Feature

Trinitite—the atomic rock

On 16 July 1945, the first atomic bomb was detonated at the Alamogordo Bombing range in New Mexico, USA. Swept up into the nuclear cloud was the surrounding desert sand, which melted to form a green glassy material called 'trinitite'. Contained within the glass are melted bits of the first atomic bomb and the support structures and various radionuclides formed during the detonation. The glass itself is marvelously complex at the tens to hundreds of micrometre scale, and besides glasses of varying composition also contains unmelted quartz grains. Air transport of the melted material led to the formation of spheres and dumbbell shaped glass particles. Similar glasses are formed during all ground level nuclear detonations and contain forensic information that can be used to identify the atomic device.

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At 05:29:45 AM local time on Monday, 16 July 1945, the nuclear age began. In a most graphic example of Einstein's famous equation ($E = mc^2$ or the original form $m = L/V^2$ where L = mass and V = the speed of light) a plutonium bomb, referred to as the 'Gadget', with a yield of 21 kilotons (equivalent to the explosive power of 21 000 tons of TNT) was detonated (Fig. 1) at the Alamogordo Bombing range, 210 miles south of Los Alamos, New Mexico. The genie was out of the bottle and has been our uneasy companion ever since. One of the products of this nuclear explosion was a green glassy material formed by melting of the surrounding desert sand. Robert Oppenheimer had chosen the name 'Trinity' for the nuclear test and the name 'trinitite' was adopted for this green glassy material.

The nuclear explosion

There are two fissionable isotopes (U-235 and Pu-239) that can be used to make atomic (fission) bombs. In both cases the basic principle is the same. A neutron interacts with a nucleus which leads to an increase in atomic mass and an unstable nucleus that splits into several pieces (fission fragments) + neutrons with a concomitant release in energy due to a loss in mass. The ^{235}U fission reaction is:

U-235 + neutron → U-236 → fission fragments + neutrons + energy

The ejected neutrons cause further fission events leading to a chain reaction. For an explosive nuclear reaction billions of fission events need to occur in microseconds. The key is to have a sufficient mass of U-235 or Pu-239 in close proximity for this explosive reaction to occur.

Two types of nuclear weapons were developed near the end of World War II. One, the 'gun type' consisted of an enriched uranium (U-235) bullet that was fired at an enriched uranium spike. The impact of these two pieces of enriched uranium produced the necessary mass density for a thermal nuclear explosion. Physicists were convinced that this type of bomb would work and only one was built and subsequently dropped on Hiroshima, on 6 August 1945.

Fig. 1. The only known colour photograph of the Trinity Test.

The second, the 'implosion type', used Pu-239 and a more 'sophisticated' design. The plutonium core was surrounded by a layer of U-238 (the tamper) and a sphere of explosive charges. The explosive charges drove the U-238 tamper inward, increasing the density of the plutonium core leading to a thermal nuclear explosion. Two of these bombs were built. One was tested at Alamogordo and the second was dropped on Nagasaki on 9 August 1945. Both types of bombs were very inefficient.

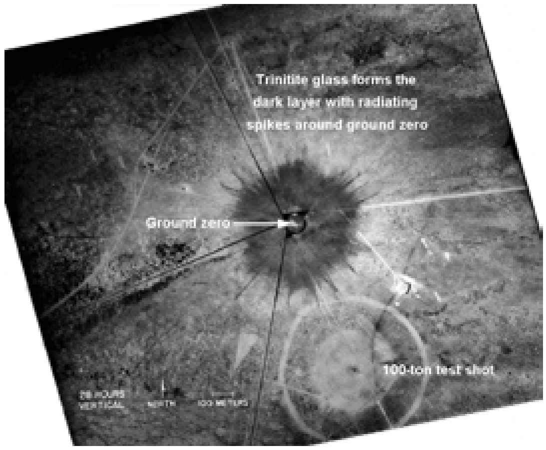

Fig. 2. Air photo of ground zero 28 hours after the Trinity Test. The dark material with radiating spikes is the trinitite glass layer. Most of this material was subsequently buried.

