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GROWTH AND DIAGENESIS OF MIDDLE JURASSIC BELEMNITE ROSTRA FROM NORTHEASTERN UTAH: INSIGHTS USING CATHODOLUMINESCENCE

B. R. O'Neill*, W. L. Manger & P. D. Hays

Department of Geosciences, University of Arkansas, Fayetteville, Arkansas 72701, United States
*corresponding author: boneill@uark.edu

ABSTRACT

Standard thin sections of fragmental belemnite rostra collected from the Middle Jurassic Curtis Member, Stump Formation, northeastern Utah, were examined by petrographic methods and cathodoluminescence (CL). Microstructure of the rostra consists of radially arranged, non-ferroan calcite crystals traversed by numerous growth rings that become more closely spaced toward the rostrum's outer margin. The rostral crystals are syntaxial across the growth rings. Diagenetic alteration is not obvious by standard petrographic inspection. Under CL, most rostral crystals are dully luminescent, while some growth rings, infilled microfractures, and the cement of the material filling the alveolus are brightly luminescent. Scanning electron microscopy of etched specimens demonstrates the continuity of the growth rings as discrete, platy, carbonate microlaminae confirming that the brightly luminescent material is actually a replacement product along the growth rings. Relationships are equivocal, however, because some growth rings do not luminesce, and other brightly luminescent bands do not correspond to obvious growth rings, when viewed in plane polarized light. Nevertheless, CL analysis clearly shows considerable diagenetic alteration of the rostra that is not obvious using standard petrographic techniques. This complex diagenetic history may impact conclusions involving rostral chemistry drawn on the assumption that they are unaltered. The crowding of growth rings and the concentration of diagenetic carbonate along their surfaces suggests the possibility that significant interruptions to growth occur along those surfaces. A rapid to slow rostral carbonate precipitation, with occasional interruptions, is consistent with a long, perhaps continuous, growth history for at least the belemnite taxa studied herein.

INTRODUCTION

Belemnite rostra are abundant in many marine horizons of Jurassic and Cretaceous age in the Colorado Plateau and western Rocky Mountain Provinces of the western portion of the continental United States (n.b. in general, the term rostrum designates the non-septate posterior portion of the belemnite phragmocone, while European practice sometimes designates that same feature the guard; see also Sælen 1989). Belemnite rostra collected from the Middle Jurassic Curtis Member, Stump Formation, exposed in northeastern Utah exhibit a complex post-depositional history involving at least two episodes of groundwater diagenesis that cannot be distinguished, for the most part, by standard thin section petrography (O'Neill *et al.* 2002a, 2002b). This situation may be common, but unrecognized, in many other belemnite occurrences, and may adversely effect conclusions based on the chemistry of what were thought to be unaltered specimens.

LITHOSTRATIGRAPHY

The name Curtis is applied widely throughout the Colorado Plateau, usually as a formation within the San Rafael Group (Peterson 1988). Typically, the name designates thin, restricted, Middle Jurassic, marine strata resting unconformably on thick, eolian sandstones of the Middle Jurassic Entrada Sandstone,

