

---

# NATURAL-COLOR NONCONDUCTIVE GRAY-TO-BLUE DIAMONDS

By Emmanuel Fritsch and Kenneth Scarratt

---

*Two new categories of gray-to-blue diamonds are described. First, two type IIb blue crystals with what appears to be a type IIa outer skin were not electrically conductive in the rough, but conducted electricity once faceted. Second, some non-electrically conductive gray-to-grayish blue diamonds from the Argyle mine, Australia, were determined to be type Ia and to contain unusually high amounts of hydrogen. This latter type of coloration, not previously reported for diamonds, may be due to hydrogen-related defects in the crystal structure.*

---

To date, all natural-color blue diamonds described in the literature have been electrically conductive. In fact, the measurement of electrical conductivity has been a major deciding factor in gemological testing for artificial coloration in blue diamonds: All natural-color stones were believed to be type IIb and electrical conductors, whereas all laboratory-irradiated stones were insulators (Custers, 1954; Liddicoat, 1987). However, the authors have examined several diamonds in the gray-to-blue range—known to be natural color because of other tests or the fact that they were obtained directly from the mine—that did *not* conduct

electricity. Moreover, the ultraviolet luminescence of these stones was significantly different from that of the majority of natural blue and bluish gray diamonds.

This report presents the gemological properties of what appear to be two new categories of blue diamonds. First, we studied two crystals that did not test positive for electrical conductivity in the rough, but were electrically conductive after they had been cut. Second, we examined four faceted stones, all from the Argyle mine in northwestern Australia, that are type Ia, insulating, gray-to-grayish blue diamonds, in contrast to the type IIb character expected for diamonds of similar color (see Box A for a detailed discussion of diamond types).

## ABOUT THE AUTHORS

Dr. Fritsch is manager of the Research Department at the Gemological Institute of America, Santa Monica, California. Mr. Scarratt is chief executive officer of the Gem Testing Laboratory of Great Britain, London.

*Acknowledgments: The authors thank Theodore Horovitz, of Th. Horovitz and Cie., Geneva, Switzerland, and R. Vainer, of M. Vainer Ltd., London, for allowing the study of two of the diamonds described here. They also are grateful for constructive comments by Dr. James Shigley, director of GIA Research, and a very helpful review by Dr. Alan Collins from King's College, London.*

Gems & Gemology, Vol. 28, No. 1, pp. 35-42.

© 1992 Gemological Institute of America

## MATERIALS AND METHODS

Table 1 gives a basic description of the six diamonds studied for this article. Stones A and B (rough and cut) and C (cut) were examined and color graded at the Gem Testing Laboratory of Great Britain (GTL-GB); faceted stones A and B, as well as stones D, E, and F, were examined at GIA Research and color graded at the GIA Gem Trade Laboratory. The color descriptions provided by each lab are noted in the table. We do not know the locality of origin of stones A and B, but stones C to F came from the Argyle mine in northwestern Australia.

Using a standard voltmeter for the stones tested in the GTL-GB and a GIA-GEM conductometer for those tested in GIA Research, we measured electrical conductivity as the difference in potential between two separate points on the surface of the diamond. We recorded ultraviolet-visible absorption spectra at liquid-nitrogen temperature using a Pye-Unicam 8800 spectrophotometer. Infrared spectra were recorded in a transmission mode on a Nicolet 510 (GTL-GB) or a 60SX (GIA Research) FTIR spectrometer at room temperature, with a resolution of 4 cm<sup>-1</sup>.

### NONCONDUCTIVE BLUE DIAMOND CRYSTALS

Stones A and B were first examined in the rough and found to be electrical insulators, although they displayed the grayish blue-to-blue colors typical of natural blue diamonds. One should note that it may sometimes be difficult to detect electrical conductivity on rough type IIb stones, because their irregular shape and etched surface may not allow a good electrical contact. Our measurements, however, were

conducted with sharp probes to ensure the best contact. These stones appeared to be a true anomaly, as the infrared absorption spectra of both were in fact typical of type IIb, electrically conductive diamonds.

