TREVOR EVANS

26 April 1927 — 10 October 2010

Elected FRS 1988

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Trevor Evans was responsible for revealing the main physical processes which take place in natural diamond both in the upper mantle of the earth, where it is stabilized by high pressure and temperature, and as it is ejected by volcanic action to the surface. By measuring the activation energies required for graphitization, he clarified the reason for its very long life as a metastable crystal, valuable both as a gemstone and as an industrial abrasive. He learned how to make diamond specimens for examination in the transmission electron microscope, which enabled his discovery of dislocation loops and platelet precipitates in nitrogen-containing (type 1) stones. In a series of exacting laboratory experiments under geologically relevant conditions he pioneered the study of the emergence of nitrogen from solution to precipitation during the ejection process. In synthetic diamonds, using high-energy electron irradiation, he was able to reproduce the sequence of all the various types of nitrogen aggregation found in natural diamond. His work played a major role underpinning the characterization of gemstones, explaining many features of their colour. For many years he led diamond research in the UK, supported by De Beers. His work stimulated and has been confirmed by research in many other laboratories around the world.

EARLY LIFE AND EDUCATION

Trevor Evans was born on 26 April 1927 in Tondu, Glamorganshire, the youngest of five children. His grandfather Thomas Evans was a Welsh-speaking railway engineer. His father
died when Trevor was 11 years old, leaving his mother and his elder brother Glyn to bring him up. He was educated in Tondu Primary School, then Bridgend Grammar School. Upon graduation in 1945 he did his compulsory National Service in the RAF. It is very revealing of his character that in the RAF he was given the alternatives of a position in ‘intelligence’ or ‘driving a lorry’. He had no hesitation in choosing the second option, joking in his later years that he had no use for intelligence. After that, at the University of Bristol, he won First Class Honours in Physics in 1952, and then went on to graduate work under Professor J. W. (Jack) Mitchell (FRS 1956), producing a thesis entitled ‘Crystal imperfection and chemical reactivity’. It was a pioneering time in dislocation physics. Bristol under Sir Charles Frank (FRS 1954) and Sir Nevill Mott FRS was at the forefront of studies of crystal growth and photographic processes, where the presence of dislocations enabled sense to be made of hitherto inexplicable phenomena of far-reaching industrial significance. Trevor continued this type of applicable research on polymers at British Nylon Spinners, and at Tube Investments, where ‘blue skies’ structural studies of thin films deposited by evaporation onto metal substrates was undertaken to support novel surface treatments potentially of commercial importance. At the same time De Beers was looking to invest in projects to improve fundamental understanding of diamond, because of both the need to assign provenance to gemstones, ‘gemmaology’, and the need to understand the frictional and wear properties of industrial diamond. It was an era in which artificial diamond was being developed, much to the consternation of De Beers. Charles Frank had caught the imagination of the scientific community with his idea that if snowflakes contain messages from the sky, susceptible to direct study, how much more significant are diamonds, bearing messages from the inaccessible depths of the Earth?—and finance was available from De Beers! It was the advent of an exciting new line of research, made all the more effective by a series of annual diamond conferences, sponsored by De Beers.

**Research works**

It seems that at Tube Investments Laboratories Trevor became acquainted with surface studies and electron microscopy, under J. W. (later Sir Jim) Menter (FRS 1966). Upon accepting a Research Fellowship held at the University of Reading and fully financially supported by De Beers, he started his remarkable research career on diamond, firstly studying the etching of surfaces with gases, particularly oxygen, leading to his ability to thin diamond sufficiently to observe defects in it by transmission electron microscopy (TEM). The initial work (1)* revealed characteristic pits which mimic known surface defects called ‘trigons’, significant in gemmology. This enabled subsequent TEM studies revealing dislocation loops and ‘platelets’, defects on cube planes, a discovery of great significance because one could see that diamonds, rather like age-hardening aluminium alloys, were host to precipitation processes which must be strongly temperature- and time-dependent (2, 3) (figures 1 and 2). Because type 1 diamonds contain nitrogen in various states of exsolution, and reveal copious arrays of platelets, whereas type 2 diamonds do not, it seemed fairly clear that the platelets are associated with nitrogen. In fact, the first suggestion of platelet precipitation had been made by Frank (1956) to explain streaking observed by Kathleen Lonsdale in X-ray diffraction patterns. He had speculated