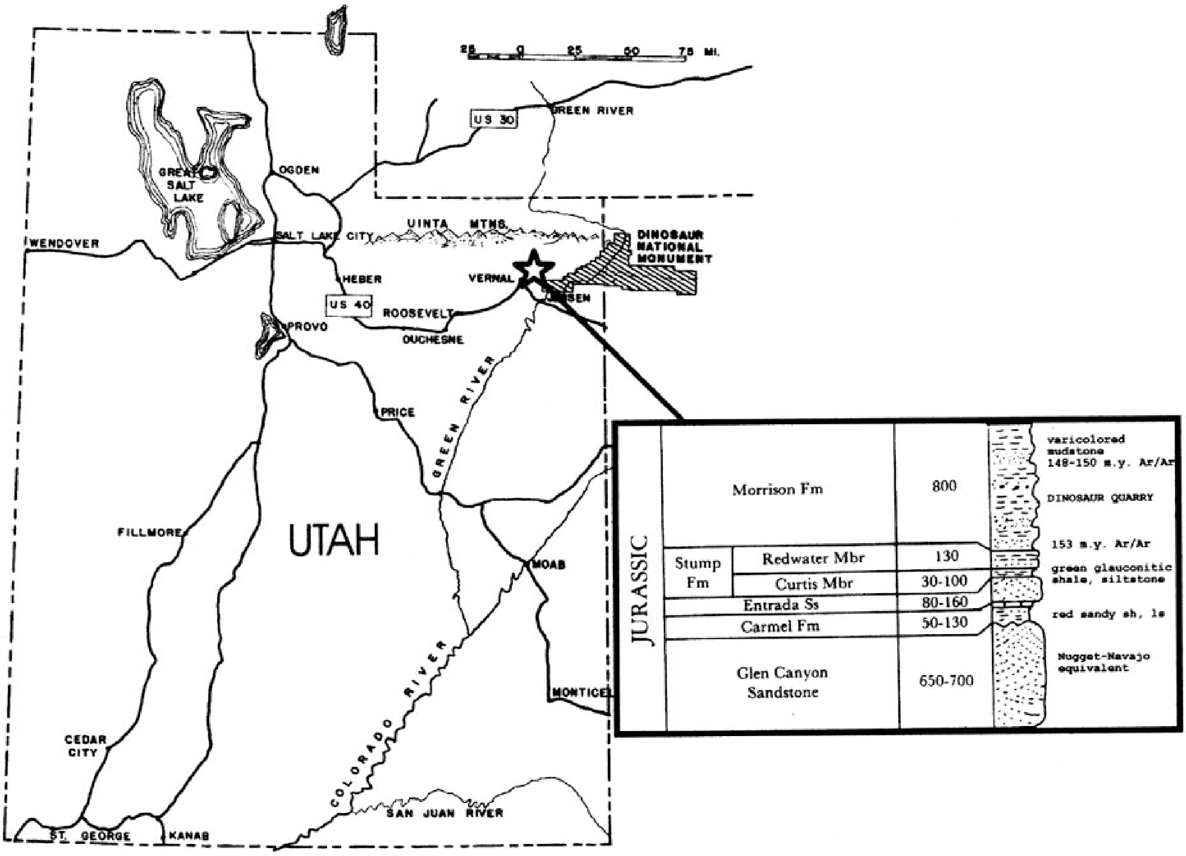
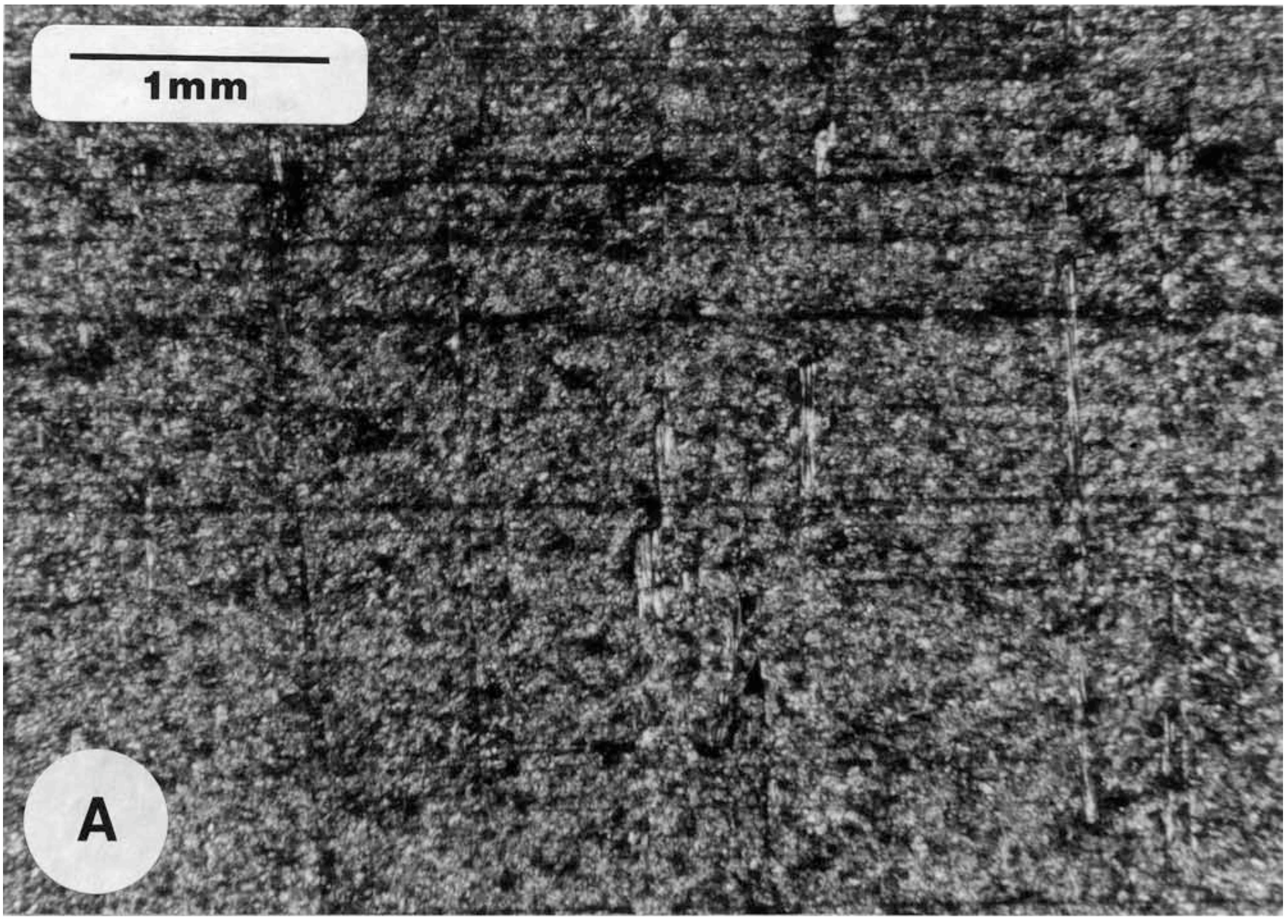


Fig. 1 Index map of Utah showing the area of the sections collected for this study (star) between the southeastern margin of the Uinta Mountains and Dinosaur National Monument (from Untermann & Untermann 1968). Inset of the Jurassic lithostratigraphy for the study area taken from Hintze (1988). Unit thicknesses are in feet. Note that the name Curtis is used as a member of the Stump Formation in this region

and either succeeded conformably by the Middle Jurassic Summerville Formation, or unconformably by the Late Jurassic Sundance Formation (Baars *et al.* 1988, Peterson 1988). In northeastern Utah, the Curtis interval is assigned as the lower member of the Stump Formation, and is separated by an unconformity from the overlying Redwater Shale Member (Hintze 1988) (Fig. 1). In this same area, the Stump Formation is overlain unconformably by the Late Jurassic/Early Cretaceous terrestrial Morrison Formation (Fig. 1).

Lithologically, the marine Curtis Member, Stump Formation, comprises a basal, light-brown, glauconitic, quartz sandstone, overlain by a succession of green-gray to brown, silty shales and interbedded light-colored, glauconitic, quartz sandstones with less common light gray to light-brown carbonate packstones and quartz-bearing, oolitic grainstones (Untermann & Untermann 1968). In northeastern Utah, the Curtis interval reaches its maximum thickness of 31 m (100 ft) in the vicinity of Dinosaur National Monument (Hintze 1988; Fig. 1).

