionally, the files were transformed into 3D models using the CTVol platform (SkyScan NV). In the present article, the μ -CT images show a bit more noise than those reported in Karampelas et al. (2010) because we used double frame averaging, while Karampelas et al. used a 10-fold frame averaging with shorter exposure times.

RESULTS AND DISCUSSION

Natural Pearls. Natural pearls are mainly characterized by an onion-like structure of nacre layers, consisting of small aragonite tablets (Gutmannsbauer and Hänni 1994; Sturman, 2009; and references therein). Additionally, pearls contain an organic substance (conchiolin) and some have cores composed of radial calcite columns, which appear darker (in cross-sections and radiographs) due to the enrichment of organic matter. When natural pearls are sawn in half (figure 2), this structure can be observed in detail with a microscope. The μ -CT images of natural pearls show these structures in three dimensions (see item 1 in the *GeG* Data Depository at www.gia.edu/gandg, and figures 6 and 7 of Karampelas et al., 2010). Scrolling through reconstructed virtual slices of a natural pearl is particularly effective for revealing the growth structures, which often are highly uniform in spherical layers. Also typically observed are: (1) fissures due to ageing/drying of

the pearl, which usually partially follow the growth rings of the nacre (see figure 3a and 3b); and (2) curved intersection lines in pearls grown together from two or more individuals (figure 3c). In radiographs, these features might be misinterpreted as cavity structures in a non-beaded cultured pearl.

Beaded Cultured Pearls. Although beaded cultured pearls are generally easy to separate from natural ones using radiography (see, e.g., figure 4 of Karampelas et al., 2010), μ -CT provides a much more detailed view of their structure. For example, the images of sample mxt 14b—an oval *P. maxima* saltwater cultured pearl from Australia—reveal that the bead broke during drilling (figure 4a). Furthermore, the large cavity at the top of this cultured pearl shows a complex structure of layers of organic matter (conchiolin) with small specks of calcium carbonate (seen as bright spots).

More challenging are cultured pearls with bead materials such as non-beaded freshwater and saltwater cultured pearls or even natural pearls of low quality (Hainschwang, 2010a,b; Hänni et al., 2010; Krzemnicki, 2010b). These are deliberately produced to resemble natural pearls as closely as possible. Although they can usually be detected by radiography, μ -CT further strengthens the identification of these cultured pearls (figure 4b).

Non-Beaded Cultured Pearls. The non-beaded cultured pearls analyzed for this study originate from both freshwater (*Hyriopsis* spp.) and saltwater (*P. maxima*, *P. margaritifera*, *P. sterna*) mollusks. The latter ones, sometimes also called "keshi" cultured pearls, have caused considerable concern in the trade (Hänni, 2006; Sturman and Al-Attawi, 2006; Krzemnicki et al., 2009; Sturman, 2009; Krzemnicki, 2010a), as increasing quantities are entering the market, often with excellent shape and color. They are thus rivaling the historic natural pearls and may, when misidentified as such, compromise the allure and rarity of the natural products. Gemmological labs are striving to establish cri-