The Trinity test

The test was originally scheduled for 4 AM but was delayed because of rainy conditions. Improving conditions led to the start of the countdown at 5:10 AM and at 5:29:45 AM (there is a slight uncertainty about the exact time) the first atomic bomb was detonated. Observers described the light as being 'brighter than a dozen suns' and the heat 10 000 times hotter than the sun. The last is a bit of an overstatement, as the estimated fireball temperature was 8430 K compared to the 5778 K surface temperature of the sun. The duration of heating was approximately 3.1 seconds and the resulting crater had a depth of approximately four feet (1.2 m) (Fig. 2). Hans Bethe (a Nobel laureate physicist and participant in the Manhattan Project), in describing the fireball wrote 'The white ball grew and after a few seconds became clouded with dust whipped up by the explosion from the ground and rose and left behind a black trail of dust particles.' Within minutes the mushroom shaped cloud had risen to 38 000 feet (11.6 km) and ultimately reached a height of 50 000 to 70 000 feet (15.2 to 21.3 km). All the structures in the immediate area were essentially destroyed and droplets of molten metal were dispersed to the north of ground zero. After the Trinity Test, J. Robert Oppenheimer, the scientific director of the Manhattan Project, is alleged to have said 'Now I am become Death, the Destroyer of Worlds', a verse from the Hindu scripture. What seems obvious in retrospect is that the scientists of the Manhattan Project were both awed and appalled by what they had wrought.

Trinitite

The Trinity site is covered with arkosic sand (Fig. 3) and this material was melted during the detonation forming a layer of green glass (trinitite). The sand is composed of quartz, microcline, albite, muscovite, actinolite, and calcite. Only quartz is found in the glasses. All the other minerals have been melted. The extent of the original glass layer is shown in Fig. 2. Shortly after the blast most of this glassy material was removed. A variety of glasses were formed (Fig. 4): (1) pancake trinitite consists of a melted glassy surface (with a light coating of sand) on top (L), and solidified globules/beads on the bottom (R); (2) red trinitite; (3) scoriaceous trinitite fragments; and (4) beads and dumbbell-shaped trinitite.

Radioactivity Sixty-five years after the detonation, the trinitite glasses are still slightly radioactive. The radioactive nuclides have three different origins. (1) Plutonium and uranium from the bomb. (2) Fission fragments produced during the fission process. Today the detectable fission fragments are Sr-90 and Cs-137. (3) Activation products produced by the interaction between the neutrons from the explosion and various nuclides. This last process is the basis of a sensitive

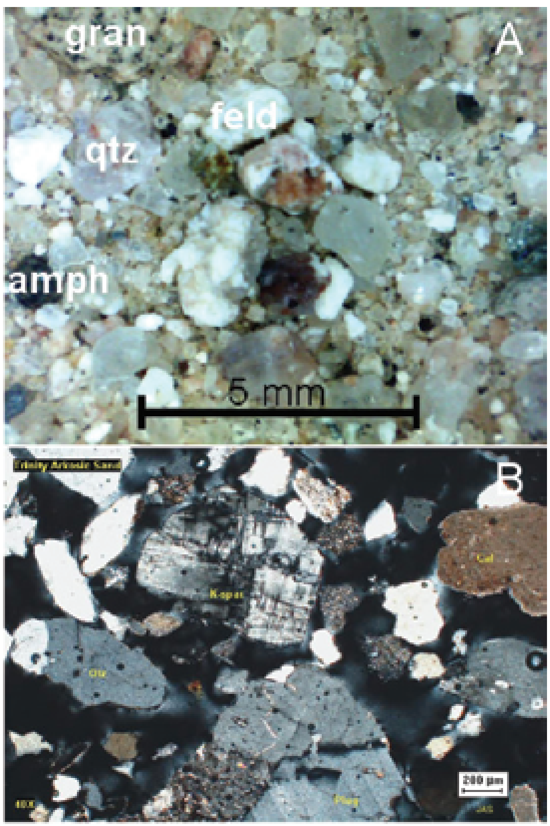

Fig. 3. Macroscopic view (top) and microscopic view (bottom) of the arkosic sand that was melted by the blast. Top view: gran = granite fragment, qtz = quartz, feld = feldspar, and amph = amphibole. Bottom view: Qtz = quartz, K-feld = K-feldspar, Plag = plagioclase, and Cal = calcite.

