THE ORIGIN OF DIAMONDS AND THE DEEP GAS HYPOTHESIS

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ダイヤモンドの成因と深部ガス仮説： Cornell 大学の Thomas Gold と Steven Soter が行なった地球深部のガスの性質と量についての最近の研究結果がもとになって，宝石学上の最大のパズルであった問題について新しいアイデアが生まれてきた。このアイデアによると，ダイヤモンドは濃縮ガスの運動によってできたと解釈することができる。このガスの成分の一つは，非生物起源のメタンで，150～250 Kmの深さにある空隙を通り，ほとんど純粋な炭素の結晶を沈澱させる。問題のガスは，我々の星（地球）の起源からあった成分で，その運動は，地球生成以後ひきつづいて行なわれている脱ガス過程の一部であると解釈される。同一起源のガスが，キンバレー岩パイプにより地殻に激しい割れ目をつくる原因にもなり，これによって，大きな垂直的な温度・圧力領域を通ってダイヤモンドを運び上げ急冷させ，通常の炭素に変換させないまま安全にダイヤモンドを地表にまで運び上げることができるのである。

Abstract: Recent work by Thomas Gold and Steven Soter at Cornell University on the nature and quantity of gases deep within the earth provide new ideas on that most puzzling of gemmological problems: the origin of diamonds. Diamonds can be interpreted as having been formed by the movement of a dense gas, one of whose constituents was abiogenic methane, through pore spaces at depths of 150 – 250 km, depositing crystals of essentially pure carbon. The gas in question is held to have been an original constituent of our planet and its movement is interpreted as part of the continuing planetary outgassing process. Gas of identical origin can be called upon to account for the violent puncturing of the earth's crust by kimberlite diatremes and the safe ferrying of the rapidly cooled diamonds through a large vertical pressure/temperature region in which slow passage would doom the diamonds to reversion to ordinary carbon.

The genesis of diamonds, which Professor Gübelin has described as "full of riddles and secrets" in his Internal World of Gemstones (1974), has a very long pedigree, having puzzled gemmologists and geologists for a number of centuries. In searching for new approaches to the diamond problem, we should first attempt to determine whether the formation of diamonds is an isolated puzzle, a scientific curiosity standing all by itself, or whether it is one of a class of interrelated matters.

Scientific enigmas are rarely resolved all on their own, one-by-one. Darwin's insights into the nature of the evolutionary process, for example, was not achieved only through observations made during his sojourn on the Galapagos Islands. Instead, it was through the combination of data acquired there, some of which were exceedingly puzzling in their own time, combined with a myriad of other observations as varied as the length of the giraffe's neck and the speckling of eggs which, once synthesized, provided a general set of ideas and principles applicable to a large number of biological problems whose underlying interrelationships had never been appreciated before.

I would like to suggest that the much-studied problem of the existence of diamonds at and near the surface of the Earth is best approached, not in isolation, but as one of a number of potentially related matters, most of which are well outside the immediate field of gemmology.

Proceedings of the XVIII International Gemmological Conference,
Journal of the Gemmological Society of Japan, Vol.8, no1-4 (Dec. 1981) pp.79-85.

We can commence by noting that the diamond problem itself can be resolved into two components:

1) the actual mode of formation of diamond crystals – which must have taken place in a region of high temperatures ($1000^\circ \sim 1300^\circ C$) and of pressures of 45,000 ~ 120,000 atmospheres.
2) the means by which the diamonds, once formed, were transported to the vicinity of the Earth's surface.

As concerns the actual crystallization of diamonds, we can imagine the dissociation of carbon dioxide at depth and the precipitation of carbon as diamond but this is a very inefficient set of reactions whose ultimate success is badly compromised by the subsidiary problem of getting rid of the great quantities of excess oxygen.

The second portion of the diamond problem is how to transport the crystals, more or less intact, without total dissolution or resorption, to a distant near-surface regime characterized by much lower temperatures and pressures. The problem is that in-between the deep regions where diamonds are thought to be crystallized and the surface region where they are actually found is a zone characterized by pressure/temperature conditions under which diamonds could not survive.

A number of scientific problems from outside the field of gemmology are potentially related to the genesis of diamonds. These can be grouped into two major categories, first, a) the deposition of naturally-occurring forms of carbon or carbon-rich materials other than diamond and second, b) problems which concern the transportation of various materials from distant and exotic geological environments. In surveying these problems I shall be depending very heavily on the work, published and unpublished, of Professor Thomas Gold and Dr. Steven Soter, both of Cornell University, on what they have called "The Deep-Earth-Gas Hypothesis". In fact, however, I believe that their ideas constitute more than a "hypothesis" and that, once adequately developed, they will provide clues to numerous important problems including earthquake prediction and the energy problem.