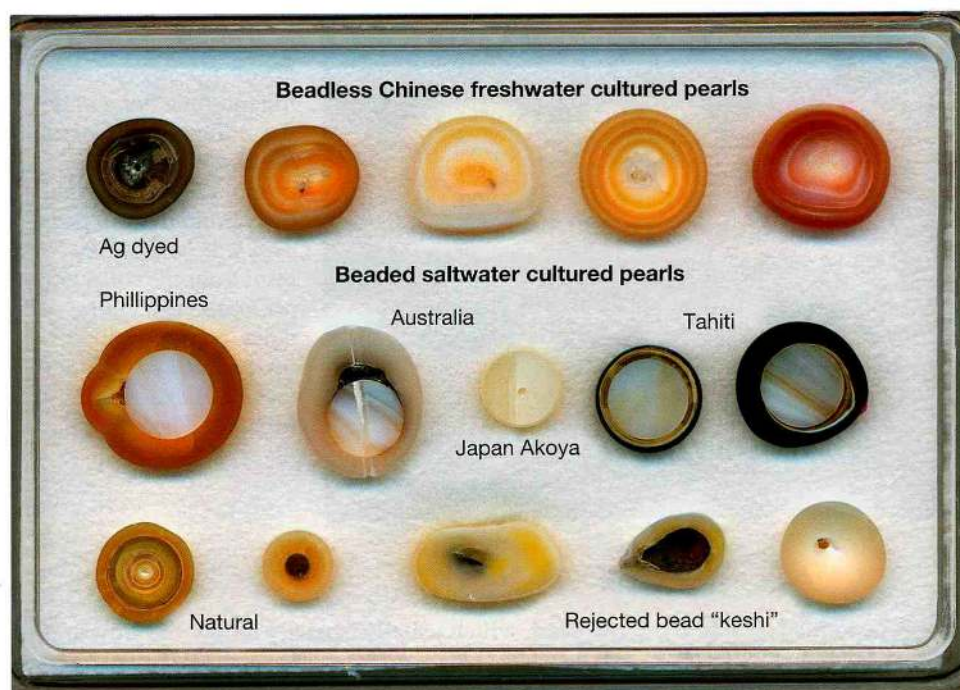


Figure 2. Shown here are sawn non-beaded freshwater cultured pearls (top), beaded saltwater cultured pearls (middle), and natural pearls and non-beaded “keshi” cultured pearls (bottom). Photo by H. A. Hänni, © SSEF.

TABLE 1. Characteristics and μ -CT resolution of the studied pearl samples.^a

| Sample no. | Type | Mollusk | Size (mm) | Shape | Color | Condition | μ -CT resolution (μ m) |
|------------|-----------------|-------------------------|-------------|-------------|-----------------|--------------|---------------------------------|
| mxt 9 | Natural SW | <i>P. radiata</i> | 6.02–6.97 | Oval | Light “cream” | Undrilled | 6.0 |
| mxt 57_2 | Natural SW | <i>P. radiata</i> | 8.32–8.55 | Button | Light “cream” | Undrilled | 3.6 |
| mxt 29 | Natural SW | <i>P. radiata</i> | 9.84–11.20 | Drop | White | Undrilled | 3.0 |
| mxt 44 | Natural SW | <i>P. maxima</i> | 9.55–19.95 | Sl. baroque | White | Undrilled | 3.1 |
| mxt 45 | Natural SW | <i>P. maxima</i> | 7.60–13.50 | Baroque | White | Undrilled | 3.5 |
| mxt 63_2 | Natural SW | <i>P. radiata</i> | 8.20–8.31 | Round | “Cream” | Drilled | 2.5 |
| mxt 63_10 | Natural SW | <i>P. radiata</i> | 8.46–8.55 | Round | “Cream” | Drilled | 2.5 |
| mxt 63_15 | Natural SW | <i>P. radiata</i> | 8.96–9.57 | Oval | Light “cream” | Drilled | 2.5 |
| mxt 63_18 | Natural SW | <i>P. radiata</i> | 9.39–10.10 | Oval | Light “cream” | Drilled | 2.5 |
| mxt 70 | Natural SW | <i>P. radiata</i> | 9.42–11.20 | Button | Light “cream” | Undrilled | 3.0 |
| mxt 3 | Natural FW | Unionida | 6.87–7.18 | Round | Slightly “rosé” | Undrilled | 3.0 |
| mxt 14b | Beaded SWCP | <i>P. maxima</i> | 8.80–11.96 | Oval | White | Drilled | 4.9 |
