Reports

First Natural Occurrence of Coesite

Abstract. Coesite, the high-pressure polymorph of SiO_2, hitherto known only as a synthetic compound, is identified as an abundant mineral in sheared Coconino sandstone at Meteor Crater, Arizona. This natural occurrence has important bearing on the recognition of meteorite impact craters in quartz-bearing geologic formations.

We report in this communication the discovery of the first natural occurrence of coesite, the high-pressure polymorph of silica. Synthesis of coesite was successfully performed by Coes (*1*) and determinations of the stability fields of quartz and coesite have been published by MacDonald, Dachille and Roy, and Boyd and England (*2, 3*). In recent years the search for natural occurrences of coesite by geologists and mineralogists, including our examination of quartz-bearing rocks subjected to shock induced by hypervelocity impact and nuclear explosion, proved unsuccessful. The identification of coesite in samples of sheared Coconino sandstone collected from Meteor Crater, Arizona, culminates this determined search.

Meteor Crater is a bowl-shaped depression surrounded by a low rim (*4*). Upturned strata of the Coconino sandstone, Toroweap formation, and Kaibab limestone, all of Permian age, and the Moenkopi formation of Triassic age are exposed in the walls of the crater (*5*). The floor of the crater is underlain by a succession of Pleistocene and Recent talus, alluvial deposits, and lake beds resting on a layer of mixed debris up to 30 feet thick, which in turn overlies a deep breccia lens up to 600 feet thick. The rim of the crater is underlain by a complex sequence of Quaternary debris and alluvium resting on disturbed Moenkopi and Kaibab strata.

The relatively undamaged Coconino sandstone in the walls of the crater is a white, fine-grained saccharoidal cross-bedded quartzose sandstone. Coesite occurs chiefly in compressed and sheared Coconino sandstone (Fig. 1), which constitutes a major part of the layer of mixed debris under the crater floor and is dispersed in the underlying breccia lens. Coesite-bearing sandstone fragments are also a major constituent of drill cuttings from near the base of the lens, 600 to 650 feet beneath the crater floor. Some coesite-bearing fragments of sandstone are also found in Pleistocene and Recent alluvium on the rim of the crater, mainly in association with sintered rocks. Coesite also is a subordinate constituent of sandstone that has largely been converted to glass (lechatelierite). The glassy fragments form large frothy chunks in the base of the Pleistocene lake beds in the crater floor, are also found as lapilli and bombs incorporated in the alluvium on the crater rim, and are dispersed as finer fragments in the mixed debris and breccia under the crater. In some samples from this crater, fine-grained coesite had previously been thought to be glass or partially devitrified glass by Merrill (*6*), Rogers (*7*), and Shoemaker (*5, 8*). Coesite occurs in the fine-grained, nearly isotropic, matrix in which the subrounded fractured quartz grains are imbedded (see Fig. 2).

The identification of natural coesite is based on its x-ray powder diffraction pattern, its optical properties, and the spectrographic analysis of a purified sample. Figure 3*A* is the x-ray powder diffraction pattern of coesite concentrated from sheared Coconino sandstone. It is identical to the x-ray powder diffraction pattern of coesite (Fig. 3*B*) synthesized by F. R. Boyd of the Geophysical Laboratory. The extra lines shown in Fig. 3*A* are primarily those of quartz, which are present as impurity in the natural coesite.

Under the microscope coesite appears in irregular grains or vaguely rectangular grains 5 to more than 50 μ in size (Fig. 4). The mineral has a mean index of refraction of 1.595 and a very low birefringence.

A chemically concentrated sample shown by x-ray pattern to contain essentially coesite, with some quartz, was spectrographically analyzed. The sample contains more than 99 percent silica and less than 1 percent of other cations. This analysis substantiates the conclusion that the mineral is SiO_2.

The occurrence of coesite at Meteor Crater has significant implications for the fields of both geology and physics. First, it demonstrates that the polymorphic transformation from quartz to coesite may occur under shocks generated by meteorite impact. It is too early at this stage to say what the pressure and temperature conditions were when coesite was formed by impact at the Meteor Crater. The presence of coesite indicates pressures in excess of 20 kilobars. The additional presence of silica glass may indicate temperatures, at least locally, of about 1000°C or higher. DeCarli and Jamieson (*9*) failed to find coesite in single quartz crystals shock-loaded to pressures up to 800 kilobars, and one of us (E.M.S.) has failed to find coesite in quartose media shocked to similar high pressures by experimental hypervelocity impact and by nuclear explosion. These results suggest that the transformation is too sluggish to take place in shock waves of very short duration, and that the sluggish quartz-coesite transformation may occur some distance behind the shock front in a shock wave of much longer duration, such as was probably produced by impact at Meteor Crater (*5*).

