ments of each decimeter graduation on the bar agreed with the assigned values to better than 0.000 000 5 m.

Throughout the experiment, the performance of the interferometer was found to be improved when the laser was substituted for the mercury-198 lamp. With the laser, the contrast of the fringe pattern remained constant over the full length of the meter, thus providing a high signal-to-noise ratio over the entire path. With mercury-198 light, a fading of the fringes and, hence, an increase of the noise level was noticeable even over the length of a decimeter bar.

The experiment has provided information about the performance of both laser and interferometer, which is now being used for further development work so that accurate length measurements by means of lasers may ultimately be performed routinely.

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K. E. Gillilland, R. B. Stephens
National Bureau of Standards, Washington 25, D.C.

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18 November 1964

Diamond Synthesis with Bridgman Opposed-Anvil Apparatus

Abstract. *Bridgman opposed-anvil, high-pressure apparatus, which was available in the early 1940's, has been used successfully to synthesize diamonds from graphite in the laboratory.*

Thermodynamically, graphite is the most stable form of elemental carbon at ordinary pressures, whereas diamond is thermodynamically stable only at very high pressures (*1*). Thermodynamic calculations also indicate that at higher temperatures still higher pressures are required for stability of diamond.

In the early 1940's Bridgman described (*2*) a simple opposed-anvil apparatus for generating pressures of over 100 kb—pressures well within the diamond-stable region suggested by thermodynamics. Before 1920 Parsons (*3*) had introduced electric-resistance heating within the pressurized cells of high-pressure apparatus. Thus in the early 1940's pressure apparatus and heating techniques were available for attaining the conditions suggested by thermodynamics for synthesis of diamond; a number of serious, but unsuccessful, efforts were made during this period.

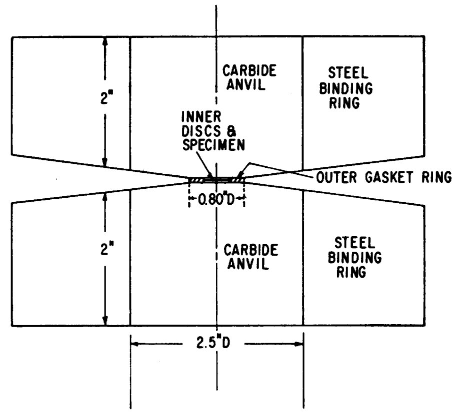

Fig. 1. Sectional drawing of the Bridgman opposed-anvil apparatus used to synthesize diamond from graphite.

This paper recounts the successful synthesis of diamonds in Bridgman opposed-anvil apparatus by a process discovered at General Electric Research Laboratory [announced, 1955 (*4*); published, 1959 (*5*)].

The anvils of the apparatus (Fig. 1) were of grade 883 Carboloy, 6.35 cm in diameter and 5.08 cm high. The working end of each piston was a truncated cone tapering at a 7-deg rise angle to a 2.03-cm diameter flat head. The pistons were pressed into strong steel binding-rings to hold the carbide in a prestressed state, as suggested by Bridgman.

The pressure cell consisted of (i) a pyrophyllite outer gasket ring, 2.03-cm outer diameter, 1.01-cm inner diameter, and 0.101 cm thick, and (ii) an inner part made of two pyrophyllite discs 1.01 cm in diameter and 0.056 cm thick. The diamond-making specimen was a graphite-nickel-graphite sandwich 0.0381 cm thick, 0.0635 cm wide, and 0.508 cm long which was inserted in a space between the two inner pyrophyllite discs. This space was formed by carving appropriate shallow grooves 0.017 cm deep in the adjacent faces of the two inner discs. One end of the sandwich-strip was connected to the top piston face by a nickel pin (0.051 cm in diameter) embedded in the top pyrophyllite disc; the other end was connected to the bottom piston face by a similar pin in the bottom disc.