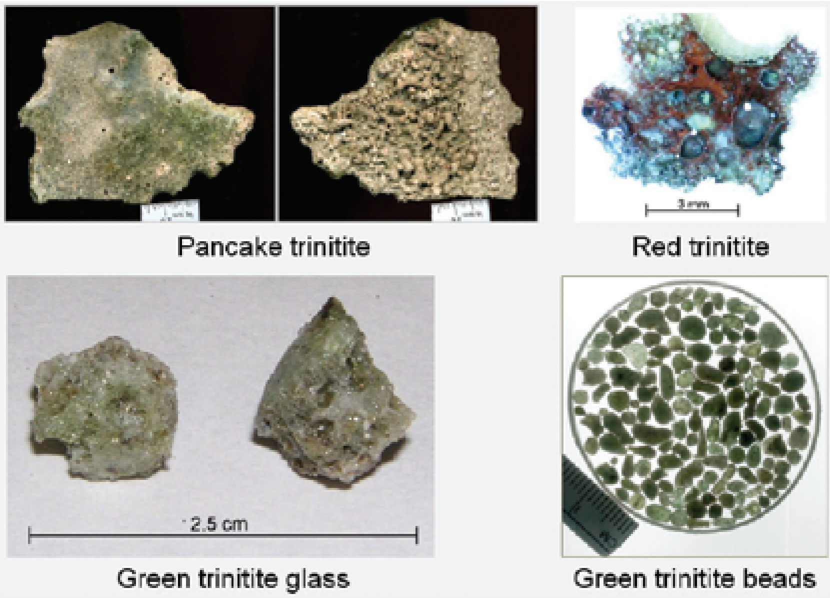

Fig. 4. Different types of trinitite glass.

method used to determine elemental abundances in a variety of materials. Neutrons, usually provided by a research reactor, interact with existing nuclides to produce radioactive isotopes of a particular element. For example, a neutron interacts with a Fe-58 nucleus to produce Fe-59, a radioactive isotope of iron that decays by a beta-emission and emits gamma rays of characteristic energies. Over 40 elements can be determined using this analytical technique. Among the activation products detectable today in trinitite are the longer half-life isotopes Co-60, Ba-133, Eu-152 and Eu-154.

Red trinitite The red trinitite (Fig. 5) is found to the north of ground zero. The red colour is due to the presence of copper in the glass. Close examination with the optical microscrope (Fig. 5A) and scanning electron microscope (SEM) (Fig. 5B–D) reveals that this glass contains a number of metallic chondrules. Using back-scattered electrons (Fig. 5B) it is possible to see the variation in the chemistry of the glass. The brightness of the image is related to the atomic number of the elements causing the scattering of the electrons. The brighter areas represent regions of higher atomic number elements. The metallic chondrules, having the highest average atomic number, stand out as bright spots in the images. A close-up of the metallic chondrule (Fig. 5C) shows that the chondrule consists of several different phases. The SEM, equipped with an X-ray detector, can be used to determine the chemistry of the material. Element maps (Fig. 5D) for lead (Pb), iron (Fe), and copper (Cu) show the distribution of these elements in the metallic chondrule. Note that the iron occurs as a globule within the metallic chondrule and the nature of the interface suggests that iron and copper occurred as two immiscible liquids. Also note that lead is only found in the copper part of the metallic chondrule. These metallic chondrules are melted bits of the first atomic bomb and the surrounding support structures—history encased in glass.

Green trinitite fragments The green trinitite fragments are glassy and vesicular (Fig. 6) and are reminiscent of scoria (but green rather than red or black). This material was widespread within the immediate vicinity of ground zero and was a significant component of the top part of the trinitite layer. When examined with the SEM the glass is found to be heterogeneous on the tens of micrometres scale (Fig. 7). Partly resorbed quartz grains are abundant in the sample. Note the rounded outline of the quartz grains and places where the glass has embayed the quartz grains. The quartz grains had begun to melt but the process was not carried to completion. However, as has been verified by X-ray diffraction studies, there are no other crystalline phases (minerals). Hence all the other minerals that were present in the sand have been melted. Also of note is that the polymorph of quartz found in these samples is alpha-quartz, the low pressure-temperature form of quartz, which is the common form of quartz found in the rocks of the