Stone A was retested for electrical conductivity both during the cutting operation and after its completion. Stone B was retested only after faceting was completed. Faceting of stone A produced a 4.15-ct fancy bluish gray pear shape; faceting of stone B resulted in a remarkable 3.06-ct fancy dark blue square cushion cut (figure 1). Stone A was found to conduct electricity after it had been blocked; both A and B did so after faceting. The infrared spectra of both stones after cutting were the same as those taken on the rough. Because stone B is significantly bluer than stone A, the former showed stronger absorption in the region above 3000 cm<sup>-1</sup>. Truly blue diamonds (those without a secondary color modifier) generally exhibit stronger type IIb absorptions in the infrared than grayish blue-to-bluish gray stones. A small hump at about 1295 cm<sup>-1</sup>, although situated in a region where absorptions due to nitrogen typically occur, is

**TABLE 1.** Description of the six natural-color diamonds.

Sample	Weight (ct)	Color	Shape	Comments	Type <sup>a</sup>	Electrical conductivity	Ultraviolet luminescence <sup>b</sup>	
							Long-wave	Short-wave
<b>A</b>								
Before faceting	12.83	Gray blue <sup>c</sup>	Roughly triangular		IIb	No	————	————
After faceting	4.15	Fancy bluish black <sup>c</sup> Fancy bluish gray <sup>d</sup>	Pear shape		IIb	Yes	V. wk. orange	Wk. to mod. orange V. long reddish orange phosphorescence
<b>B</b>								
Before faceting	5.38	"Royal blue" <sup>c</sup>	Roughly triangular	Radiation stains	IIb	No	————	————
After faceting	3.06	Fancy blue <sup>c</sup> Fancy dark blue <sup>d</sup>	Square cushion	Internally flawless	IIb	Yes	Inert	Mod. orange Reddish orange phosphorescence
<b>C</b>	0.30	Grayish blue <sup>c</sup>	Emerald cut	From Argyle mine	Ia	No	Strong yellow Wk. to mod. phosphorescence	Wk. orangy yellow Wk. to mod. phosphorescence
<b>D</b>	0.34	Fancy gray <sup>d</sup>	Round brilliant	From Argyle mine	Ia	No	Strong yellow Wk. to mod. phosphorescence	Wk. orangy yellow Wk. to mod. phosphorescence
<b>E</b>	0.75	Fancy gray <sup>d</sup>	Marquise	From Argyle mine	Ia	No	Not tested	Not tested
<b>F</b>	0.68	Fancy gray <sup>d</sup>	Pear	From Argyle mine	Ia	No	Mod. yellow Wk. to mod. phosphorescence	Wk. yellow Wk. to mod. phosphorescence

<sup>a</sup> As determined by infrared spectroscopy.

<sup>b</sup> Abbreviations: v. = very, wk. = weak, mod. = moderate.

<sup>c</sup> Color terminology of the Gem Testing Laboratory of Great Britain.

<sup>d</sup> Color terminology of the GIA Gem Trade Laboratory.

a feature observed in the spectra of all natural type IIb diamonds (see, e.g., Smith and Taylor, 1962).

From our observations, one can only assume that the outer skin of both crystals consisted of a different diamond type, one that is not electrically conductive. This layer was not detected by infrared spectroscopy, either because it was probably of type IIa diamond, and therefore did not modify the shape of the infrared spectrum, or because it was of type Ia but too thin to induce a measurable absorption. The nonconductive layer was undoubtedly removed during faceting, so that the two stones conducted electricity afterward. This is a good example of the presence of two different diamond types within the same crystal, a concept that is not always made clear in the gemological description of diamonds (again, see Box A).

Interestingly, faceted stones A and B were also found to exhibit unusual luminescence behavior after faceting. Most natural blue diamonds are inert to ultraviolet radiation, both long- and short-wave, or show only an extremely weak yellow phosphorescence to short wavelengths. When exposed to long-wave U.V. radiation, stone B was inert but stone A emitted a very weak orange luminescence. When exposed to short-wave U.V., however, both stones produced a reddish orange luminescence of weak-to-moderate intensity. This light emission was followed by a persistent reddish orange phosphorescence after the ultraviolet lamp was turned off. The phosphorescence lasted unusually long in stone A: It was visible for more than four minutes in a completely darkened room. These two stones are therefore similar in their fluorescence characteristics to the Hope diamond (Crowningshield, 1989). Sometimes, blue



Figure 1. The crystals from which this 4.15-ct fancy bluish gray pear shape (stone A) and 3.06-ct fancy dark blue cushion modified brilliant (stone B) were fashioned were not electrically conductive, although the faceted stones are. Diamonds courtesy of Mr. R. Vainer and Mr. Th. Horovitz; photo by Robert Weldon.

diamonds are represented as having been cut from the same rough as the Hope because of their orangy red luminescence. Stone B provides a well-documented counter-example to this naive belief.