| mxt 31 | Beaded SWCP | <i>P. maxima</i> | 10.49–10.92 | Round | Yellow | Half drilled | 3.5 |
| HAH_1 | Beaded SWCP | <i>P. maxima</i> | 9.12–9.25 | Round | White | Undrilled | 3.6 |
| HAH_2 | Beaded SWCP | <i>P. margaritifera</i> | 9.26–9.47 | Round | Dark gray | Undrilled | 3.6 |
| mxt 21_1 | Beaded SWCP | <i>P. maxima</i> | 6.55–18.54 | Baroque | White | Undrilled | 4.0 |
| mxt 37_1 | Non-beaded SWCP | <i>P. maxima</i> | 9.19–12.98 | Baroque | White | Undrilled | 2.6 |
| mxt 37_17 | Non-beaded SWCP | <i>P. maxima</i> | 8.05–11.10 | Oval | White | Half-drilled | 2.3 |
| mxt 61_14 | Non-beaded SWCP | <i>P. maxima</i> | 6.59–8.56 | Button | Yellow | Undrilled | 3.5 |
| mxt 61_20 | Non-beaded SWCP | <i>P. maxima</i> | 6.91–7.62 | Oval | White | Undrilled | 3.6 |
| mxt 68 | Non-beaded SWCP | <i>P. maxima</i> | 12.68–12.92 | Round | Light “cream” | Drilled | 3.6 |
| mxt 197 | Non-beaded SWCP | <i>P. maxima</i> | 10.66–14.95 | Drop | White | Half drilled | 3.6 |
| mxt 198 | Non-beaded SWCP | <i>P. maxima</i> | 10.00–13.28 | Drop | White | Half drilled | 3.9 |
| mxt 21_2 | Non-beaded SWCP | <i>P. maxima</i> | 14.30–20.52 | Baroque | White | Undrilled | 4.0 |
| mxt 1 | Non-beaded FWCP | <i>Hyriopsis</i> spp. | 10.58–11.41 | Oval | Light orange | Undrilled | 4.9 |
| mxt 2 | Non-beaded FWCP | <i>Hyriopsis</i> spp. | 8.51–10.82 | Sl. baroque | White | Undrilled | 4.0 |
| mxt 13a | Non-beaded FWCP | <i>Hyriopsis</i> spp. | 9.80–13.70 | Drop | White | Undrilled | 5.4 |
| mxt 97 | Non-beaded FWCP | Unionida | 14.38–16.30 | Button | Light “cream” | Undrilled | 4.2 |
| mxt 98 | Non-beaded FWCP | Unionida | 15.70–17.56 | Oval | White | Undrilled | 3.7 |
| mxt 99 | Non-beaded FWCP | Unionida | 17.54–20.84 | Oval | Orange | Undrilled | 4.6 |