Second, the occurrence of coesite at Meteor Crater suggests that the presence of coesite may afford a criterion for the recognition of other impact craters on the earth and perhaps ultimately on the moon and other planets. According to the data of Boyd and England (*3*) coesite probably cannot form at pressures of less than about 20 kilobars— a pressure not likely to be reached near the surface of a planet for a long enough period of time for coesite formation except by the mechanism of impact. However, coesite must persist in the low-pressure regime for a significant period of geologic time if it is to be a useful tool in the recognition of ancient geologic structures.

Third, the discovery of coesite in a natural environment puts it in the category of a true mineral (*10*).

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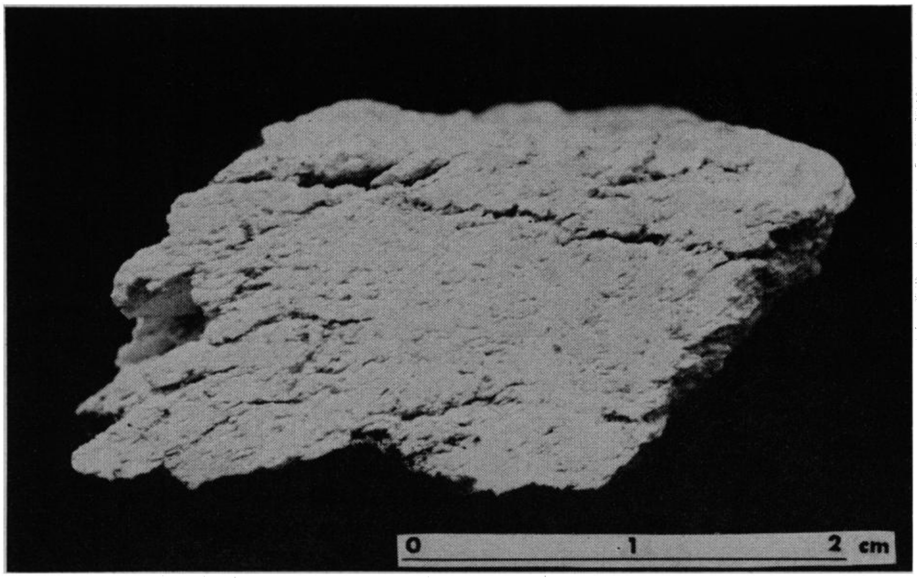
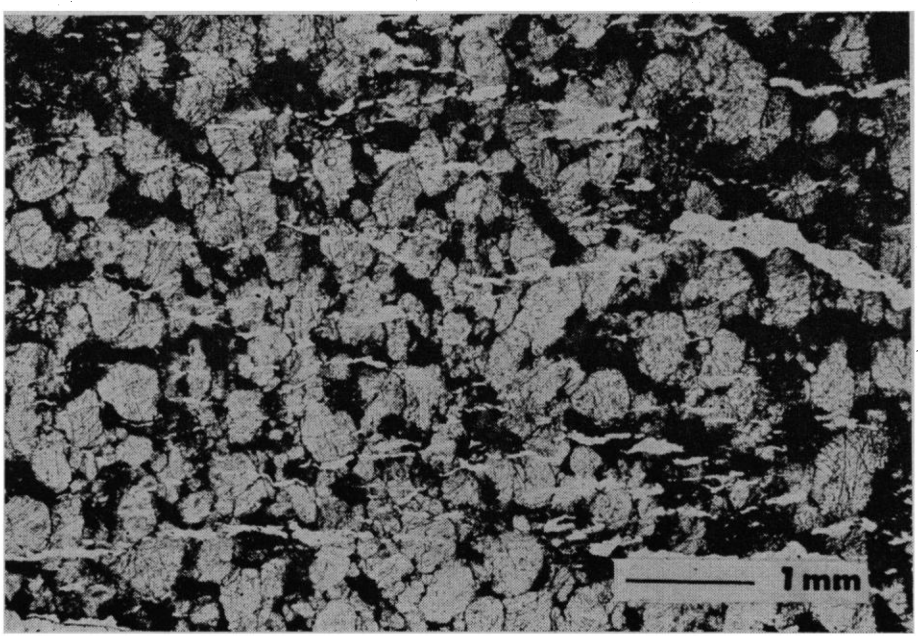
Type manuscripts double-spaced and submit one ribbon copy and one carbon copy.