Of additional interest was the presence in stone B of brown radiation stains on the surface of the rough (figure 2). Such stains are known to result from irradiation by alpha particles, possibly coming from uranium radioisotopes (Meyer et al., 1965). Although they are fairly common on type Ia diamonds, radiation stains have been reported only once before on type IIb diamonds (Hargett, 1991).

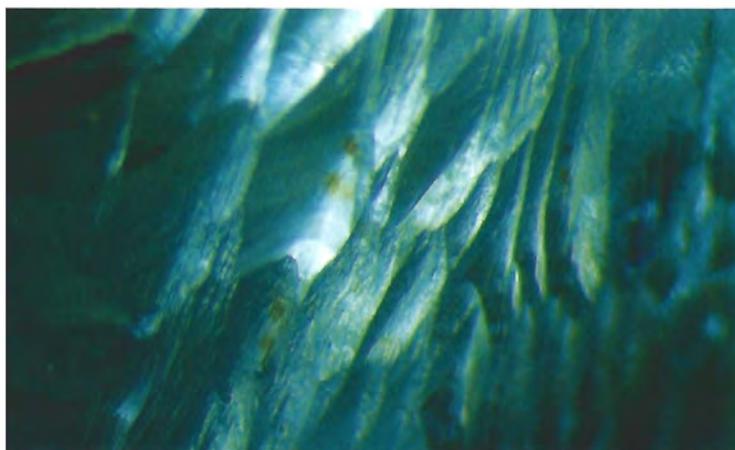


Figure 2. Brown radiation stains were observed on the surface of stone B before it was faceted. Photomicrograph by Kenneth Scarratt; magnified 10 $\times$ .

## BOX A: A NOTE ON DIAMOND TYPES

An ideal diamond crystal is colorless and its structure is made exclusively of carbon atoms, regularly arranged in a perfect lattice. Most natural gem diamonds, however, contain a number of defects and/or impurities, which may significantly affect some of the physical properties, such as color or electrical conductivity, of the stone. Some impurities such as nitrogen or boron may substitute for carbon atoms, which means that one carbon atom is replaced by one nitrogen or boron atom in the diamond structure. When a carbon atom is missing, the empty volume it leaves in the structure is called a vacancy.

To account for the differences in physical properties observed, in 1934 Robertson et al. conveniently grouped diamonds into two main "types"—type I and type II. Historically, these types have been distinguished on the basis of their ultraviolet transparency and absorption in the infrared—specifically in the 1000–1400  $\text{cm}^{-1}$  section (also called "the nitrogen region") of the mid-infrared range (Clark et al., 1979).

The characteristic absorption features in the infrared spectra of type I diamonds (see figure A-1) have been attributed to the presence of nitrogen in a number of different forms. Type I diamonds can be further subdivided into types Ia and Ib depending on the form that the nitrogen takes within the crystal structure of the individual stone. The nitrogen in type Ia diamond is present in various aggregated forms. The A aggregate is a pair of singly substituting nitrogen atoms, and the B aggregate is formed from an even number of nitrogen atoms, not exceeding eight (Bursill and Glaisher [1985] propose four nitrogen atoms surrounding a vacancy). The presence of one of these two aggregates allows type Ia diamonds to be further categorized into two subdivisions, types IaA and IaB, according to which aggregate is involved. However, most Ia diamonds contain both the A and the B forms in various proportions (and are sometimes noted for this reason as type IaAB; the spectrum of the type Ia diamond in figure A-1 is that of a type IaAB diamond). Another aggregate center, the N3 center, composed of three nitrogen atoms surrounding a vacancy, is believed to be formed by a minor side reaction during the main aggregation process of A to B (Woods, 1986). This aggregate is responsible for the N2 and N3 systems, which are best known to gemologists as "Cape lines" or "Cape series" in the visible-range absorption spectrum. Note that the A and B aggregates have characteristic absorption features in the infrared (and none in the visible), whereas the N3 center has typical absorption features in the visible (but none in the infrared).