Fig. 2 Thin section photomicrographs of belemnite rostrum. **A**, unstained, longitudinal section of specimen (RFR-4) from Red Fleet Reservoir locality viewed in plane polarized light under low magnification. Dorsal surface is toward top of view. Growth rings (numerous dark horizontal lines) exhibit close and irregular spacing, but seem to be more closely spaced toward dorsal margin. Edges of calcite rostral crystallites parallel to the section plane are shown as lighter, nearly vertical lines. Note that they are continuous across growth lines; **B**, same specimen viewed at slightly higher magnification under crossed-nicols (dark areas are crystallites at extinction). Note the syntaxial character of the rostral crystallites as they cross the growth lines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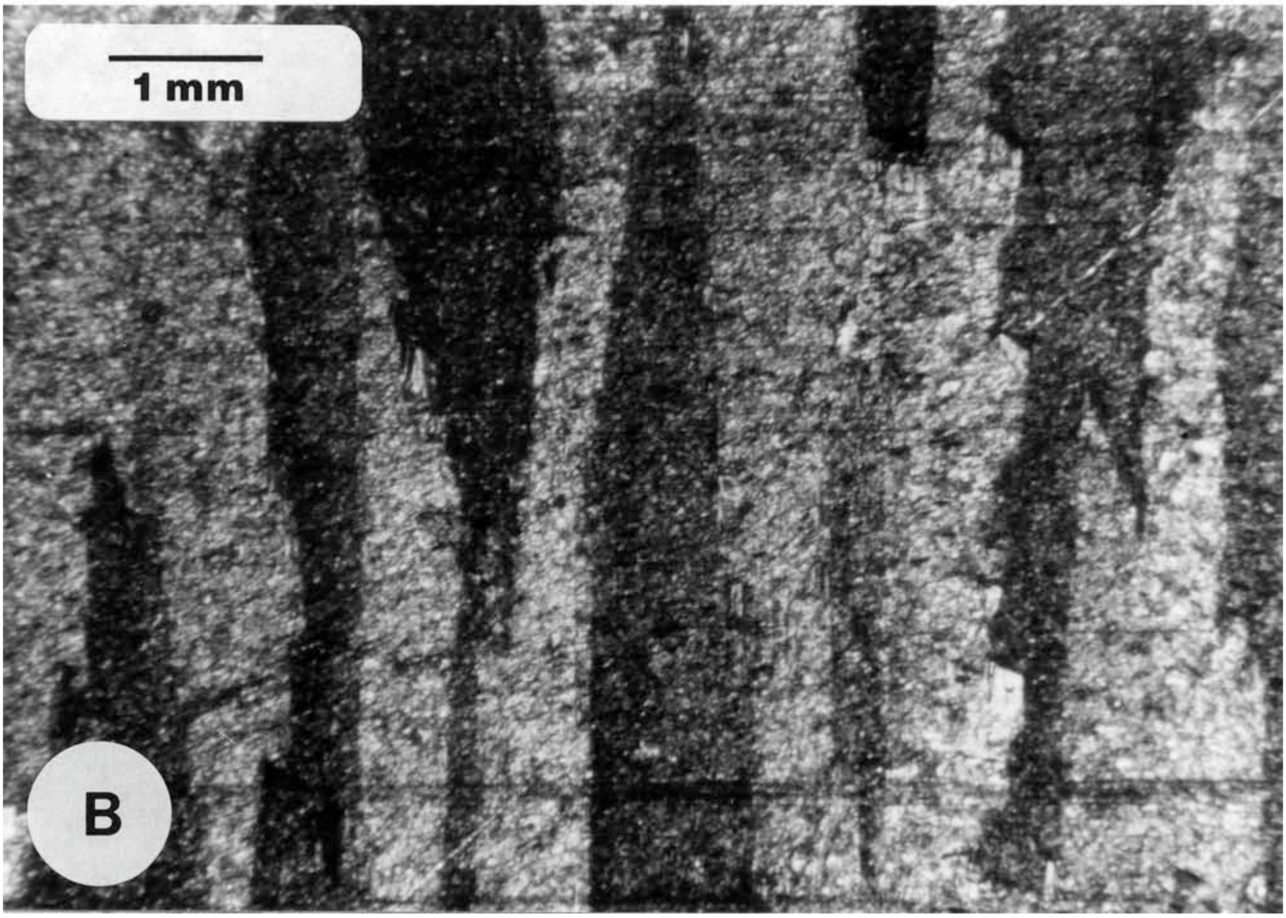
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LOCALITIES

The material utilized for this study was collected along the south flank of the eastern Uinta Mountains, near Dinosaur National Monument, in northeastern Utah (Fig. 1). Three localities were available within the Middle Jurassic Curtis Member, Stump Formation, which is almost continuously exposed as a thin, nonresistant interval packaged between thicker, ridge-forming sandstones along the south flank of the main Uinta uplift. Several hundred, mostly fragmental rostra were collected as surface float at each locality; local stratigraphic control was established by reference to persistent sandstone and limestone beds. There is a variation of large through small specimens present at all three localities. No attempt was made to treat the material taxonomically, but the results reported herein are derived from the larger specimens usually referred to *Pachyteuthis densus* (Meek) (Untermann & Untermann 1968, Hansen 1969).

In addition to surface collections, *in situ* rostra were collected by excavation of productive shale intervals. It is worth noting that the Curtis Member at these northeastern Utah localities does not exhibit concentrations of rostra as "rostral coquinas" that have been reported from elsewhere in the literature, and seem to be typical of many belemnite occurrences (e.g. "Belemnite Battlefields" Thenius 1973, Hewitt 1980). Whether these Utah belemnite occurrences are semelparous thanatocoenoses remains an open question (Hewitt 1980).