The apparatus was pressure-calibrated in the usual way by inserting a thin strip of bismuth in place of the nickel-graphite specimen and by observing the force on the pistons required to produce the well-known 25- and 88-kb electric resistivity transitions of bismuth.

In the diamond-making experiments the cell, compressed at room temperature to a pressure of approximately 90 kb, was heated until the nickel strip just melted, as indicated by abrupt rise in resistance. The nickel and graphite were allowed to react for about 30 to 60 seconds at temperature. Then the temperature was lowered quickly; and this reduction was followed by a more deliberate reduction of pressure. After several successful experiments with nickel as the catalyst metal, iron was successfully substituted for the nickel.

In each successful case approximately the central third of the catalyst metal strip melted and reacted with the graphite adjacent to it to form a crust of small diamond crystals (Fig. 2). The unmelted stubs of nickel did not react with the graphite and remained uncarburized and ductile. The central metal which had melted was carburized and brittle, but contained no diamond crystals. The diamond crystals were all at the interface between metal and graphite and were all covered with skins of the catalyst metal, as is usually the case with this process; they were identified by scratch tests on sapphire and by x-ray diffraction patterns.

Opposed-anvil Bridgman high-pressure apparatus, which is conventionally used for studies in the temperature

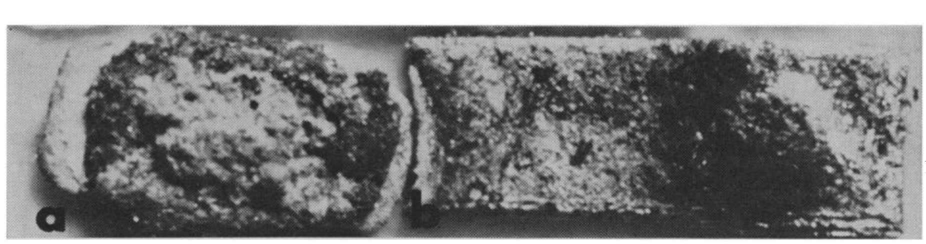

Fig. 2. Specimens from an experiment with nickel as catalyst. *a*, Crust of diamond crystals on metal that was melted and carburized; *b*, unmelted, unreacted stub. These are the central and right sections of nickel, respectively; the left section, mate to the right, is not shown; *a* measures roughly 0.126 by 0.063 cm.

range of −190° to 300°C, can be used with internal electrical heating to temperatures around 1500°C. With transient heating techniques much higher peak temperatures could be reached satisfactorily.

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29 October 1964

Paleozoic Mollusk: Hyolithes

Abstract: *An unusually well-preserved Ordovician fossil from Czechoslovakia shows that the enigmatic paired structures once thought to be outgrowths of the operculum of* Hyolithes *are really independent structures lying between the operculum and the aperture of the shell. The find seems to provide conclusive proof of the morphologic uniqueness of hyolithids.*

A recent textbook on paleoecology (*1*) summarizes conclusions of a paper on *Hyolithes* as follows: "Yochelson (1961) reexamined the Middle Cambrian fossil *Hyolithes carinatus* from the Burgess shale of British Columbia. Walcott had interpreted two structures at the apertural end of this shell as support for the fins like those of modern pteropods. Yochelson showed, however, that the structures in question were attached to the operculum and must have functioned as props to hold the operculum open during feeding. Thence he deduced that that animal could not have moved very much or the props would not have functioned. Yochelson therefore concluded that *Hyolithes* was virtually a sedentary benthonic organism, not planktonic as had formerly been supposed." The presumption regarding "outgrowths of the operculum" and their function was only one of the lines of evidence suggesting a benthonic habitat; other points were the large sizes and thick shells of some hyolithid specimens, the curved ventral surface, the anterior ventral shelf-like extension of the aperture in many genera, and the presence of a calcified operculum. The Burgess specimens are preserved essentially as two-dimensional compressions. Although the conclusion quoted seems to be mainly correct, the discovery of a remarkably preserved specimen shows that Yochelson's morphologic interpretation (*2*) was in error.