Type Ia diamonds usually contain large amounts of nitrogen impurity (1000 ppm is common, but they may

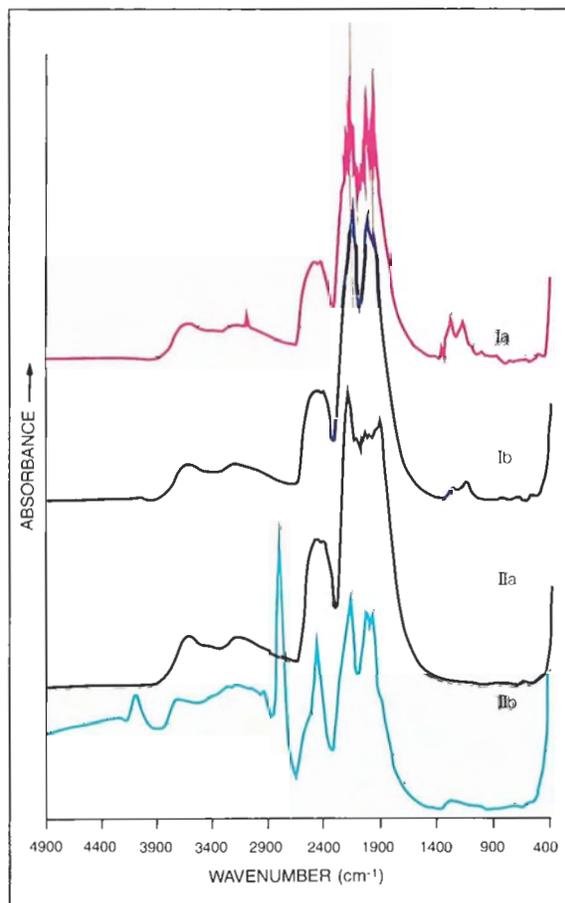


Figure A-1. These infrared spectra illustrate the four basic types of diamond. Each type can be characterized by its transmission in the 1000–1400  $\text{cm}^{-1}$  range. In addition, absorption in that range identifies some of the kinds of aggregates present in type Ia diamonds.

have up to 3000 ppm; see Field, 1983). Depending on the strength of the "Cape series," type Ia diamonds may vary in hue from near-colorless (possibly a weak band at 415 nm, with none of the other bands in the series being present) to a deep "Cape" yellow (in which all of the bands in the series are present in some strength, particularly the 478-nm band). Other factors may sometimes affect the color, and type Ia diamonds are effectively opaque to wavelengths shorter than 300 nm. The vast majority of gem diamonds are type Ia.

Type Ib diamonds are distinguished by the fact that the nitrogen atoms they contain are dispersed in isolated substitutional sites (i.e., one nitrogen atom replaces one carbon atom in a number of carbon atom sites). These nitrogen atoms produce a characteristic infrared absorption feature with a peak at  $1131\text{ cm}^{-1}$  (again, see figure A-1). Type Ib diamonds contain only small amounts of nitrogen (usually about 25 to 50 ppm, but 500 ppm has been reported for synthetic type Ib diamonds; Clark et al., 1979; Field, 1983). The dispersed nitrogen atoms are responsible for the continuous and gradual absorption of wavelengths shorter than 560 nm (Clark et al., 1979). Therefore, type Ib diamonds generally do not show sharp absorption lines in the hand-held spectroscopic, in contrast to type Ia stones. Their absorption in the visible region tends to produce a deep yellow (in rare instances, brown) body color. Because of the deep yellow color, such diamonds are sometimes referred to in the trade as "true canaries." Type Ib diamonds are said to be rare, at least among gem-quality crystals.

The total amount of nitrogen present in type I diamonds is the sum of nitrogen contained as singly substituting nitrogen, A and B aggregates, N3 centers, and other nitrogen-containing defects that do not absorb in the visible or infrared range.

Type II diamonds do not show any of the nitrogen-related absorption features in the infrared that are present in type I stones (again, see figure A-1), and therefore they are believed to contain no significant amount of nitrogen (Field, 1979). It is interesting to note that the definition of type II diamonds actually rests on an instrumentation limit, that is, the detection limit of the infrared spectrometer used. With the advances that have been made in infrared spectroscopy, especially the development of the more sensitive Fourier-Transform infrared (FTIR) spectrophotometer, a diamond formerly identified as a pure type II might today be called, for example, a type Ia diamond with a very low nitrogen content.