^a Abbreviations: FW = freshwater, SW = saltwater, FWCP = freshwater cultured pearl, SWCP = saltwater cultured pearl, Sl. = slightly.

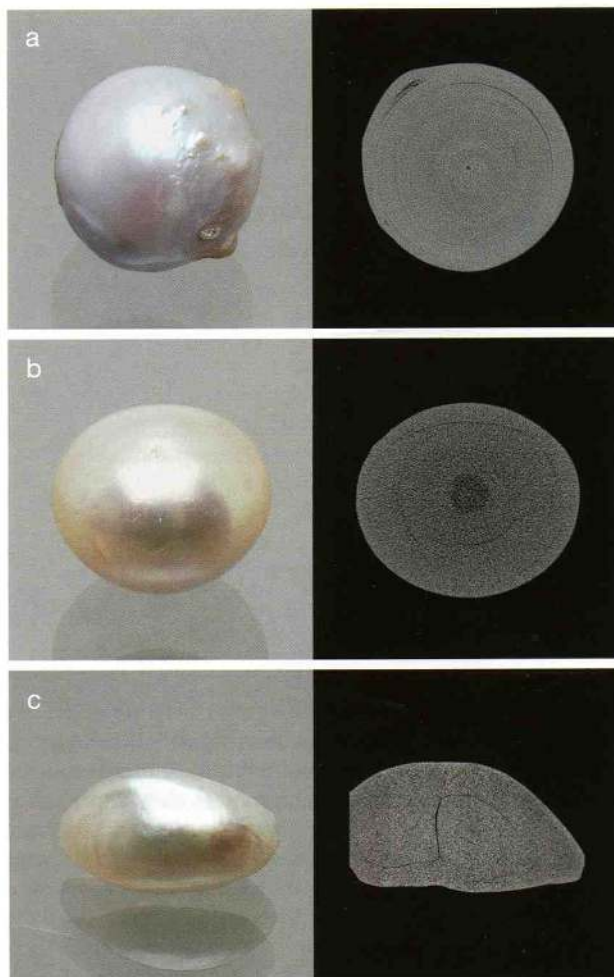


Figure 3. These photos and tomographic sections of natural pearls include (a) a *Unionida* natural freshwater pearl (sample mxt 3) from Mississippi showing a small dark dot in the center due to organic matter; (b) a *P. radiata* natural saltwater pearl (mxt 9) from the Persian Gulf showing a larger dark central zone consisting of columnar calcite interlayered with some organic matter as well as partially concentric fissures; and (c) a *P. maxima* natural saltwater pearl from Vietnam (mxt 44) showing structures due to the merging of two pearls during the growth history. The fine highly concentric circular structure seen in the tomographic section of (a) is an artifact, and is not the same as the growth structure of the pearl (see Karampelas et al., 2010). Photos by M. S. Krzemnicki, © SSEF. See also Data Depository item 1.

teria for separating these non-beaded saltwater cultured pearls from their natural counterparts. To better understand the structures in these cultured pearls, we have differentiated them into two categories: (1) cultivation from a piece of mantle tissue only, and (2) cultivation from mantle tissue after the bead inserted at the same time has been rejected.

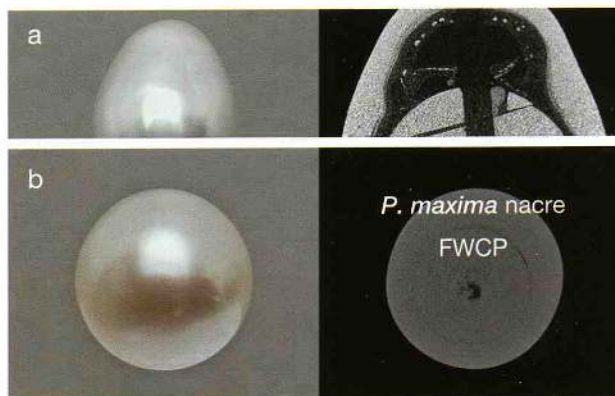
If a non-beaded cultured pearl is grown directly from a

NEED TO KNOW

- X-ray computed microtomography is effective for separating natural from cultured pearls, even those that contain pearls as bead materials.
- Natural pearls are mainly characterized by a uniform onion-like structure of nacre layers and conchiolin.
- Freshwater non-beaded cultured pearls contain small curved cavity structures in their centers.
- Saltwater non-beaded cultured pearls ("keshi") may show these curved structures, as well as larger cavities or calcareous spots in their center.

piece of inserted mantle tissue—such as Chinese freshwater products, but possibly other varieties (Hänni, 2008)—then a small curved cavity structure ("moustache") will be present in its center (Scarratt et al., 2000). This cavity structure represents the outline of initial nacre formation within the wrinkled mantle tissue after it has formed the pearl sac in the mollusk. The "moustache" may be difficult to see on radiographs, often requiring magnification. When we scroll through tomographic sections, however, this irregu-

Figure 4. Photos and tomographic images of beaded saltwater cultured pearls are shown for (a) a *P. maxima* specimen from Australia (mxt 14b) with a bead that broke during drilling, as well as a large cavity containing many small white calcium carbonate spots; and (b) a *P. maxima* sample (HAH_1) containing a non-beaded Chinese freshwater cultured pearl as the nucleus. The irregular cavity structure of the non-beaded cultured pearl nucleus is evident in the center. Photos by M. S. Krzemnicki, © SSEF. See also Data Depository item 2.