* Numbers in this form refer to the bibliography at the end of the text.
Figure 1. The first published image of dislocation loops in diamond, in this case a nitrogen-containing (type 1) stone. The paper (2) describes the method of thinning the diamond for examination in the transmission electron microscope and suggests that the loops are produced as a result of ‘quenching’, that is, the rapid cooling of the stone as the volcanic magma carrying it reaches the surface of the Earth. This paper ushered in the long sequence of studies in many laboratories clarifying the exsolution processes taking place in natural diamond. The long side of the image corresponds to 16 µm in the field of view, making the smallest visible loop about 100 nm in diameter.

that silicon might be the culprit. Using diffraction contrast in the electron microscope, it was possible to show that the platelets could account for the X-ray results (4). Very soon after Evans & Phaal published their results (2, 3), several theories were advanced for the structure of the platelets, based on nitrogen–carbon bonding in various ways. Trevor himself was always very cautious, and, so far as we are aware, offered no hypothetical detailed crystallographic structure. Of consuming interest was: what could one learn about the geological history of diamond? And how might it impact gemmology? It was one of the early triumphs of TEM to see directly the legacy of an apparently simple solid-state process taking place over geological time.

‘Diamonds are forever’ is the famous advertising slogan, but actually diamond is thermodynamically unstable under normal conditions, degenerating to graphite. Stability requires pressure and temperature higher than values given by the ‘Berman–Simon’ line, achieved deep in the Earth’s mantle. In order to understand something of the genesis of diamonds which manage to arrive at the surface of the Earth, borne there by volcanic upsurge, the first step is to study the kinetics of transformation to graphite under a range of temperatures and pressures replicating geological conditions.

A series of experiments using high pressure–high temperature apparatus combined with TEM and optical spectroscopy followed. Both exsolution and graphitization processes were successively clarified, with some spectacular results. The critical step in graphitization of
Biographical Memoirs

Figure 2. Images of platelets on cube planes in a synthetic diamond heat-treated at 2400°C and 2500°C under a stabilizing pressure. The platelets, lying on cube planes normal to the reciprocal lattice vector (400) as shown, are viewed edge-on. The bright lobes on either side of them are regions of high strain due to the displacement outwards of the diamond lattice. Reproduced from (10).

low index planes at ambient pressure in a temperature range near 2000°C was thought to be the detachment of single surface atoms, followed by their migration and crystallization in graphitic form. This mechanism seems to be widely accepted. For \(\{111\}\) surfaces, an activation energy of 12.0 eV, and for \(\{110\}\) surfaces 7.5 eV, is required. On the former surfaces, the surface atoms are triply bonded, but on the latter, doubly bonded, which neatly accounts for the difference, and also explains the development of etch figures such as trigons. For graphitization to occur at room temperature, vast times are required, about \(10^{100}\) years, so the duration of ‘forever’ in the advertising slogan indeed exceeds the age of the Universe (5).