Type II diamonds that do not conduct electricity are designated type IIa. They may contain up to 20 ppm of nitrogen (not detected by infrared spectroscopy; Badzian et al., 1986). These diamonds are very transparent in the short-wave ultraviolet range, down to approximately 230 nm. By testing stones for their short-wave ultraviolet transparency, gemologists have generally been able to successfully separate type IIa diamonds from other diamonds in the absence of sophisticated equipment (Fryer, 1981). Unless type IIa diamonds contain structural defects, they do not absorb visible light; therefore, they are usually colorless. While famous colorless diamonds such as the Cullinan and Koh-i-Noor gems are type IIa, other type IIa diamonds may have a yellow to brown or pink body color, due to unknown color centers (Collins, 1982). Type IIa gem diamonds are believed to be rare.

Type II diamonds that conduct electricity have been called type IIb. Natural-color blue diamonds reported prior to this article have all been type IIb. Type IIb stones show a distinct spectrum extending over the whole mid-infrared range that is quite different in appearance from that of the other types (again, see figure A-1). Such stones contain boron as an impurity, in concentrations of a few parts per million or less (Lightowers and Collins, 1976; Badzian et al., 1986). They transmit light down to about 230 nm (as do type IIa). The boron atoms create an absorption in the near infrared that extends into the visible range, absorbing some of the red and orange; therefore, type IIb diamonds are commonly blue. However, their color often shows a gray component, and sometimes they are pure gray. Occasionally, when very pale, they appear to be near-colorless.

The differences in these diamond types relate to differences in trace-element chemistry. For example, the average nitrogen concentration decreases from types Ia to Ib to II. Boron has so far been reported only in type IIb stones (Field, 1979). Hydrogen has been found exclusively in type I stones (Fritsch and Scarratt, 1989). Diamond types are, therefore, more than just a convenient way to classify diamonds on the basis of their infrared spectra; they also have potentially important geochemical significance. For example, different types of diamond may represent different geologic origins.

The relative rarity of the various diamond types reported here reflects the figures provided in the preponderance of the literature (e.g., Field, 1983). Although it provides a "common wisdom" on the subject, one should keep in mind that the proportions cited (presumably) for all diamonds mined may not necessarily apply to diamonds of gem quality, or to colored diamonds or any other subgroup. For example, Tolansky and Rawle-Cope (1969) demonstrated that there is an unusually high proportion of type IIa diamonds among high-clarity microdiamonds, whereas type IIa diamonds are reported (by Field, 1983) as being uncommon in gem quality.

In many articles describing diamonds, it is generally implied that one diamond crystal contains only one diamond type. Actually, most diamond crystals are a more or less homogeneous mixture of different types. For example, most natural type Ib diamonds have a type IaA component, too, which can be recognized in their infrared spectra. Also, Milledge et al. (1989; see also Boyd et al., 1987) demonstrated that type Ia diamond shows very thin growth banding of various "nuances" of diamond types, such as a strong variation in the relative proportion of A and B aggregates. Gemologists should remember, for gem identification procedures, that many gem diamond crystals may not be composed of one single diamond type.



Figure 3. Stone E in this study is a natural-color gray non-electrically conductive type Ia diamond from the Argyle mine, in northwestern Australia. Stone courtesy of Argyle Diamonds; photo by Robert Weldon.

### NONCONDUCTIVE GRAY-TO-GRAYISH BLUE DIAMONDS FROM ARGYLE

Stones C to F were all tested as faceted stones. Although the gray-to-grayish blue colors they display resemble those normally seen in natural type IIb, electrically conductive, diamonds (figure 3), they do not conduct electricity. Moreover, their ultraviolet-visible absorption spectra differ significantly from that which is perceived as normal for gray-to-blue diamonds (Collins, 1982), as do their infrared spectra.

These stones fluoresced a moderate to strong yellow to orangy yellow to long-wave ultraviolet radiation, and a weak to moderate yellow to orangy yellow to short-wave U.V. They also displayed a weak to moderate yellow phosphorescence to both wavelengths. Although we could find no prior reference to such luminescence behavior in natural gray-to-blue diamonds, it is not uncommon for type Ia faceted diamonds.

