

## **Chemical Data on a Colorless Arkansas Diamond and its Black Amorphous C-Fe-Ni-S Inclusion**

A. A. GIARDINI

*Department of Geology*

AND CHARLES E. MELTON

*Department of Chemistry*

*University of Georgia, Athens, Georgia 30602*

### **Abstract**

A 27-element emission spectrographic analysis of "inclusion-free" fragments of an 0.885 carat type II colorless Arkansas diamond, previously crushed for a mass spectrographic analysis of occluded gas, showed detectable traces of Na, Ca, Al and Si. XRD and chemical analyses of a thin ( $<2\mu\text{m}$ ), lustrous, black, opaque, totally-enclosed inclusion lying on (111) of the same diamond showed it to be amorphous and, in decreasing order of abundance, heterogeneously composed mainly of C, Fe, S, and Ni. It is speculated that the black material represents epigenetic carbonization of diamond on (111) by included gas and decomposition products of iron sulfide and iron nickel sulfide inclusions.

### **Introduction**

Previous analyses of trace impurities in African diamonds have been given by Chesley (1942), Raal (1957), Bunting and Van Valkenburg (1958), and others. The literature shows no such data for Arkansas, U. S. A., diamond. For geochemical comparison, a 27 element semi-quantitative emission spectrographic analysis has been made on 0.02 g of colorless and inclusion-free diamond (at a magnification of 90) obtained from a crushed 0.885 carat Arkansas specimen.

The specimen was colorless, type II, and in the form of a cleavage plate approximately  $0.6 \times 0.6 \times 0.14$  cm. It contained a centrally located and totally-enclosed single, thin ( $<2\mu\text{m}$ ), near-rectangular ( $0.1 \times 0.2$  cm), lustrous, black, opaque inclusion lying parallel to (111). The diamond came from the Smithsonian Institution Roebbling Collection. It has been crushed earlier by Melton and Giardini (1975) for analysis of occluded gas by mass spectrometry. The STP volume of the gas released at  $200^\circ\text{C}$  and  $10^{-11}$  atm was  $2.7 \times 10^{-4}$  cc, and consisted of 76.9 vol  $\text{H}_2\text{O}$ , 8.2  $\text{N}_2$ , 7.2  $\text{CO}_2$ , 5.4  $\text{H}_2$ , 1.2  $\text{CO}$ , 0.9  $\text{CH}_4$ , 0.2  $\text{CH}_3\text{CH}_2\text{OH}$ . Only a gentle impact was needed to crush the diamond. Essentially all of the black inclusion adhered to and was exposed on the cleavage surfaces of 7 diamond fragments.

Previous descriptions and analyses of black inclusions in African diamonds have been given by Sutton (1921), Sharpe (1966), Harris (1968, 1972), and Harris and Vance (1972). Identified minerals are pyrrhotite, pyrite, pentlandite, cohenite, magnetite, hematite, ilmenite, and graphite. The first data for black included matter in Arkansas diamond are reported here.

### **Trace Element Analysis**

A 0.02 g sample of colorless and inclusion-free fragments of the diamond was selected at 90x under a binocular microscope equipped with polarizers. The fragments were digested at room temperature in concentrated HF and  $\text{H}_2\text{SO}_4$ , rinsed, boiled in aqua regia, repeatedly rinsed with deionized distilled water, briefly ignited at  $800^\circ\text{C}$  in a clean platinum crucible, mixed with 0.1 g of spectrographic-grade graphite, dried at  $400^\circ\text{C}$ , mixed in a clean plastic vial, transferred to preformed electrodes, and analyzed with a 21 foot Wadsworth-mount Jarrell-Ash spectrograph. Twenty-seven elements were sought. Detection limits are given in Table 1. Significant quantities of Na (70 ppm), Al (70 ppm), Ca (140 ppm), and Si (175 ppm) were detected. Accuracy is estimated at  $\pm 30$  percent.

TABLE 1. Emission Spectrographic Analysis of Trace Impurities in Colorless, Inclusion-Free, Type II Arkansas Diamond\*

Element ppm	Element ppm	Element ppm
Ag < 7	Cu < 70	P < 700
Al 140	Fe < 70	Pb < 7
B < 7	K < 140	Si 245
Ba < 7	Li < 70	Sn < 7
Be < 7	Mg < 70	Ti < 42
Ca 147	Mn < 7	V < 7
Cd < 7	Mo < 7	W < 70
Co < 140	Na 77	Zn < 420
Cr < 7	Ni < 28	Zr < 14

\* Wadsworth-mount Jarrell-Ash 21-foot spark source spectrometer. Inclusion-free based on binocular microscope examination at a magnification of 90. The microscope was equipped with polarizers. Respective detection limits for Al, Ca, Na, and Si are < 70, < 7, < 7 and < 70 ppm.

### Black-Inclusion Analyses

About half of the inclusion (4 diamond fragments) was scraped off with a diamond edge, and mounted on a glass fiber for X-ray diffraction analysis. A 16 hour exposure yielded no pattern. An additional 24 hours yielded a trace of the major diffraction line of graphite. The included material is, therefore, primarily amorphous.

The black material on the remaining 3 fragments was chemically analyzed *in situ* with a MAC-400s electron microprobe equipped with a Canberra model 8100 energy-dispersive analyzer. The latter showed the presence of Fe, Ni, S, and a trace of Cl. Fe, Ni, and S were then analyzed with the microprobe. Analyses were conducted of 15 kV and 0.05 mA. Since it was not possible to establish the chemical state of Fe and Ni, reference standards of Fe, FeO, FeS<sub>2</sub>, and Ni were used. Analytical data are given in Table 2.