A latex cast of the external impression of a hyolithid from the Late Ordovician (Caradocian) Chlustina beds from Prague, Czechoslovakia, is portrayed in Fig. 1. The operculum which covers the lower end of the tubelike shell shows concentric growth lamellae and is curved to cover the rounded anterior shelflike extension; the outer edge of this ventral surface may be seen at the lower left, just below the operculum. Only the anterior part of the tubelike shell is preserved; growth lines are prominent and closely spaced on the dorsum.

To the left, between the operculum and the main part of the shell, is the structure which Yochelson designated a prop. This structure is evidently not an outgrowth from the side of the operculum, but is a third hard part, physically independent of both operculum and tube; the inner tip of this structure was probably attached to the inner surface of the operculum by ligaments or muscles. Earlier observations indicate that such structures are paired. In this specimen the critical part of the other side of the aperture is not preserved; a reconstruction is shown in Fig. 2. The length and curvature of the paired support is reconstructed partly from Middle Cambrian specimens figured by Yochelson (Fig. 3), but mainly from unbroken isolated structures which almost certainly belong to the Czechoslovakian species.

To the best of our knowledge, the illustrated specimen is the only one which unequivocally demonstrates the relation of these paired structures to the other two hard parts. One specimen in the Naturhistoriska Riksmuseet of Sweden shows the cross section of a structure between the operculum and shell (*3*). Although the isolated structures are not uncommon as fossils in the Cambrian, associations of the three types of hard parts are exceedingly rare. To the few occurrences noted by Yochelson, Marek (*4*) added several listings from the Paleozoic strata of Czechoslovakia; although rare, occurrences of the structures are widely distributed geologically and geographically.

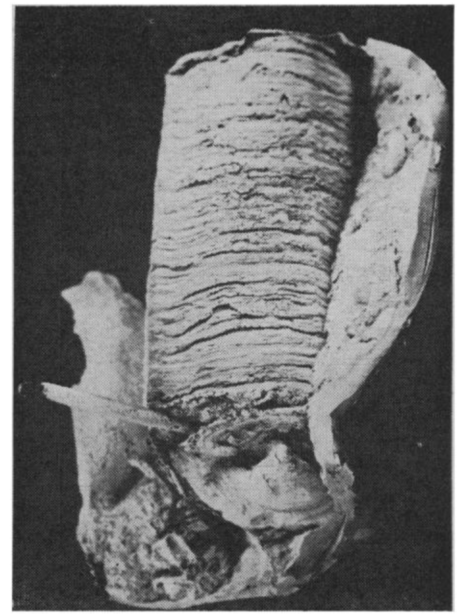

Fig. 1. Latex replica of an external mold of *Hyolithes striatulus* (Barrande), 1847; approximately × 3. Specimen in the collections of the Geological Institute, Czechoslovak Academy of Sciences, Prague.

Among other characteristic features of the hyolithid operculum are elongate paired depressions on the interior of the operculum. Marek (*4*) surmised that these depressions, commonly reflected as bulges on the exterior of the operculum, accommodated the interior ends of the supports, but he was not able to prove this point conclusively before the collection of the illustrated specimen. Despite paucity of direct evidence, there is now sufficient indirect evidence to conclude that the paired structures are characteristic of the entire group.

The assumption that the exterior bulges of the operculum essentially reflect the tips of the paired structures aids reinterpretation of their function. First, it is apparent that these struc-

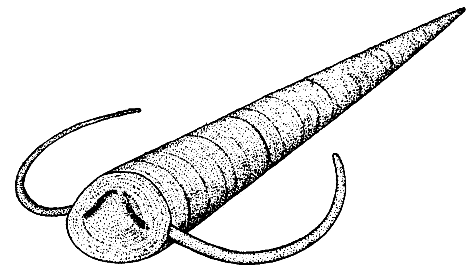

Fig. 2. A reconstruction of *Hyolithes striatulus* (the specimen); approximately natural size.