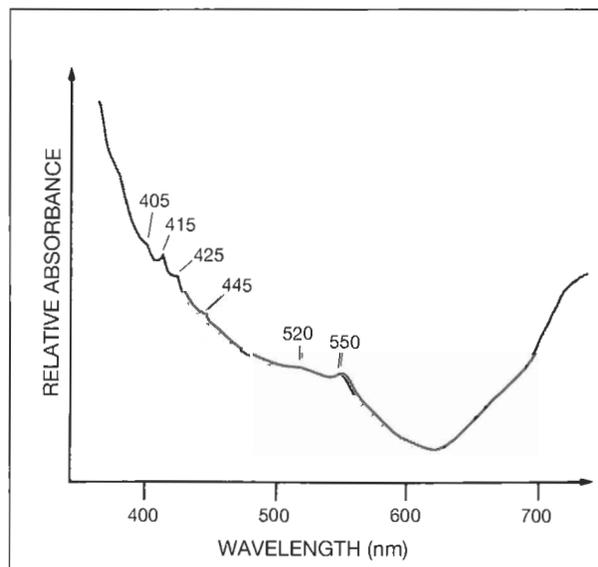
The U.V.-visible absorption spectra of stones C to F (figure 4) show two bands, at 405 and 415 nm, that are superimposed on the increasing absorption toward the ultraviolet (the "U.V. cutoff"). They represent the N3 center, which is responsible for the "Cape lines" commonly found in the visible spectra of type Ia diamonds but has not been reported to occur in natural blue diamonds. Two weak absorptions at about 425 and 445 nm are accompanied by a broad, complex absorption system that has an apparent maximum at about 550 nm and a distinct shoulder near 520 nm. Absorption increases from approximately

600 nm toward the infrared. With the exception of the N3 system, these features have not been described previously in the literature on the spectra of diamonds (although some features at approximately the same wavelengths but with different shapes or widths have been reported).

At present, we cannot explain the variation in hue among these stones. Answering this question would require a detailed study of transmission spectra and thus the availability of parallel-window samples of known thickness, which are virtually impossible to obtain on gem-quality—especially faceted—diamonds of such great value.

Since the spectra of stones C to F reveal that they are type Ia rather than IIb, their lack of electrical conductivity cannot be explained by a zonation of diamond type within the stone, as in the situation described for the two pieces of rough. Most remarkably, the infrared spectra of all four stones show very sharp bands at about 1498, 2786, and 4499  $\text{cm}^{-1}$ , with two very intense ones at 3107 and 3237  $\text{cm}^{-1}$  (figure 5). There are also a number of related absorptions in the near-infrared (around 5555, 5880, 6070, 7500, 7850, 8255, and 8615  $\text{cm}^{-1}$ ), some relatively new to the scientific literature (Fritsch et al., 1991). In fact, the spectrum in figure 5 is similar to that reported by Fritsch and Scarratt (1989) as typical for a group of

Figure 4. The U.V.-visible absorption spectrum of the gray diamond (stone E) in figure 3 proves that it is a type Ia diamond.