Among the naturally-occurring carbon-rich materials we should note are various types of coal.

One problem concerning coal is the remarkable purity of many of its deposits, difficult to understand in view of the great amount of inorganic material observed to be transported by floating trees and vegetable matter. The traditional image of coal swamps or peat bogs has to be modified so as to remove all soil, sand and pebbles from each root and rootlet for such deposits.

A second puzzling occurrence of coal is as unburned, unaltered, fragments occasionally found in contact with or included in kimberlites. We should ask what kind of eruption a kimberlite eruption can be if it fails to either ignite or drive the volatiles out of such coal.

Many coal deposits are associated with underlying beds of refractory clays but in some cases the standard geochemical explanations make no sense: that is, a thin bed of coal is hypothesized to have leached the iron and alkalies from a very much thicker bed of clay. Furthermore, there are some localities in which the bottom levels of the underlying refractory clay appear to be more highly leached than the uppermost clay in contact with the coalbed (Hopkins, 1901).

Some coal deposits contain enigmatic balls of barely fossilized leaves and twigs.

Others contain fossilized wood with an absolute carbon content much higher than the original living trees. The question to be posed is the source of the "new" carbon, inserted after the death of the tree. Methane, usually found in coal mines and implicated in the recent accident near Yubari, might serve as such a source.

Finally, before leaving the subject to coal, we should note that some rare coal deposits, such as the Albert Coal of New Brunswick, Canada, are clearly not sedimentary, but appear to have been injected in a liquid state into vertical fissures in a host rock, much like a vein of igneous rock (Hitchcock, 1865).

When we turn to oil and gas we find the situation similarly confusing. The amount of research spent on the origin and occurrence of petroleum is immense and yet, bizarre as it sounds, there is still no firm agreement among professionals on the fundamental question whether oil and gas are organic or inorganic in origin. One specialist, writing in the Bulletin of the American Association of Petroleum Geologists (Porfir'ev, 1974), concludes that "the organic theory of the origin of petroleum does not correspond to the modern state of knowledge in the fields of geology, geochemistry, geophysics, thermodynamics, astrophysics and other sciences; in fact it is an outmoded, outdated concept" whereas another specialist, A.I. Levorsen, who literally "wrote the book" on petroleum occurrences, stated that "Theories that uphold the inorganic origin of petroleum have few supporters today" (1958) "for several good reasons. In the first place, optical rotary power is a characteristic of petroleums" and "(a)s far as is known, the phenomenon is almost entirely confined to organic matter and is observed only where biological agencies have prevailed". (This was written in 1958 but the judgment expressed here is still the rule in the petroleum industry.)

The resolution of these conflicting statements is entirely possible, and even straightforward, but it required a very great and clear-thinking scientist to arrange the contradictory evidence in its proper order. As early as May 1961 Sir Robert Robinson, the British chemist, had summed up his own conclusions, with which I am in full agreement, writing that

" . . . the arguments for a biological and an abiological origin of petroleum are alike incontrovertible. Hence a duplex origin of mineral oil is envisaged" (Robinson, 1962). Elsewhere Robinson actually referred to his "proofs" which he called "a strong word used advisedly with full implication". I have cited Robinson's forceful conclusions in order to avoid reviewing a long list of anomalous observations concerning occurrences of oil and gas. I would, nevertheless, like to note three odd aspects of petroleum geology which are particularly illustrative,

– first, the tendency for oil and gas occurrences to line up vertically one above another so that one well may produce from several horizons. This suggests that particular geographical spots were predisposed to be suitable for oil formation throughout much of geological time whether or not the local climate was suitable for the accumulation and decay of great quantities of organic matter. In some instances such areas of multiple oil horizons are also associated with coal beds.

– we must also contend with the fact that deep gases found below oil fields are generally richer in methane than gases produced from higher levels within the same field or well. This is difficult to reconcile with the conventional view of methane (a light gas with a natural tendency to rise) as a break-down product of biogenic liquid petroleum. But if methane is not a break-down product of petroleum then, similarly, perhaps it is not a break-down product of coal. Why then is it found in association with both oil and coal?

– in addition, any overall view of the oil problem should not neglect the many enigmatic occurrences of oil and gas in igneous rocks with no nearby sediments as credible source rocks.

Graphite is another naturally occurring form of pure carbon. Concerning deposits of this mineral the authors of Dana's System of Mineralogy note "there is no general agreement as to the physical-chemical conditions leading to the formation of large bodies of graphite" (Palache et al., 1944). Graphite was, however, long ago noted to be commonly associated with limy sediments (Clark, 1921), a vaguely suggestive association of two carbon-bearing substances, reduced and oxidized, faintly evocative of the poorly understood association of kimberlites with cabonatites, carbonatites in this comparison being thought of as "igneous limestones". A recent study of the graphite problem has reached the surprising and perhaps inexact conclusion that graphite found in all grades of Precambrian metamorphic rocks have the same source, namely, "organic carbon" (Mancuso and Seavoy, 1981).