Of enduring interest, occupying many argumentative sessions at the annual diamond conferences, was the nature of the platelets and the related ‘voidites’, which often accompanied them. Voidites are nanometre-sized precipitates looking empty in the microscope, discovered by Trevor’s student Robert Stephenson in 1978 (Stephenson 1978). The platelets decompose into dislocation loops and voidites, a process briefly reported in an article published in the same year in the technical journal *Diamond Research* (8), but not properly understood until much later, 1995 (11). Prior to this last publication, in the midst of all the controversy about the role of nitrogen, much unpublished and difficult work attempting to understand the structures in the diamond-stable regimen of high temperature and pressure culminated in Trevor’s remarkable suggestion that they looked ‘against all reasonable arguments after heating for a short time in the graphite stable region, when the pressure was slightly below the Berman–Simon line’. This worked spectacularly and, to quote Trevor, the
‘fragments of surviving diamond were found to contain platelets which had been converted to dislocation loops and voidites within a minute or two—this was the most satisfying result of the whole lot as it seems so irrational’. It is now widely accepted that the voidites are nitrogen agglomerates resulting from discontinuous precipitation at platelets as the diamond is ejected from where it is stable in the mantle. The platelets themselves are mostly interstitial carbon containing variable amounts of nitrogen resulting from the aggregation of single substitutional nitrogen ions into A-centres (doublets) and B-centres (quadruplets plus a carbon vacancy, thereby ejecting a carbon, which becomes interstitial). In simple terms, one can think of the diamond as suffering the ‘bends’ as it surfaces from the depths of the upper mantle. Trevor’s picture of this process has been confirmed in outline, with details added, by high resolution analytical work in other laboratories (Fallon et al. 1995).

The molecular state of nitrogen in diamond in the stages leading up to voidite formation is responsible for the variable yellow coloration of some diamonds. In addition to difficult work at high temperatures and pressures, Trevor enhanced the rates of agglomeration by prior electron irradiation in the Van der Graaf accelerator available at Reading, thereby introducing controlled defects into the diamond. His group were able to reproduce in synthetic stones all the nitrogenous molecules found in natural diamond including platelets, confirming the second-order character of the chemical reaction converting A-centres to B-centres (9). This is of the greatest interest to gemmologists concerned with diamond ‘tampered’ with irradiation, as well as fundamental to understanding the optical properties of diamond. In many ways, this work clinches the pattern of nitrogen exsolution processes.

Another pioneering project was to induce plastic flow in diamond. At high enough temperatures, diamond, like other brittle materials, can flow, a process thought to produce ‘brown’ diamonds. In a series of extremely difficult experiments, both indentation and bending were studied. The former was achieved by pushing the edge of one stone against the edge of another and measuring the plastic displacement (6). The difficulty of deforming small gemstones and instrumenting the stress and strain is not to be underestimated! Figure 3 shows in outline how it was accomplished. Creep was observed with activation energies which by comparison with germanium can be used to estimate a melting temperature of diamond around 3000°C.

Trevor’s work laid a sound foundation for understanding defect processes in diamond. Before his work, many regarded diamond as scarcely a ‘material’ in the modern sense of the word. Nowadays one thinks of it still as the hardest material known, but susceptible to the same defect processes as are all crystals.

Values

In his role as a professor of physics at Reading University, Trevor was very much aware of the need for sound general education, as well as specialist training. We quote from remarks he made at the onset of his professorial career in 1968, firstly on teaching:

‘In the teaching of undergraduates, one is generally concerned with two types . . .

The first type will use his physics in his future career as a specialist in research or in development work. The single subject course caters for these students. I am in favour of broadening the single subject course by introducing other optional topics in the final year in addition to the existing theoretical physics option. I would suggest that several (perhaps six)
optional topics should be introduced; the special Honours student would then take a proportion of them. Each topic could be presented in about ten to fifteen lectures. This would mean a decrease in the number of existing lectures given on the compulsory topics . . . .

The second type of student would not require such detailed knowledge of physics in his future career and a more general course is applicable. For these students I would be in favour of a broader choice of subjects than they have at present. For instance, if a student intends to go into the management or executive side of industry, inter-faculty choices like physics, mathematics and economics should be made available to him.

Secondly, on the role of research:

I would like it to be felt in the Physics Department that a technique in a particular research group should be regarded as a ‘service’ to the other research groups.
I would also like to encourage co-operation between the Physics Department and industry, the research associations and the establishments of the Ministry of Technology. I think of this in terms of research students working in the Department on problems of interest to these organisations, with visits and exchange of information taking place between the organisations and the Department.

One can express only praise for these views, written in 1968.

**PERSONAL LIFE**

On a personal level, as head of the Physics Department, Trevor was a popular figure, touring it regularly, talking to technicians, research students, staff and assistants in the coffee lounge. For twenty years, he acted as Warden of Wantage Hall of Residence, resigning only on his retirement.