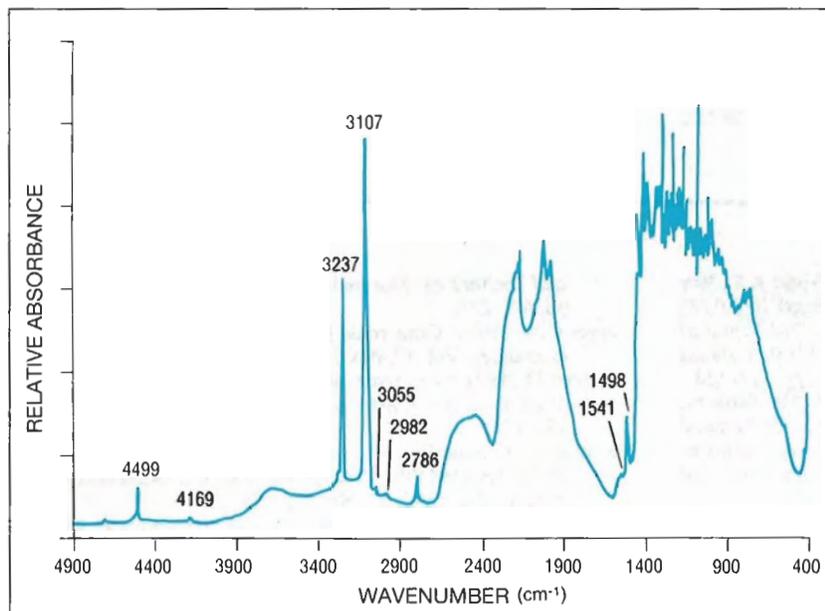


Figure 5. The room-temperature mid-infrared absorption spectrum of stone E, while unusually intense for diamonds, is typical of those recorded to date for gray-to-blue diamonds from the Argyle mine, Australia. The sharp bands at 2786, 3107, 3237 and 4499  $\text{cm}^{-1}$  are due to hydrogen. The "noise" between 1400 and 600  $\text{cm}^{-1}$  is due to complete absorption of these energies by the diamond.

diamonds with a gray component to their color. The sharp bands at 3107 and 3237  $\text{cm}^{-1}$  in figure 5 have been attributed to hydrogen complexes (Woods and Collins, 1983; Davies et al., 1984). They are, however, unusually intense in these Argyle diamonds.

In fact, these unusually intense absorption features related to hydrogen have been observed in over 100 colored diamonds from various sources that we have studied. We have found distinctive absorption features or behavior (a list is provided in Fritsch et al., 1991) in all of these "hydrogen-rich" diamonds, which can be brown to yellow to gray, gray to blue or violet, white (opalescent), or exhibit a "chameleon" behavior. The broad absorption complex around 550 nm reported for the stones examined for this article is one of these unusual absorptions, and is responsible for a gray-to-blue coloration. This absorption complex has been observed in more than a dozen stones, always in association with very strong hydrogen bands in the infrared. This suggests that the presence of the 550-nm absorption complex and the other unusual absorption features associated with it correlates to the presence of hydrogen-related defects. Quantitative research is ongoing to confirm this hypothesis.

## DISCUSSION AND CONCLUSIONS

The samples described here demonstrate the existence of natural-color gray-to-blue diamonds that do not test positive for electrical conductivity, some in

the rough and others in faceted form. We conclude that there are natural-color non-electrically conductive gray-to-blue diamonds, and that the absence of electrical conductivity should not be used as the sole criterion in identifying a diamond in this color range as treated. Of course, electrically conductive gray-to-blue natural diamonds are invariably of natural color (with the exception of the currently very rare, noncommercially available near-colorless diamonds that have been treated with blue synthetic diamond thin films; as reported by Fritsch in Koivula and Kammerling, 1991). Therefore, gray-to-blue diamonds can no longer be separated from their treated counterparts on the basis of electrical conductivity alone.

We have also described here a number of previously unreported absorption features in the visible spectrum that appear to be responsible for a newly observed kind of blue-to-gray coloration in gem diamonds. We believe that these features may be related to the presence of unusually high concentrations of hydrogen. Previously, nitrogen—mostly in combination with structural defects—and boron were the only trace elements thought to play a role in the coloration of diamonds. To the best of our knowledge, this is the first time that hydrogen has been suggested as a cause of color in diamonds.

So, when a gray-to-grayish blue diamond does not test as electrically conductive, luminescence must be taken into greater consideration. If the stone exhibits a yellow to yellow-green luminescence that

is stronger to long- than short-wave ultraviolet radiation, and produces a moderate yellow phosphorescence after exposure to both wavelengths, it is probably a natural-color diamond that belongs to the

new category of blue-to-gray diamonds described here. We recommend, however, that U.V.-visible and infrared absorption spectroscopy be used to confirm this diagnosis.