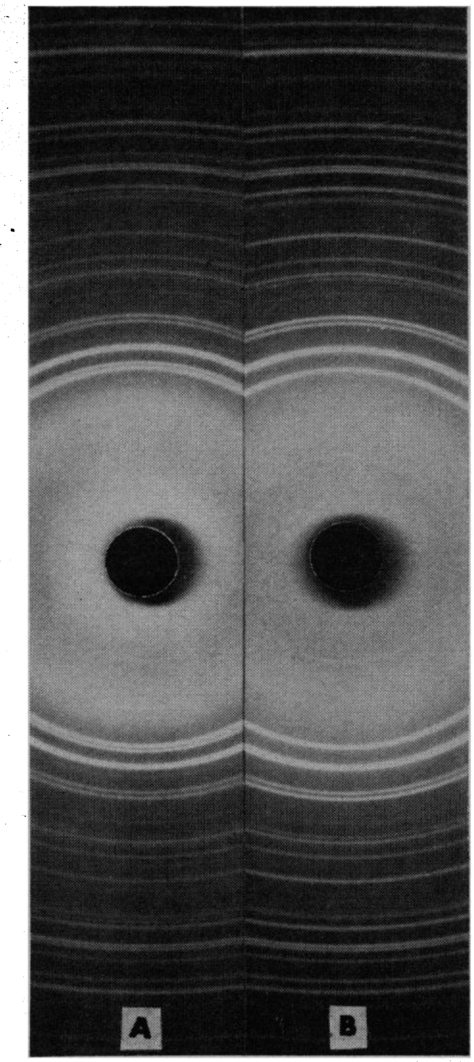
Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each.

For further details see "Suggestions to Contributors" [*Science* **125**, 16 (1957)].







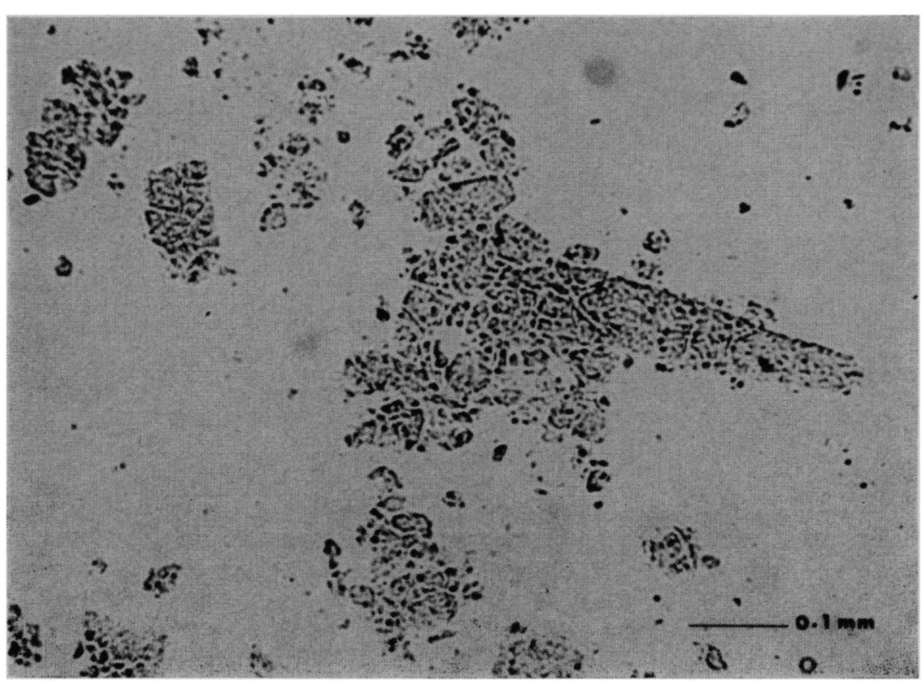


Fig. 1 (top, left). Sheared Coconino sandstone. Fig. 2 (middle, left). Photomicrograph of sheared Coconino sandstone (plain reflected light). Fractured quartz (gray) in matrix (dark) which contains coesite. Fig. 3 (top, right). (*A*) Natural coesite with minor amounts of quartz; (*B*) synthetic coesite. Fig. 4 (bottom, left). Natural coesite with inclusions of quartz (plain reflected light). The photograph was taken with coesite in 1.540 oil and is slightly out of focus.

References and Notes

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10. We are indebted to the Barringer Crater Company for granting access to its property and for the many courtesies extended during the investigation at Meteor Crater. Specimens of drill cuttings and cores from Meteor Crater were made available by the geology department of Princeton University. We wish also to acknowledge the assistance of our colleagues J. J. Fahey, who helped to chemically concentrate the coesite sample; Harry Bastron, who made the spectrographic analysis; and B. J. Skinner, who aided in x-ray correlations. We are indebted to W. T. Pecora and B. J. Skinner for discussion of the problems and for their constructive criticism of the manuscript. Part of this work was done on behalf of the Division of Research of the Atomic Energy Commission. Publication was authorized by the director of the U.S. Geological Survey.

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Sound Production by the Satinfin Shiner, Notropis analostanus, and Related Fishes

Abstract. Several sounds are produced by minnows. Only one is not of purely mechanical origin, and it is classed as a "biological" sound. This sound is variously produced by males when fighting and chasing as well as during courtship. Females emit a similar sound. Testosterone injections and elevated temperatures result in an increased rate of biological sound emission.