Another carbon-rich material is schungite, a graphite-plus-water mixture whose very rare occurrences present intractible problems to both field geologist and laboratory mineralogist.

To conclude these remarks on the geological occurrences of carbon-containing materials, let us also note that, of all the chemical elements present in sedimentary rocks, carbon is apparently the only one whose presence cannot be quantitatively accounted for by the grinding up and weathering of igneous rocks.

Now let us examine the next set of problems potentially allied to diamonds, that of materials transported from exotic geological domains:

The most exotic domain of all is the region from which meteorites have come. Meteorites are extra-terrestrial materials whose chemical compositions are thought to indicate the early composition of the Solar System. Some meteorites are overwhelmingly carbonaceous. Others, although primarily metallic, contain massive inclusions of carbon. Most meteoriticists feel it safe to assume that the deep earth contains or once contained quantities of carbonaceous materials and that the carbon-rich meteorites are dried-out, dessicated, examples of an important fraction of the primordial materials from which our planet was formed.

Another material which has arrived on the surface of the Earth from an exotic provenance is helium, second most common element in the universe but rare on the surface of the Earth where it forms no stable solid compounds and, as a gas, is so light that it rises and escapes from the top of the atmosphere. Lake Kivu, in central Africa, which is known for its exceedingly high content of dissolved methane, also contains great quantities of dissolved helium. The ^3He content of the helium in Lake Kivu indicates that this particular helium, at least, is <u>not</u> the product of radioactive decay but is due to the continuing loss of deep gases that were trapped in the Earth at the time of its formation (see Alexander and Ozima, 1978). If helium, an exceedingly light gas, is still rising to the surface of the Earth, then it follows that any other heavier gases of primordial provenance might well be doing the same.

Another substance with an exotic origin is atmospheric radon. One of the accepted but poorly understood precursors of earthquakes is radiogenic radon^{222} gas (Wakita <u>et</u> <u>al</u>., 1980) which, with a half-life of only 3.82 days, can hardly have come from very deep. Radon atoms are so rare that they can only have been introduced into the atmosphere in measurable quantities by a carrier gas and various constraints in both space and time suggest that the carrier gas itself cannot have come from very far. The most logical carrier gas for the radon is simply the mixture of gases normally found in soils. The question then arises – what is the exotic force that has pushed the soil gases up from below? A reasonable hypothesis would be that it is the upwards flow of a third gas.

These considerations, incidently, permit us to understand another curious earthquake precursor, the bizarre pre-quake behaviour of animals. This is well attested to for many species of creatures, ranging from fish to cats and ducks to cuckoos (Tributsch, 1980). It is often thought that the pre-quake behaviour of animals is due to an electrical effect of some sort but Helmut Tributsch (1980) eliminated most of the electrical hypotheses in his study of the case of a livestock train standing in the Italian town of Pontebba awaiting customs clearance on the evening of an earthquake. "The wagons were boxes of sheet iron with several rectangular openings only. The cattle and horses had been fed and watered. Under normal circumstances they stay quiet. Approximately 15 – 20 minutes before the earthquake, however, the animals started to show discomfort and produce excessive noise. The transportation workers decided to notify their superiors, fearing poisoning or disease. These wagons (Faraday cages) cannot apparently shield these pre-earthquake signals. Nor could small vibrations preceeding the quake have been responsible for the unrest. There was only one, relatively strong, foreshock within one minute of the main quake . . . " (Tributsch, 1980). It would seem to me that the simplest explanation for such phenomenon is the one that was suspected by the transport workers themselves, although there is certainly room for informed disagreement both on this point and on many others I have presented. It also seems to me that the most logical source of the malaise which affects animals is a gas coming from below. The accumulated evidence, the superior olofactory sensitivity of many animals, and the fact that their noses are in many cases closer to the ground than ours, all combine to suggest this explanation.

Fish-kills, in which enormous numbers of dead fish of diverse species are found floating on the surface of the sea, constitute another class of well documented unexplained phenomenon which can be understood by the notion of gases arriving from below, as are earthquake lights, lights seen in the sky before and during the course of earthquakes. This too is not a rare phenomenon. Hundreds of occurrences have been reported and such lights have actually been photographed in Japan as far back as the 1920s or 1930s. In most cases earthquake lights are faint and difficult to describe in meaningful manner, especially if one is being badly shaken up at the moment of their occurrence but one report from southern Germany classified them as a sea of flames, "gas-like and not electrical in nature" (Schmidt and Mack, 1912 – 1913). The date of this observation, November 16th, 1911 is significant. At that epoch an observer might well have been quite familiar with both gas lights and electricity.