ROSTRAL PETROGRAPHY

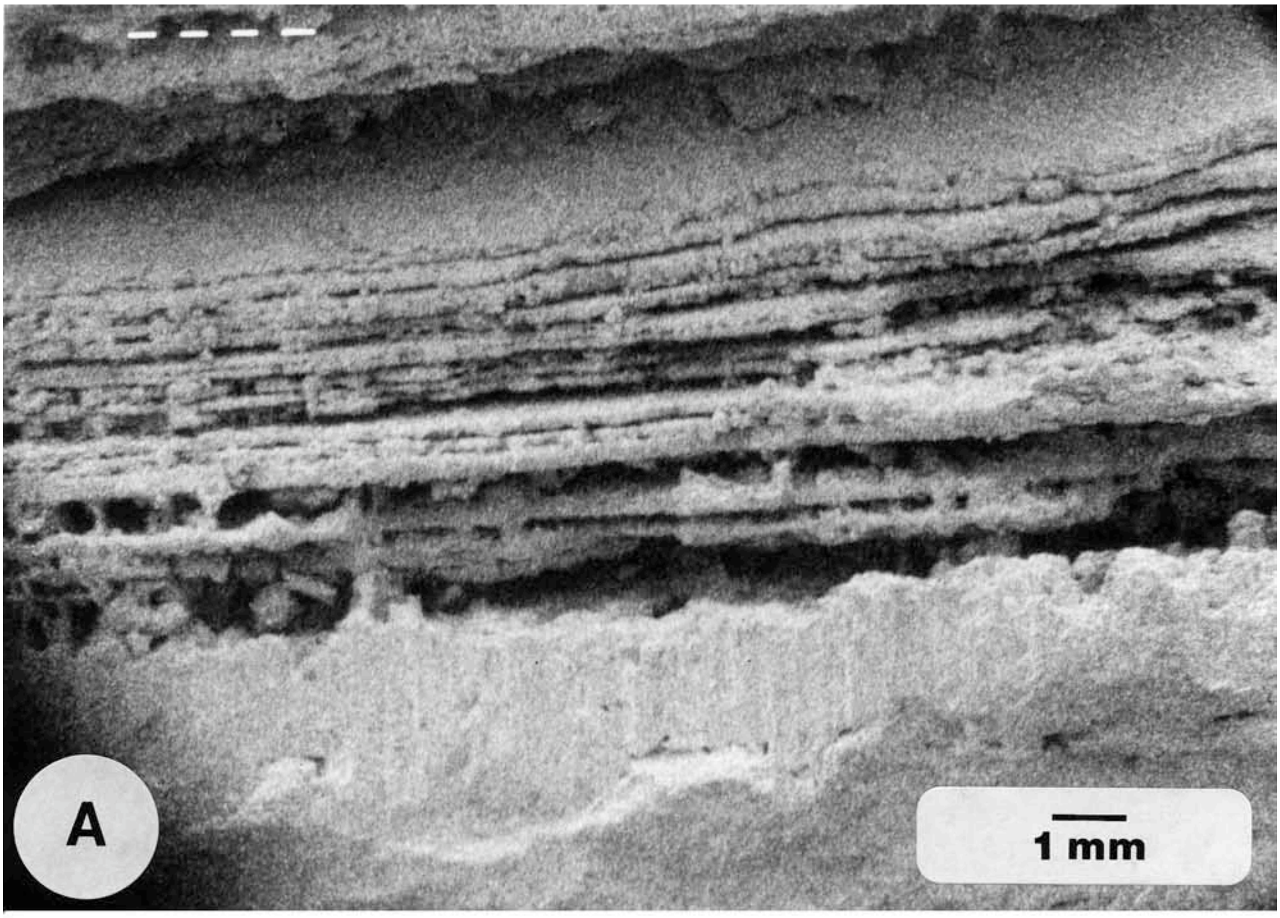
Radially arranged crystals of non-ferroan calcite form the belemnite rostrum. The original composition of the belemnite rostrum is still somewhat in question, but probably was low-Mg calcite (Veizer 1974, Sælen 1989, Barbin 2000). No other carbonates that can be identified by staining were observed in the Utah rostra. Based on assumed composition, staining and petrographic examination, one might conclude that these specimens are unaltered, but that is not the case.

Growth is initiated at the protoconch, and the rostral carbonate is periodically added by simultaneous accretion over the outer surface of the rostrum (Mutvei 1964, Doyle 1985, Sælen 1989). Consequently, each period of carbonate addition replicates the entire structure; the surface of the rostrum is all the same generation of precipitated carbonate. In section, the rostrum exhibits numerous, obvious, concentric, apparent discontinuities in crystallite formation that have been interpreted traditionally as growth increments and called growth rings following Sælen (1989). Fig. 2A is a photomicrograph of a standard petrographic thin section of an unstained, longitudinal section of a belemnite rostrum viewed under plane polarized light at low magnification. There are two features of interest visible in this section. First, growth rings are closely spaced, although the growth ring thickness and spacing are both irregular. Second, the radially arranged calcite crystallites forming the rostrum maintain their continuity as they cross the growth rings. Most crystallites extend the entire thickness of the rostrum even though they cross numerous growth rings. In Fig. 2B, the same specimen is viewed at higher magnification with crossed nicols. The syntaxial character of the rostral crystallites is clearly visible as they cross the growth rings.

SCANNING ELECTRON MICROSCOPY

Scanning electron microscopy (SEM) was utilized to examine the relationship of the radiating rostral crystallites and the growth rings. SEM photographs (Fig. 3) of a specimen from our locality near Dinosaur National Monument confirm the thin section observations that calcite crystallites are continuous as they cross the irregularly spaced growth rings. SEM photographs also demonstrate that the growth rings are mineralized, and are less susceptible to etching than are