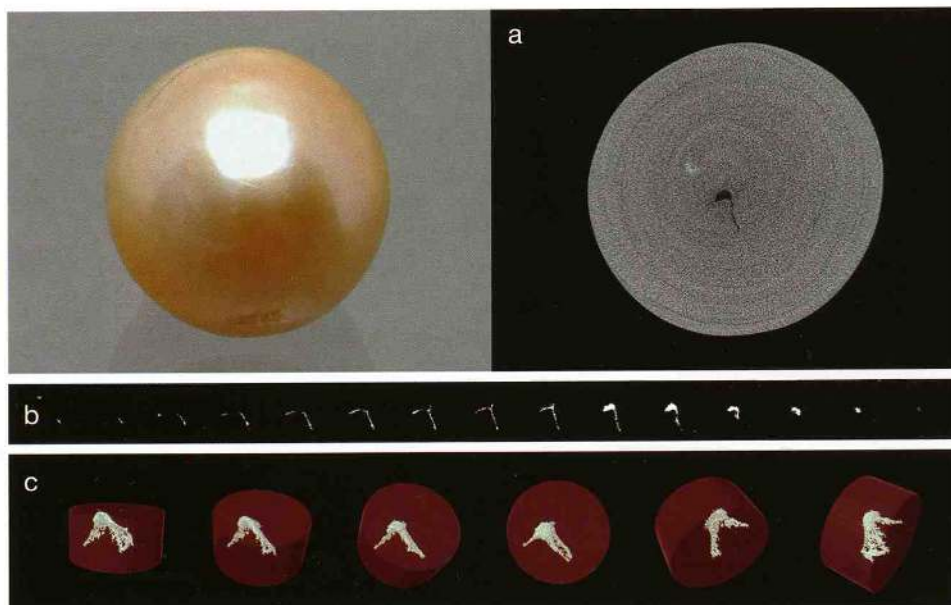
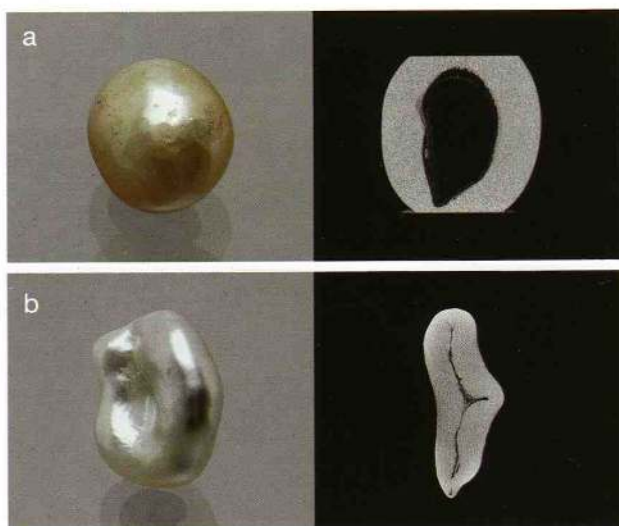


Figure 5. This non-beaded freshwater cultured pearl (mxt 1) from China has a characteristic curved "moustache" that was barely visible with radiography. With μ -CT, this structure is clearly seen in: (a) a transaxial (horizontal) section, (b) a series of overlying transaxial sections transformed into black/white bitmap files, and (c) movie stills that show it from different angles. Photo by M. S. Krzemnicki, © SSEF. See also Data Depository item 3.

larly curved structure is much more obvious (figure 5a) and can even be visualized in three dimensions (figure 5b,c). In the μ -CT images of some samples, we also observed portions with a slightly darker gray appearance (not necessarily located in the center), which were similar to those described by Soldati et al. (2008) and Wehrmeister et al. (2008) as vaterite-rich zones within freshwater cultured pearls. However, more research is needed to verify this.

Figure 6. Vertical (coronal) tomographic sections of these non-beaded saltwater cultured pearls show: (a) a large smoothly curved cavity structure (mxt 61_14; *P. maxima*, Australia), and (b) an irregular cavity structure due to a collapsed pearl sac (mxt 37_1). Photos by M. S. Krzemnicki, © SSEF. See also Data Depository item 3.



For the cultured pearls grown after bead rejection, we have observed two types of features, possibly dependent on the stage at which the bead was rejected. For beads rejected during the first generation of cultivation, the mantle tissue inserted (commonly into the gonad) behaves as described above, forming a pearl sac and subsequently precipitating calcium carbonate (Hänni, 2006). Thus, we expect to see a rather small and thin curved "moustache" structure in the cultured pearl (similar to figure 5c) or a small rounded hollow cavity. These cultured pearls are often button- to oval- and drop-shaped. Alternatively, for those formed after bead rejection during a second (or later) cultivation period (i.e., when a preexisting pearl sac, usually in the gonad, was filled again with a bead that was rejected shortly thereafter), we observe larger cavities within the cultured pearl (figure 6a), often slightly curved (Farn, 1984; Hänni, 2006; Sturman, 2009). In cases where the pearl sac collapsed, we will see large and flat irregular cavity structures (figure 6b) in pearls, which often show a baroque shape.