## REFERENCES

- Badzian A., Simonton B., Badzian T., Messier R., Spear K.E., Roy R. (1986) Vapor deposition synthesis of diamond. In *S.P.I.E. Proceedings Series, Vol. 683, Infrared and Optical Transmitting Materials*, Society for Photooptical Instrumentation Engineers, Bellingham, WA, pp. 127–138.
- Boyd S.R., Mathey D.P., Pillinger C.T., Milledge H.J., Mendelssohn M., Seal M. (1987) Multiple growth events during diamond genesis: An integrated study of carbon and nitrogen isotopes and nitrogen aggregation states in coated stones. *Earth and Planetary Science Letters*, Vol. 86, pp. 341–353.
- Bursill L.A., Glaisner R.W. (1985) Aggregation and dissolution of small and extended defect structures in type Ia diamond. *American Mineralogist*, Vol. 70, Nos. 5–6, pp. 608–618.
- Clark C.D., Mitchell E.W.J., Parsons B.J. (1979) Color centres and optical properties. In J.E. Field, Ed., *The Properties of Diamond*, Academic Press, London.
- Collins A.T. (1982) Color centres in diamond. *Journal of Gemmology*, Vol. 18, No. 1, pp. 35–75.
- Crowningshield R. (1989) Grading the Hope diamond. *Gems & Gemology*, Vol. 25, No. 2, pp. 91–94.
- Custers J.F.H. (1954) Dr. Custers lectures in London on colouring diamond. *The Gemmologist*, Vol. 23, No. 275, pp. 101–102.
- Davies G., Collins A.T., Spear P. (1984) Sharp infrared absorption lines in diamonds. *Solid State Communications*, Vol. 45, No. 5, pp. 433–436.
- Field J.E. (1979) *The Properties of Diamond*. Academic Press, London.
- Field J.E. (1983) Diamond: Properties and definitions. Paper presented at the DeBeers 1982 Diamond Conference.
- Fritsch E., Scarratt K.V.G. (1989) Optical properties of some natural diamonds with high hydrogen content. In A. Feldman and S. Holly, Eds., *S.P.I.E. Proceedings Series, Vol. 1146, Diamond Optics II*, Society for Photooptical Instrumentation Engineers, Bellingham, WA, pp. 201–206.
- Fritsch E., Scarratt K.V.G., Collins A.T. (1991) Optical properties of diamonds with an unusually high hydrogen content. In R. Messier, J.T. Glass, J.E. Butler, R. Roy, Eds., *MRS International Conference Proceedings. New Diamond Science and Technology*, Materials Research Society, Pittsburgh, PA, pp. 671–676.
- Fryer C.W. (1981) Gem trade lab notes: IIb or not IIb. *Gems & Gemology*, Vol. 17, No. 1, p. 43.
- Hargett D. (1991) Gem trade lab notes: Type IIb with natural irradiation stains. *Gems & Gemology*, Vol. 27, No. 3, pp. 174–175.
- Koivula J., Kammerling R.C. (1991) Gem News: Bluish gray synthetic diamond thin films grown on natural diamonds. *Gems & Gemology*, Vol. 27, No. 2, pp. 118–119.
- Liddicoat R.T. Jr. (1987) *Handbook of Gem Identification*, 12th ed. Gemological Institute of America, Santa Monica, CA.
- Lightowers E.C., Collins A.T. (1976) Determination of boron in natural semiconducting diamond by prompt particle nuclear microanalysis and Schottky barrier differential-capacitance measurements. *Journal of Physics D*, Vol. 9, pp. 951–963.
- Meyer H.O.A., Milledge H.J., Nave E. (1965) Natural irradiation damage in Ivory Coast diamonds. *Nature*, Vol. 206, p. 392.
- Milledge H.J., Mendelssohn M.J., Boyd S.R., Pillinger C.T., Seal M. (1989) Infrared topography and carbon and nitrogen isotope distribution in natural and synthetic diamonds in relation to mantle processes. In *Extended Abstracts. Workshop on Diamonds, 28th International Gemological Congress*, The Geophysical Laboratory, Washington, DC, pp. 55–60.
- Robertson R., Fox J.J., Martin A.E. (1934). *Philosophical Transactions*, Vol. A232, London, pp. 463–535.
- Smith S.D., Taylor W. (1962) Optical phonon effects in the infrared spectrum of acceptor centres in semiconducting diamond. *Proceedings of the Physical Society*, Vol. 79, pp. 1142–1153.
- Tolansky S., Rawle-Cope M. (1969) Abundance of type II diamond amongst natural microdiamonds. *Diamond Research*, pp. 2–6.
- Woods G.S. (1986) Platelets and the infrared absorption of type Ia diamonds. *Proceedings of the Royal Society of London A*, Vol. 407, pp. 219–238.
- Woods G.S., Collins A.T. (1983) Infrared absorption spectra of hydrogen complexes in type I diamonds. *Journal of Physics and Chemistry of Solids*, Vol. 44, pp. 471–475.