The black inclusion surface was smooth and continuous prior to microprobe analysis. Afterwards, it was observed to be blistered on sites probed with the electron beam. The blistering may reflect volatilization of elemental sulfur, or possibly hydrocarbons.

During the analysis, Fe and S were determined in one series of 20 spot-scans, and Ni in a subsequent series. Fe and S concentrations were observed at all locations, but rose and fell together with location. Ni also varied with location, but was found only at 4 of 20 sites. No correlation of Fe, S, and Ni was observed. The variations may be due to a variable subminimal thickness of the inclusion, to the observed blistering, or both. The measured edge thickness of the inclusion varied between 1 and 2 microns.

The presence of Fe and S at all sites, and absence of Ni at most sites, suggests a possible preexistence of two iron-sulfur compounds; probably pyrrhotite and pentlandite (Harris, 1972). If so, the low sulfur content could be due to (a) sulfur volatilization during the 200°C high-vacuum exposure when the diamond was crushed in the earlier gas analysis, and (b) electron-beam-induced volatilization (blistering).

The observed maximum of about 30 percent as the combined total for Fe, Ni and S, the opaque nature of the inclusion, and the graphite trace after 40 hours of X-ray exposure, suggested carbon as a fourth constituent. Subsequent to probe analysis, the inclusion (~10<sup>-6</sup> cc) was scraped from its diamond substrate with a clean stainless steel blade into a clean quartz tube. Binocular microscope examination at 90x showed no presence of admixed diamond. The tube was evacuated to 10<sup>-10</sup> atm, partially backfilled with pure O<sub>2</sub>, heated to 700°C, and the resultant gas analyzed with a mass spectrometer (10<sup>-13</sup> atm background pressure). The combustion gas was mainly CO<sub>2</sub> (net CO<sub>2</sub>: SO<sub>2</sub> ratio = 2500:1). Carbon is confirmed, therefore, as a principal constituent of the black inclusion.

### Discussion

Chesley (1942) analyzed 33 diamonds from various sources by emission spectrometry and found Ca, Al, and Si and usually Mg to be persistent impurities. Raal (1957) performed similar analyses on 25 African diamonds and found Ca, Al, Si, Mg, Fe, and Cu as principal impurities. Bunting and Van Valkenburg (1958) analyzed 3 type I and 3 type II diamonds, and found Na, Ca, Si, and Cu as principal impurities in

TABLE 2. Microprobe Data on the Black Material Included in an 0.885 Carat Colorless Type II Arkansas Diamond.

Element*	Locations analyzed	% Range of composition	% Average composition	Reference standards
Fe	20	0.22 - 22.7	12.3	Fe
		0.25 - 25.5	13.7	FeS <sub>2</sub>
		0.31 - 31.9	17.2	FeO
Ni	20	0 - 3.64	0.002 0.63*	Ni
S	20	0.18 - 0.75	0.42	FeS <sub>2</sub>

\* Since the chemical state of the inclusion is not known, iron concentrations are given according to Fe, FeO and FeS<sub>2</sub> standards. Nickel was found at only 4 of the 20 sites analyzed. The average concentration for the 4 sites is 0.63%; for the 20 sites the average is about .002%.

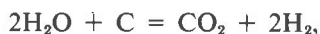
the former and Na, Ca, Si, Mg, Fe, and Cu in the latter.

The diamonds referred to above were not screened for possible included matter, and some were colored. Nevertheless, with the possible exception of Mg, Fe, and Cu (see sensitivity limits, Table 1), the principal impurities in the Arkansas diamond are similar to those in diamonds from the above sources.

Harris (1968, 1972) and Harris and Vance (1972) have made detailed studies on black included matter in diamond. Their study of several hundred African diamonds identified black material as graphite, pyrrhotite and pentlandite, separately or together. Furthermore, Harris and Vance (1972) have shown experimentally that graphite often can be formed on mineral inclusions and internal fracture surfaces in diamonds by heating to a temperature of about 900°C. On the basis of the work described by Evans (1965) on nonequilibrium carbonization of diamond in CO<sub>2</sub>, and Roedder (1965) on CO<sub>2</sub> in olivine, Harris and Vance (1972) interpreted graphite inclusions as being epigenetic to diamond, and as having formed at temperatures above 900°C after pressure release arising from volcanic breakthrough of the kimberlite.

The chemistry of the black material found in the present Arkansas diamond appears to be consistent in principle with the findings of Harris (1968) and Harris and Vance (1972). Their model for epigenetic carbonization appears consistent with that proposed by Green and Gueguen (1974) for kimberlite emplacement.

Melton and Giardini (1974, 1975) found that gas occluded in diamonds at 200°C is not principally CO<sub>2</sub>, but usually a mixture mainly of H<sub>2</sub>O, H<sub>2</sub>, CO<sub>2</sub>, N<sub>2</sub>, CH<sub>4</sub>, and CO. The H:O ratio has been found consistently to be about 2:1, and water often is the principal constituent. However, according to the equilibrium reaction,



occluded gas in the diamond could transpose at elevated temperature primarily to CO<sub>2</sub> and H<sub>2</sub>.

The reported occurrence of pyrrhotite, pentlandite, and graphite as black inclusions in diamond (Harris,

1968) invites speculation that the carbon and Fe, Ni, and S found in the Arkansas inclusion may be decomposition products from preexisting gas and syngenetic iron sulfide inclusions. If correct, the amorphous state may indicate an epigenetic reaction-temperature somewhat below the experimental temperatures employed by Harris and Vance (1972).

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