He suffered serious kidney problems, first apparent in the early 1960s. In the 1980s he started dialysis and eventually had a transplant. It was while he was recovering from this that the surgeon who carried out the operation congratulated him on his elevation to a Fellowship in the Royal Society. Trevor replied that he would like to congratulate the surgeon for receiving a Gold Medal of the Royal College of Surgeons and expressed his relief that it was for his contribution to the field of kidney transplantation. Throughout this ordeal, Trevor remained extremely positive, as he always was. When one commiserated with him over the consequences of his treatment, he simply shrugged it off, saying: ‘Just think of the alternative!’ Five years later, the surgeon, Peter Morris, then Nuffield Professor of Surgery at Oxford University, was himself made an FRS in 1994, as Trevor was delighted to inform him.

Trevor was a congenial member of the Royal Society Club, a lively participant in conversations at the dinner table, always able to find common ground with his fellow diners. L.M.B. recalls lively discussions about nitrogen in diamond, mostly to do with techniques for observing it, and how it behaves. It might have been any problem in applied physics, but Trevor endowed it with appropriate sparkle, exclaiming with satisfaction as he looked around the table: ‘We are a class act!’ It is a pleasure here to record Trevor’s sympathetic and helpful advice to L.M.B. at a difficult career juncture. Trevor was an enthusiastic gardener in his home at Tutts Clump, which, with his wife Pat, he maintained, specializing in growing the vegetables and the composting. His retirement cake was iced as a garden with a compost heap. Trevor always displayed enthusiastic support for Welsh rugby, which he followed throughout his life. On his tours of the laboratory, he publicly gloated when his side had won, but found jokes to tell against his side when it lost. He once described a competitive kickabout with Dr Henry Dyer, a Director of De Beers and Managing Director of De Beers Industrial Diamond Division, as a test match between South Africa and Wales. He was able to enjoy common ground with everyone!

A charming and revealing story can be retold here in Trevor’s assumed words: ‘I was at this rather smart dinner of important people, seated next to a lady who clearly regarded herself as being in a different class to me. After taking one look at me, she devoted herself to her other neighbour. However, after a while, having exhausted him, she turned to me and said (eyeing me with distaste): ‘and what do you do?’ ’Compost, mainly’.
OVERALL ASSESSMENT

Trevor was a practical scientist. He believed in doing experiments. It was not that he did not appreciate the importance of theoretical physics, indeed he made elegant use of theory to produce far-reaching interpretation of his results. It was just that speculative theoretical work was not for him. In a lengthy series of demanding work at very high temperatures and pressures he teased out the significance of his two outstanding discoveries in natural type 1 diamonds: dislocation loops and platelet precipitates of nitrogen. His work underpins the determination of the provenance of gemstones and the understanding of the optical and plastic properties of all types of diamond, as well as having geophysical significance. His gift of friendship and his humanitarian spirit informed his research, teaching and administration, enabling him to relate to people in universities, institutes and industry.

RECOGNITION AND AWARDS

Trevor acted as a consultant for De Beers Industrial Diamond Division from 1961, and De Beers Diamond Trading Company from 1977. From 1978 he was a member of the Diamond Research Committee, which organized research activities sponsored by De Beers at universities in the UK, and from 1986 ran the diamond CVD (chemical vapour deposition) project of De Beers. These activities ended in 2002. In 1962 he was elected a Fellow of the Institute of Physics, London, in 1988 a Fellow of the Royal Society of London, and in 1995 a Foreign Associate of the Royal Society of South Africa.

ACKNOWLEDGEMENTS

An excellent account of Trevor’s work in the context of carbon science is an article by P. J. F. Harris (2018). We are indebted to Dr Harris for valuable comments and advice. Dr Roger Stewart, who succeeded Trevor as Head of Department, provided much useful material. Readers wanting more details can consult Trevor’s 1976 review article (7) and his remarkable wide-ranging review article ‘Diamond—a letter from the depths’ (10).

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