Alexander von Humboldt (1889), commenting on an earthquake he witnessed at Cumana, Venezuela on December 14th, 1797 referred to "earthquake flames" on the banks of the river Manzanares with no elaboration, as though it was a well-established phenomenon. During the earthquake of May 3rd, 1887 in Sonora, Mexico, similar flames were observed to char branches of trees which overhung fissures in the ground (Goodfellow, 1888).

I have not by any means exhausted my list of interrelated anomalies – which also include unexplained booming noises in the atmosphere ("brontides"), earthquake aftershocks (difficult to explain if earthquakes are a phenomenon of brittle fracture only), mud volcanoes, certain classes of reports of unidentified flying objects, snakes which come out of their holes in midwinter only to freeze to death, sounds like the rushing of wind during earthquakes, foggy "earthquake weather" prior to wintertime earthquakes, the so-called "crypto-explosion" structures, the tendency for water to rise in wells before earthquakes, and so on – but I hope to have made my point that there is an enormous diversity of interlocking evidence for the presence of great quantities of an inflammable carbon-rich gas at depth in the Earth and for its release, imperceptibly or violently, from time to time. A mixture of gases in which primordial methane is a common component, rising to the Earth's surface for the first time since the Earth was formed seems to be implied, or at least consistent with the observations.

We have now surveyed or mentioned approximately thirty troublesome scientific problems and at this point can return to the genesis of diamonds and their safe delivery to the surface of the Earth. The correct approach to the first of these, the problem of diamond genesis and the origin of the exceedingly pure carbon from which diamonds are constituted, may well fall along the folloiwng lines:

Methane-rich fluid at pressures unknown from laboratory studies, technically a gas but at pressures sufficient to give it many of the properties of a liquid, partially dissociates at great depths within the Earth. It does this more readily than would CO_2 under the same conditions. Diamond crystals then grow at preferred sites along the path of the fluid flow by a process not so very different to the deposition of many other minerals, that is, by the circulation of mineralizing fluids (usually, however, envisaged as aqueous) along paths of least resistance within rocks. The fluid in question may also contain CO_2 whose equilibrium with respect to CH_4 is thought to be very delicate at the pressures and temperatures envisaged, and ready to be tilted very far one way or the other as a result of minor changes in the chemical composition of the surrounding rocks (Gold and Soter, personal communication). These facts, once quantitatively or semi-quantitatively understood, may eventually account for the occurrence of inclusions containing both CO_2 and CH_4 within certain diamonds (Melton and Giardini, 1974) and for the common association of carbonatite pipes with kimberlite pipes.

The diamonds, once formed in this manner, could not be transported to the surface of the Earth by any conventional mechanism such as by erosion of the overlying rocks or by transport in a normal volcanic eruption. Any such mode of transport would cause the diamond to pass through a zone of pressure/temperature conditions in which it was not stable and would degrade. To this, the second half of the diamond problem, Gold and Soter (personal communication) have asked: "How then can a diamond ever get to the surface?" The answer they supply is that the diamond must be cooled so fast that there is not enough time for the crystal structure to degrade. "Once at the surface, the diamond is 'metastable' at the low temperatures and is safe despite the low pressure. Such rapid cooling, or 'quenching', is most readily accomplished if the diamond is driven upward by a gas rather than carried up by entrainment in a molten liquid (Anderson, 1979). A gas, having relatively low viscosity, can move much faster than a liquid. But more importantly, a gas ascending to the surface from the realm of the diamonds (from, say, 45 kilobars) will be decompressed by a factor of 45,000 and will violently expand. Since there is no external energy input, such a rapidly expanding gas must undergo an extreme drop in temperature. The diamond will be refrigerated with respect to the temperatures in the wall rock of its conduit. A more efficient natural 'quenching' of a hot diamond would be difficult to imagine" (Gold and Soter, personal communication).

It is in this manner, I believe, that we should envisage the eruption of kimberlites.

Before concluding I would like to speculate on the reason why diamond-bearing kimberlites are usually found near the heart of stable cratons, far from other centers of extrusive activity such as vulcanism (see Dawson, 1970). In such environments the deep gas is effectively capped and under most circumstances cannot rise. It therefore takes a particularly violent event, entailing substantial overpressures, to bring the gases to the surface. It is perhaps only these particularly rapid decompressive events which specifically favor or permit the transport of intact diamonds from depth.

Working out the details of the geology of diamond deposits may still not be easy but the correct approach is, I believe, now available through application of Gold and Soter's concept of high-pressure, upward-moving, carbon-rich primordial gases from great depths within the Earth.

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