Fig. 3 Longitudinal section of naturally etched belemnite rostrum (DNM-1) viewed with Scanning Electron Microscope. Gold coated specimen from locality near Dinosaur National Monument. **A**, low magnification exhibits irregularly spaced growth rings that provide a stepped appearance to the ventral portion of this rostrum because they have been mineralized. **B**, etch pitting of another area on the same specimen emphasizes the continuity and resistance to solution of the mineralized growth rings near its dorsal margin. Top of this view is the dorsal surface of the rostrum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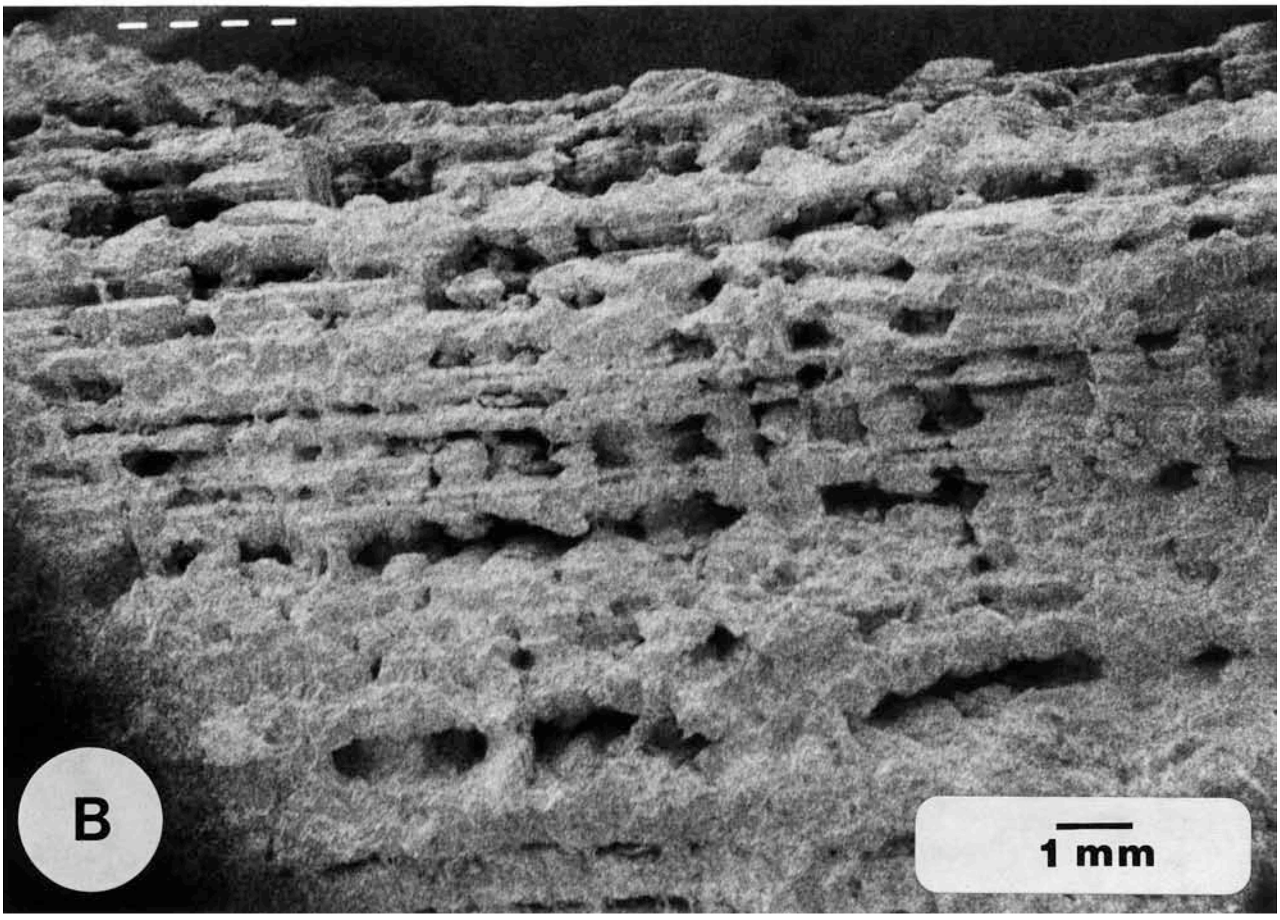
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the rostral crystallites (Fig. 3; compare with Sælen 1989). In both photographs, the irregularly spaced growth rings exhibit a thickness and continuity as a result of mineralization. The etch pitting in both these views reflects mostly removal of rostral carbonate between the growth rings, and not dissolution along the growth rings. The mineralized growth rings in this specimen exhibit equal or greater resistance to dissolution than do the associated rostral crystallites (Fig. 3B; see also Sælen 1989).

CATHODOLUMINESCENCE

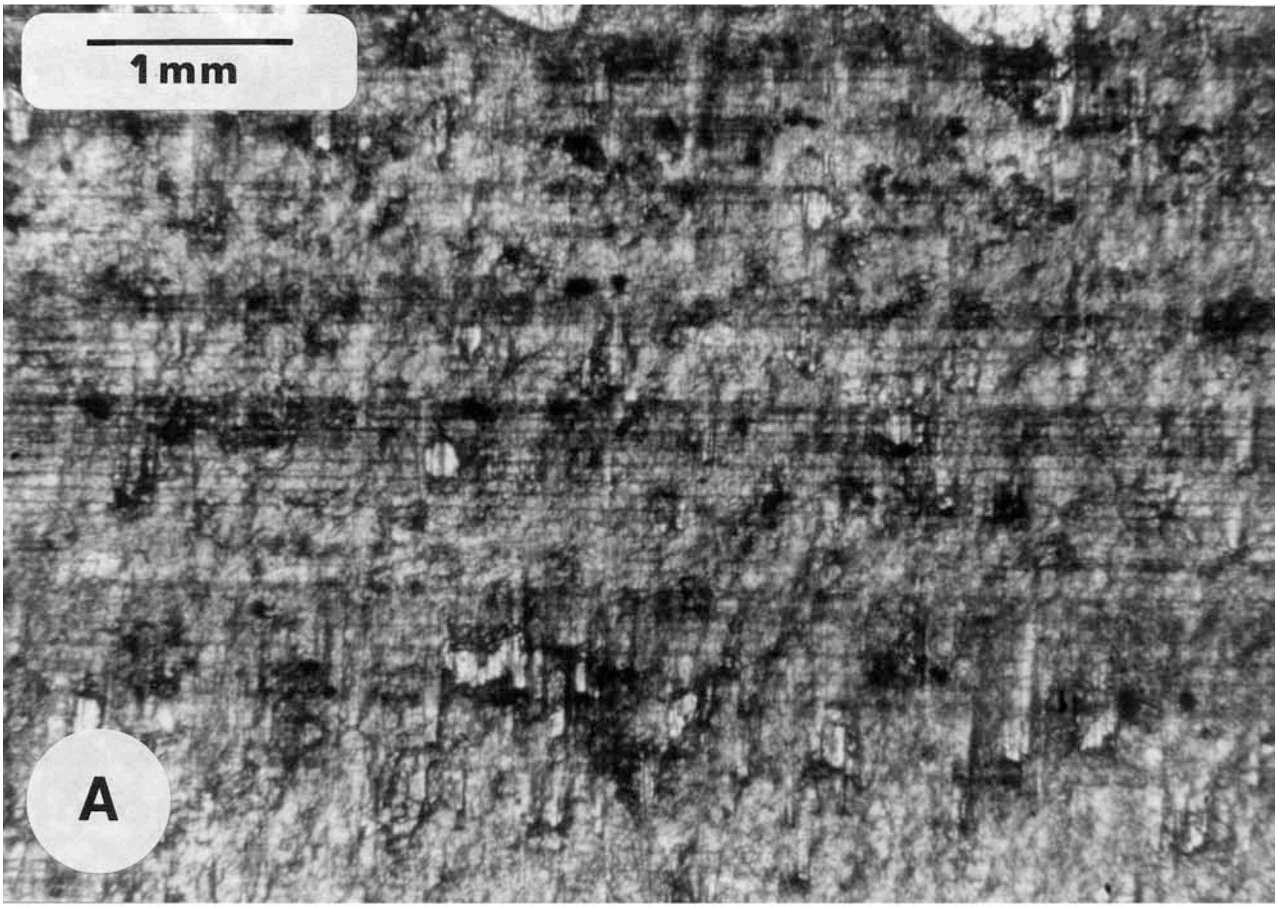
Application of cathodoluminescence (CL) to standard thin sections of rostra illustrates a far more complex mineral chemistry than would be suggested by standard petrography and staining. Luminescence signatures are caused by trace elements and provide clues to the diagenetic history of the carbonate under study (Barbin 2000, Machel 2000). Trace elements affecting CL can be grouped as either activators, sensitizers (more important in photoluminescence), or quenchers (Machel 1985, 2000). Without going into the details of the trace element geochemistry, for calcite the chief activator is manganese, and the chief quencher is ferric iron, although other trace elements, such as rare earth elements, can play significant roles (Machel 1985, 2000, Habermann *et al.* 1996, 2000). Description of the CL signature has evolved to discrimination as either non-luminescent, intrinsic blue, dully luminescent red/orange, or brightly luminescent orange/yellow (Meyers 1974, Machel 2000, Habermann *et al.* 2000). Detailed discussion of the application and interpretation of CL for carbonates can be found in standard references such as Sippel and Glover (1965), Meyers (1974), Marshall (1988), and Pagel *et al.* (2000). The CL analysis described herein was performed using an ELM 2A Luminoscope (serial number 207) manufactured by Nuclide Corporation (now MAAS), Acton, Massachusetts, United States, mounted on an Olympus petrographic microscope. A figure of merit (Marshal & Kopp 2000) was not calculated, but the observation and photography of the thin sections discussed herein was performed with an electron gun current of 15 ± 1 keV 0.7 ± 0.1 ma and a beam focused to a 1 x 2 cm ellipse. Photomicrographs were taken with exposure times of five and seven minutes using Kodak Gold 200 ASA film.