In recent years it has been demonstrated that marine fishes produce a wide variety of sounds, some of which must have a biological function (*1–3*). Little work has been done on fresh-water fishes, although aquarists and several European investigators have occasionally heard their sounds (*4, 5*). *Phoxinus laevis*, a cyprinid of Europe, has been studied in detail, but the only reported sound produced by this fish was one caused by the emission of a bubble of air (*5*).

Several kinds of sounds have been recorded from *Notropis analostanus* (*6, 7*). These were a scratchy sound produced when the fish hit the bottom gravel under various conditions, a high-pitched noise when air bubbles were released from the mouth, occasional chewing sounds, and finally one or more sharp knocks produced most frequently during reproductive activities. All except the latter are mechanical sounds, and superficially they do not appear to have any biological function, although they cannot be overlooked as potential stimuli to the fish. The knocks (similar to the sound made when one strikes wood with his knuckle) appeared under conditions that identified them as "biological" sounds. They were produced when the males fought and when the males and females courted, and appeared not to be a sound primarily associated with necessary movements. We follow the use of the terms "biological" and "mechanical" sounds as proposed by M. P. Fish (*1*), although there is reason to believe that the two categories grade into each other on an evolutionary basis, and may soon outlive their usefulness.

The single knocks, made when a male chased and fought with a male, contained frequencies from below 85 cy/sec up to between 2000 and at least 11,000 cy/sec, and lasted between 11 and 60 msec with greater intensities in the lower frequencies, as analyzed with a Kay Sonagraph model recorder. These single knocks were produced rapidly and intensely (40 to 60 msec, tapering to below 12 msec at highest frequencies) when a male chased another male, but they could be united into a very close series (11 to 24 msec, tapering very slightly to below 12 msec at highest frequencies) when two males fought each other. Similarly a purring sound occurred when a male actively courted a female. This appeared to be basically the same sound, but it was emitted more rapidly and less intensely. In all cases the male made these sounds (isolated, fighting a mirror image, and so forth), but isolated females also produced fainter, less frequent knocks than males, so that it was impossible to know which sex made the sound during courtship.

Biological sounds similar to the knocks of *N. analostanus* have been heard in other species of minnows. Occasional knocks were heard when a male chased another male of *Gila* (Clinostomus) *vandoisula* and *Notropis spilopterus*, and a large series of knocks were heard when several to many males chased a female of *Semotilus* (Margariscus) *margarita*.

The structure that produced the "biological" knocks has not been located. The sound was still produced, seemingly unaltered, when various organs were experimentally manipulated as follows: angle of jaws, base of pectoral girdle, pharyngeal arches cut through; operculum, pelvic fins, pectoral fins, anal fin, dorsal fin cut off; the air bladder punctured and removed; and the body cavity injected with petrolatum.

A series of males of *Notropis analostanus*, at the beginning of the breeding season (June and early July), were placed in water at different temperatures (Table 1). The production of sound decreased significantly at the lower temperatures. This fish breeds in water of 20° to 30°C. Individuals injected with testosterone at 25° to 27°C with a 10-hour photoperiod produced many more sounds than fish injected with sesame oil and normal control fish from 5 to 10 days after injection. The activity of those injected with testosterone was considerably greater than that of the control group.

Over the past 30 years many German and Dutch workers have demonstrated that *Phoxinus laevis* and other fresh-water fishes are able to hear and that this ability extends into frequencies not heard by nonostariophysid species of fish (*4, 8*). This ability to hear sounds of frequencies up to as high as 7000 cy/sec or more is enhanced by the weberian apparatus which connects the air bladder to the inner ear. However, the only sounds that have been heard from minnows are "nonbiological" sounds such as the chewing sounds made by goldfish and the emission of air from the air bladder of *P. laevis*. This suggested to the German and Dutch workers that the acuity of hear-

Table 1. The range and average number of sounds produced by males of *Notropis analostanus*, kept in 15-gal aquaria with an 18-hour photoperiod at various temperatures, during 5-minute listening periods, in June and July 1959. Three recordings were taken for each of three experiments (average usually based on nine readings), each with four males except for day one where data were available for only two experiments (average based on six readings). Some deaths occurred in one experiment at the highest temperature.

Temp. (°C)	Days after beginning of experiment									
	1		2		3		4		5	
	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.
29–30	109–280	231	35–328	176	8–207	102	101–191	157	64–161	121
23–24	27–206	70	12–43	23	14–193	69	18–101	41	11–49	25
18–19	10–69	27	14–213	82	18–129	60	6–100	37	4–96	43
13–14	3–13	5	1–7	4	0–23	6	4–18	9	2–24	11
7–9	0–5	1	0	0	0–3	1	1–6	2	0–3	1