In some cases, especially in *Pinctada* spp. mollusks, small "additional" cultured pearls may form within the pearl sac, probably due to injuries during bead insertion (Hänni, 2006). Their internal structures are quite characteristic, often showing one or two small nacreous spots in the center (similar to the calcium carbonate spots seen in figure 4a), surrounded by an organic-rich core and a nacreous outer layer. Figure 7 shows a sliced specimen consisting of a pair of such "additional" cultured pearls attached to a beaded cultured pearl that formed within the gonad of a *P. maxima* oyster. The white calcareous spots in the centers are clearly visible. This feature is also evident in the μ -CT scans of a similar beaded cultured pearl (*P. maxima*) with an "additional" cultured pearl attached (figure 8a). However, the "additional" cultured pearls need not be attached to a beaded cultured pearl, and may be found loose in the pearl sac. Figure 8b shows a complex case that

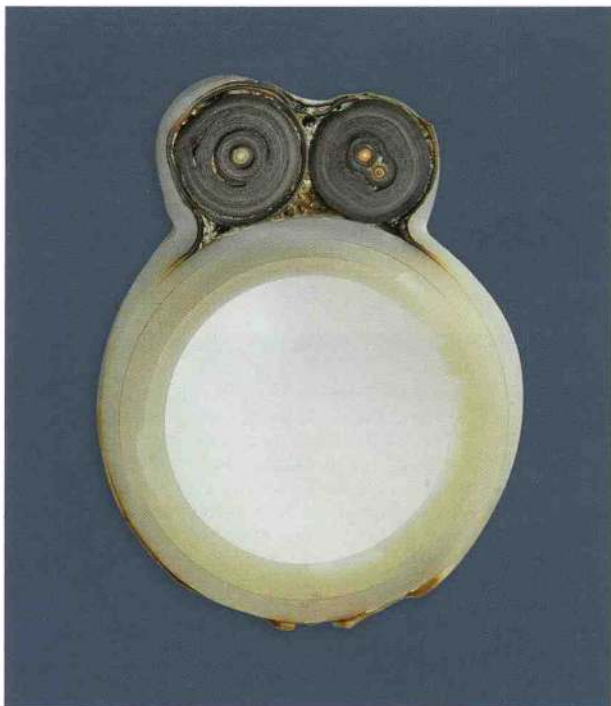


Figure 7. This sliced specimen (12 mm in diameter) shows a beaded cultured pearl with two attached cultured pearls that formed additionally in the pearl sac (in the gonad of *P. maxima*). Note the white calcareous spots in the centers of these “additional” non-beaded cultured pearls. Photo by H. A. Hänni, © SSEF.

appears to consist of an “additional” non-beaded cultured pearl (again with a light-appearing spot in the center) that was apparently overlooked when harvesting a first-generation beaded cultured pearl from the pearl sac in the gonad of a *P. maxima* oyster. Soon after, a second bead was introduced into the existing pearl sac, but was rejected. As a result the pearl sac collapsed, producing the complex internal pattern of this baroque-shaped cultured pearl.