Figs 4 and 5 illustrate photomicrographs of unstained thin sections of the longitudinal and transverse sections of separate Utah belemnoid rostra viewed in plane polarized light and CL respectively. The nonferroan calcite forming the Utah belemnite rostra displays one of the three distinct luminescent signatures. The bulk of the crystallite palisades between the growth rings are described as intrinsic blue (Fig. 5). We have already shown by staining that they contain no iron, which would be a quencher. Obviously, they contain no trace elements that would provide a bright CL signature either. Non-luminescence/intrinsic blue CL is a common situation in biogenic carbonates (Sælen 1989).

The red/orange color of some of the crystallite palisades between the growth rings, most of the growth rings themselves, and some fractures not visible in plane light are described as dully luminescent (Fig. 5). Note that this dull signature is concentrated along some of the growth rings in Fig. 5A, and near the center of the rostrum in Fig. 5B. In both specimens, the dull signature exhibits cross-cutting relationships with the growth rings and crystallite palisades moving toward the margins of the specimen. We are currently investigating trace element distributions to see if we can determine the chemistry causing this signature (see Habermann *et al.* 1996). This dully luminescent signature is clearly diagenetic because of the cross-cutting relationships with the intrinsic blue carbonate that is interpreted as original. This diagenetic phase most likely reflects the effects of groundwater (Fig. 5).

The bright orange/yellow color seen in both views is described as brightly luminescent. In the longitudinal

Fig. 4 Photomicrographs of unstained thin sections of different Utah belemnites from the Red Fleet Reservoir locality viewed in plane polarized light. **A**, longitudinal section of specimen RFR-3; note the numerous, irregularly spaced growth rings and similarity to specimen in Fig. 2A. Top of view is just below the dorsal surface. **B**, transverse section of specimen RFR-6; note prominent fracture extending across entire view. Specimen is lightly etched, and relief of rostral crystallites is visible. Note also the concentric growth rings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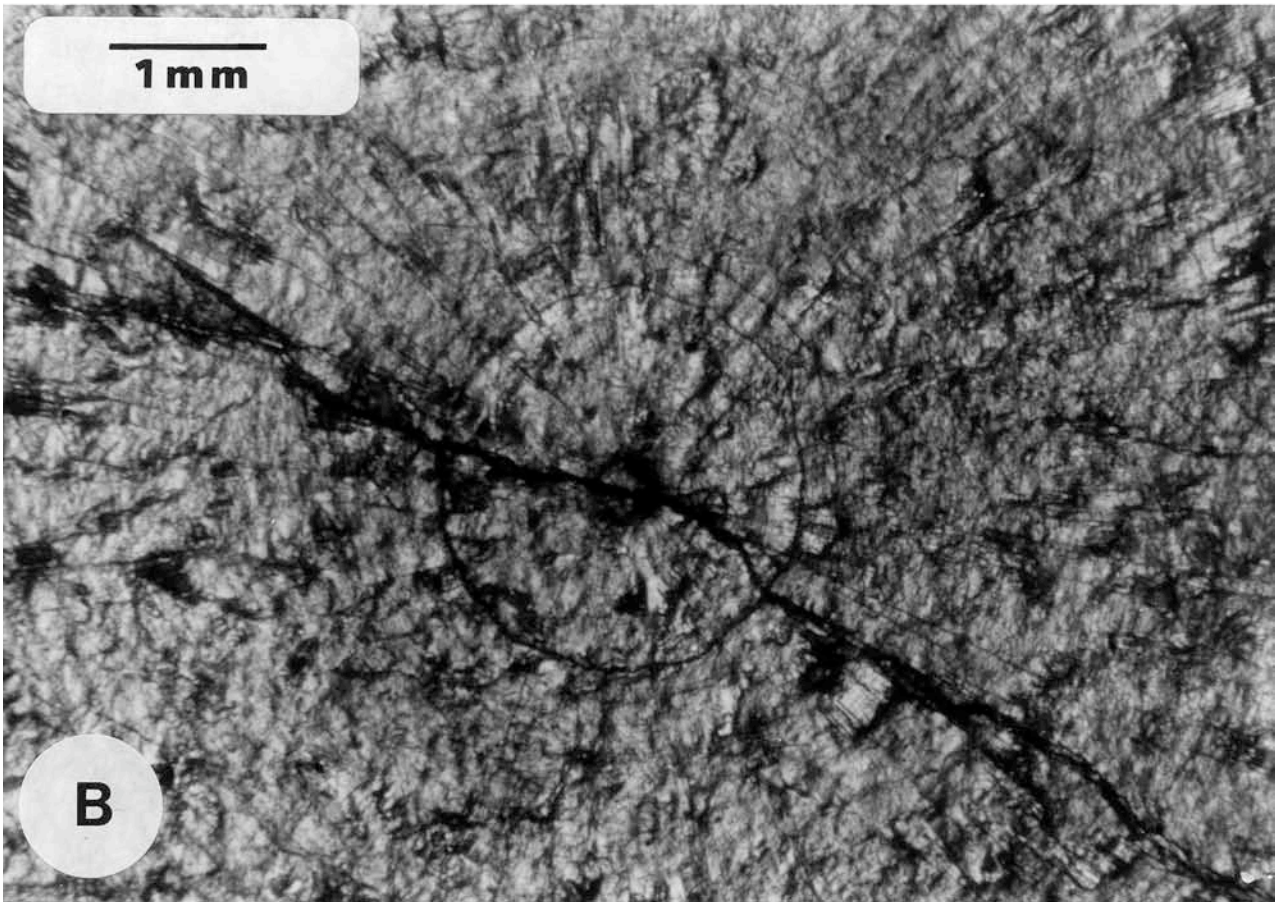
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section (Fig. 5A), it is scattered near the dorsal surface (top of picture), but not in earlier portions of the rostral interior. In the transverse section (Fig. 5B), it is seen at the center of growth, where it prominently outlines one of the interior growth rings, and fills the fracture extending from the top to the bottom of the specimen. This signature probably reflects manganese content. This brightly luminescent carbonate is clearly diagenetic and represents a later paragenetic phase than that of the dully luminescent carbonate. The brightly luminescent carbonate is also interpreted as the result of groundwater activity.

Comparison of the longitudinal section under plane polarized light (Fig. 4A) and CL (Fig. 5A) demonstrates that not all the growth rings are mineralized equally, which may explain the differential etching seen with SEM (Fig. 3). Furthermore, some growth rings seen clearly using CL are not obvious using transmitted light. Similarly, a fracture filled with dully luminescent calcite is only visible with CL.

Perhaps the most striking feature of the transverse section is that the fracture filled with opaque minerals, probably goethite, clearly visible in the plane polarized light view (Fig. 4B), is hardly visible under CL (Fig. 5B). In contrast, fractures that were not obvious in the plane polarized light view can be observed under CL, and the growth rings are easily distinguished by the distribution of the dully and brightly luminescent carbonate in this rostrum.

CONCLUSIONS

Distinctive CL signatures are consistently developed in the belemnite rostra collected from northeastern Utah, and compare favorably with those described by Sælen (1989) from western Europe. While standard petrographic techniques and staining suggest that these rostra are unaltered, CL reveals a considerable diagenetic alteration. If the Utah material is typical of other belemnites studied using only standard petrographic techniques, then these complex, but unrecognized, diagenetic histories may impact conclusions drawn on the assumption that the rostra are typically unaltered, e.g. Urey *et al.* 1951 (see also Veizer 1974, Hewitt 1980).

We believe that CL also provides some insight into the character of the growth rings and potentially the longevity of the individuals. Belemnite growth obviously is not uniform, since growth ring spacing is irregular, particularly toward the margin of the rostrum. Logically, it follows that the numerous growth rings representing interruptions to growth are also of variable duration as well. The fact that the growth rings and certain portions of the rostrum are selectively replaced suggests the probability of slight differences in the chemistry of the calcite forming the rostrum. Trace element concentrations may be time related and their association with replaced growth rings toward the margin of the rostrum might suggest a slowing of growth. Slower growth associated with numerous interruptions to growth leads us to conclude that rostrum precipitation may have taken longer than the three to four years or less than one year time spans commonly cited in the literature for belemnite longevity (Stevens 1965, Godwin 1998).