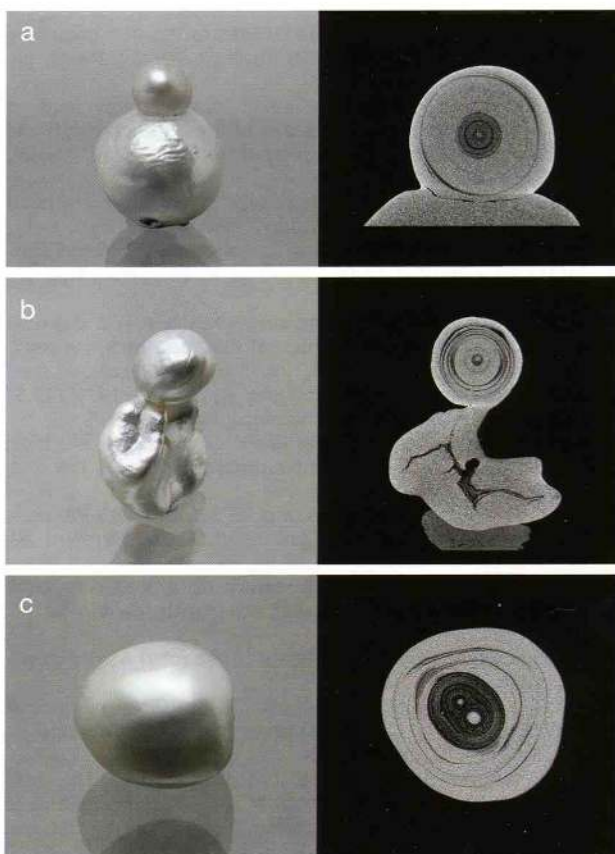
Furthermore, the loose “additional” cultured pearls may be harvested and used as “keshi” cultured pearls (Krzemnicki, 2010a). Figure 8c shows such a loose “additional” cultured pearl, again with a calcareous spot in the center. These cultured pearls show a disturbing resemblance to natural pearls, and can be identified only by careful observations of radiographs or μ -CT scans (Krzemnicki, 2010a). We have also found indications that attached “additional” cultured pearls (such as in figure 8a) have been seen from beaded cultured pearls and then used as beads for new cultured pearls, deliberately imitating the internal structures of natural pearls as much as possible.

CONCLUSIONS

The separation of natural from cultured pearls can be quite challenging, especially in light of new developments in pearl cultivation. X-ray computed microtomography is a powerful technique for visualizing internal structures that provide diagnostic evidence of natural vs. cultured pearl

origin. The advantage of this method lies in its high-resolution 3D modeling capability (see also G&G Data Depository and www.ssef.ch). In contrast, traditional radiography only provides a condensed 2D image of pearl structures. Small curved or folded cavity structures indicative of tissue culturing may only be discernible by carefully examining multiple radiographs taken at various orien-

Figure 8. These non-beaded saltwater cultured pearls show some particularly interesting features; all have a small calcareous spot in the center. (a) An “additional” cultured pearl is attached to a beaded cultured pearl (mxt 21_2; *P. maxima*) from Australia. (b) A baroque-shaped specimen (mxt 21_1; *P. maxima*) shows complex structures formed by a non-beaded cultured pearl attached to a non-beaded cultured pearl with a large irregular cavity structure due to a collapsed pearl sac (see also Data Depository item 4). (c) This “additional” cultured pearl (mxt 61_20) probably formed due to injuries during grafting of a silver-lipped pearl oyster (*P. maxima*). Although the structures are similar to those seen in natural pearls, the presence of calcium carbonate spots surrounded by organic-rich layers and subsequent nacre deposition is characteristic of these cultured pearls. Photos by M. S. Krzemnicki, © SSEF.



tations. Furthermore, fissures may be misinterpreted as cavity structures, as their 3D position within the pearl is not readily visible in radiographs. (For more details on advantages and limitations of the μ -CT method, see Karampelas et al., 2010.)

Although all the described internal features may be

discernible with careful radiography, μ -CT provides additional useful structural information. Based on our experience, we conclude that μ -CT shows great potential for pearl testing. However, additional problematic samples need to be studied to fully assess the advantages of this method as compared to X-ray radiography.