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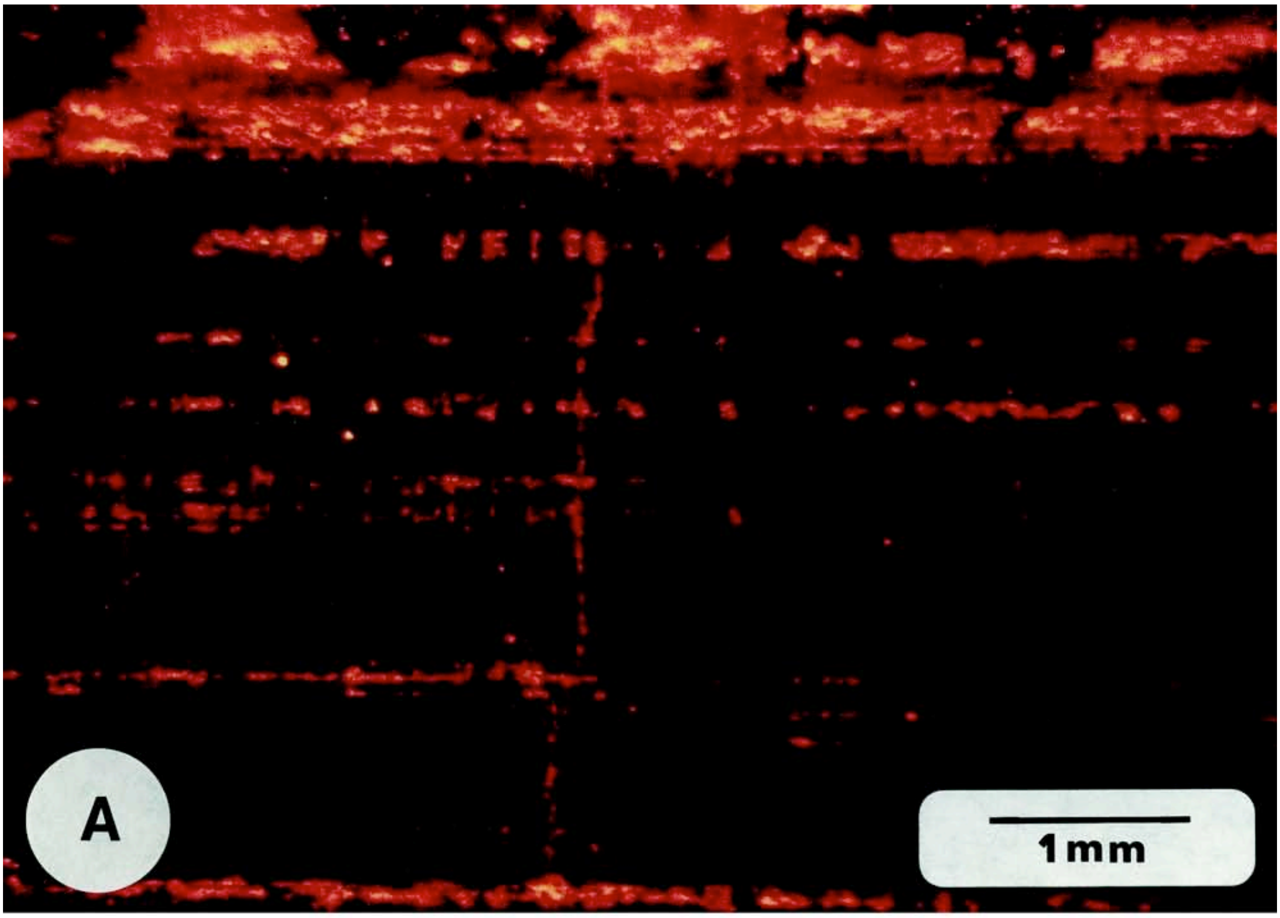
Fig. 5 Photomicrographs of the CL signatures of the same Utah belemnites from the Red Fleet Reservoir locality illustrated in Fig. 4. **A**, longitudinal view of specimen RFR-3. Intrinsic blue luminescent palisades between the dully luminescent (red/orange) growth rings dominate the view with minor brightly luminescent (orange/yellow) carbonate near the dorsal surface (top of picture). Note that not all the growth rings visible in Fig. 4A have a luminescent signature. The vertical fracture with a clearly visible, dull signature is not obvious in Fig. 4A. **B**, transverse view of specimen RFR-6. Intrinsic blue luminescent palisades occupy areas between the dully luminescent (red/orange) growth rings. Patches of dully luminescent carbonate also appear to have replaced some areas of crystallite palisades. The center of the rostrum, some of the growth rings, and some fractures are replaced or filled with brightly luminescent (orange/yellow) carbonate. Note that the prominent fracture visible in Fig. 4B is non-luminescent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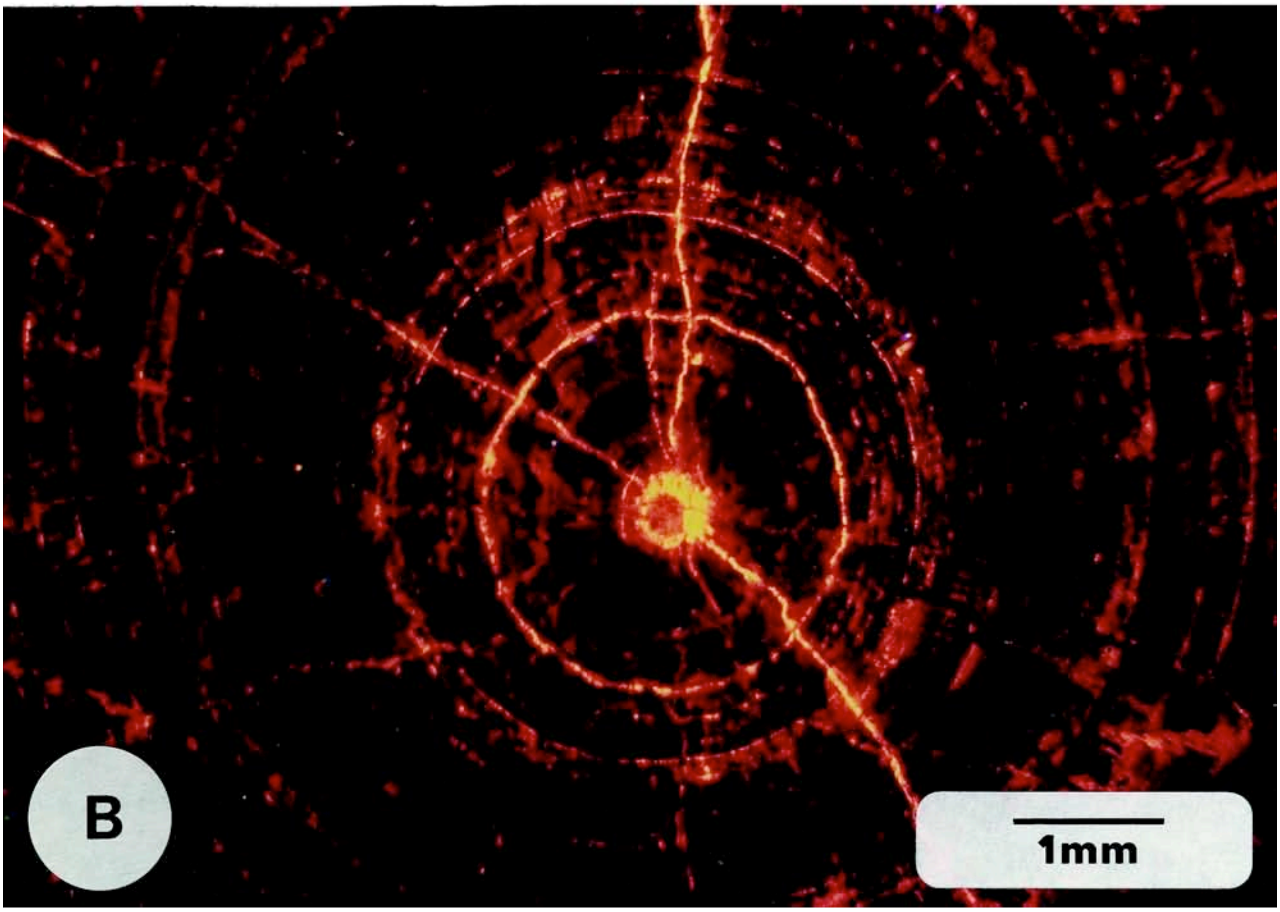
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