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REFERENCES

- Akamatsu S., Zansheng I.T., Moses T.M., Scarratt K. (2001) The current status of Chinese freshwater cultured pearls. *G&G*, Vol. 37, No. 2, pp. 96–113.
- Farn A.E. (1980) Notes from the laboratory (on non-nucleated cultured pearls). *Journal of Gemmology*, Vol. 17, No. 4, pp. 223–229.
- Gutmannsbauer W., Hänni H.A. (1994) Structural and chemical investigations on shells and pearls of nacre forming salt- and freshwater bivalve molluscs. *Journal of Gemmology*, Vol. 24, No. 4, pp. 241–252.
- Hainschwang T. (2010a) A difficult new type of cultured pearl entering the market. *Gemnotes*, Vol. 1, No. 2, pp. 6–11, www.gemlab.net/website/gemlab/fileadmin/user_upload/GEMNOTES/Gemnotes-16-05-10.pdf [date accessed: May 18, 2010].
- Hainschwang T. (2010b) The pearl story continues — A *Pinctada maxima* pearl beaded by a natural *Pinctada maxima* pearl. *Gemnotes*, Vol. 1, No. 3, pp. 5–7, www.gemlab.net/website/gemlab/fileadmin/user_upload/GEMNOTES/Gemnotes-24-06-10.pdf [date accessed: June 28, 2010].
- Hänni H.A. (2006) A short review of the use of 'keshi' as a term to describe pearls. *Journal of Gemmology*, Vol. 30, No. 1–2, pp. 52–58.
- Hänni H.A. (2007) A description of pearl farming with *Pinctada maxima* in South East Asia. *Journal of Gemmology*, Vol. 30, No. 7–8, pp. 357–365.
- Hänni H.A. (2008) Gem News International: *Pinctada maxima* cultured pearls grown beadless in the mantle. *G&G*, Vol. 44, No. 2, pp. 175–176.
- Hänni H.A. (2009) How much glass is in the ruby? *SSEF Facette*, No. 16, pp. 8–9.
- Hänni H.A., Krzemnicki M.S., Cartier L. (2010) Appearance of new bead material in cultured pearls. *Journal of Gemmology*, Vol. 32, No. 1–4 (in press).
- Karampelas S., Michel J., Zheng-Cui M., Schwarz J.-O., Enzmann F., Fritsch E., Leu L., Krzemnicki M.S. (2010) X-ray computed microtomography applied to pearls: Methodology, advantages, and limitations. *G&G*, Vol. 46, No. 2, pp. 122–127.
- Kawano J. (2009) Observation of the internal structures of pearls by X-ray CT technique. *Gemmology*, Vol. 40, No. 478, Issue 7, pp. 2–4 [in Japanese].
- Krzemnicki M.S. (2010a) Trade Alert: "Keshi" cultured pearls are entering the natural pearl trade. *SSEF Newsletter*, May, www.ssef.ch/en/news/news_pdf/newsletter_pearl_2010May.pdf [date accessed: May 12, 2010].
- Krzemnicki M.S. (2010b) Addendum: ... And what happens with the beaded cultured pearls? *SSEF Newsletter*, May, www.ssef.ch/en/news/news_pdf/newsletter_pearl_2010May_add.pdf [date accessed: May 20, 2010].
- Krzemnicki M.S., Friess S., Chalup P., Hajdas I., Hänni H.A. (2009) New developments in pearl analysis: X-ray microtomography and radiocarbon age dating. *Journal of the Gemmological Association of Hong Kong*, Vol. 30, pp. 43–45.
- Scarratt K., Moses T.M., Akamatsu S. (2000) Characteristics of nuclei in Chinese freshwater cultured pearls. *G&G*, Vol. 36, No. 2, pp. 98–109.
- Soldati A.L., Jacob D.E., Wehrmeister U., Hofmeister W. (2008) Structural characterization and chemical composition of aragonite and vaterite in freshwater cultured pearls. *Mineralogical Magazine*, Vol. 72, No. 2, pp. 577–590.
- Strack E. (2006) *Pearls*. Rühle-Diebener Verlag, Stuttgart, Germany, 707 pp.
- Sturman N. (2009) The microradiographic structures of non-bead cultured pearls. GIA Thailand, Bangkok, August 20, www.giathai.net/pdf/The_Microradiographic_structures_in_NBCP.pdf [date accessed: Oct. 1, 2009].
- Sturman N., Al-Attawi A. (2006) The "keshi" pearl issue. *G&G*, Vol. 42, No. 3, p. 142.
- Webster R. (1994) *Gems: Their Sources, Description, and Identification*, 5th ed. Rev. by P. G. Read, Butterworth-Heinemann, Oxford, UK, 1026 pp.
- Wehrmeister U., Goetz H., Jacob D.E., Soldati A.L., Xu W., Duschner H., Hofmeister W. (2008) Visualization of the internal structure of freshwater cultured pearls by computerized X-ray microtomography. *Journal of Gemmology*, Vol. 32, No. 1–2, pp. 15–21.