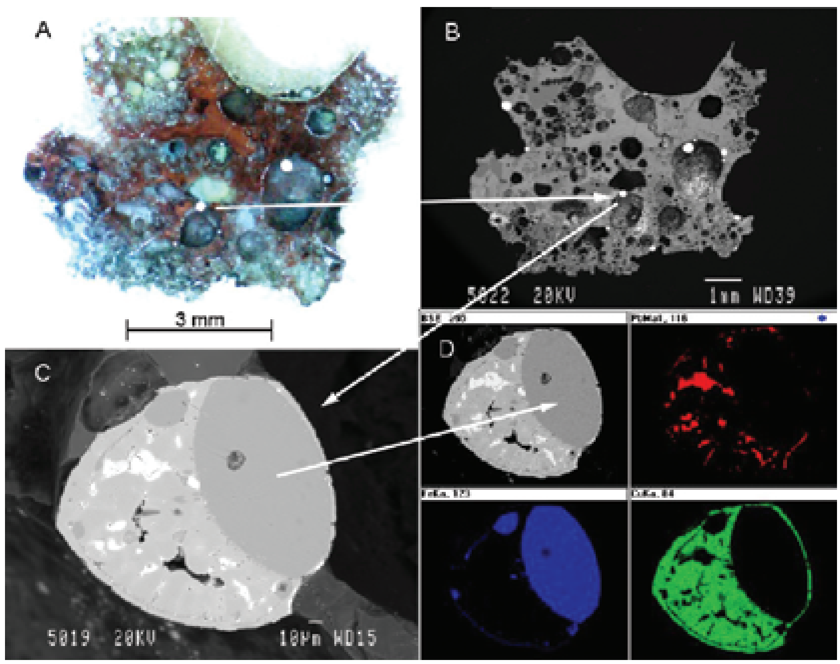

Fig. 5. Red trinitite. Upper left, macroscopic view of glass fragment. Note the bright bits which are metallic chondrules. Upper right, the same fragment imaged by a scanning electron microscope (SEM) using back-scattered electrons (BSE). Brightness corresponds to the average atomic number, the brighter the image the higher the atomic number. Lower left, close-up SEM BSE image of one of the chondrules. Note the three distinct phases (based on brightness) that can be seen in this image. Lower right, element maps showing the distribution of lead, iron and copper. The grey areas in the BSE image correspond to blobs of melted iron. The lighter grey is copper (copper wire from the trinity site, which also gives the glass its red colour) and the brightest areas are lead. These are bits and pieces of the first atomic bomb and the support structure.

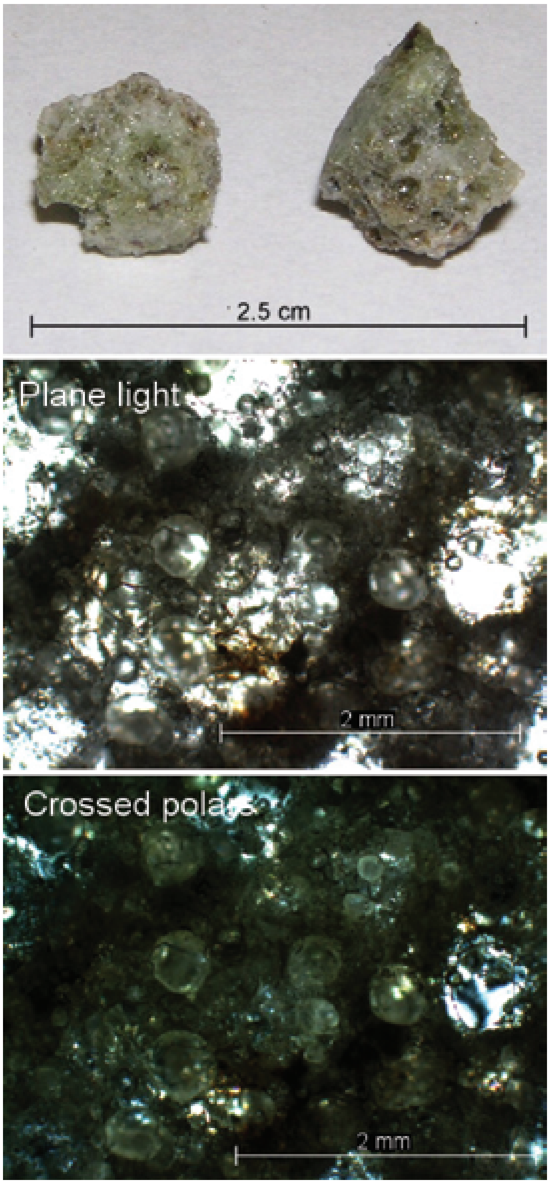

Fig. 6 (left). Trinitite glass fragments, typical of the type of material that is found in the immediate vicinity of ground zero. The lower two panels are thin section images of one of these fragments.

Earth's crust. The overpressure and temperature of the atomic detonation was not sufficient to produce a higher pressure-temperature polymorph of quartz. Chemical analyses for the glass (points labelled on Fig. 7) are given in Table 1 and show the variability in the chemical composition of the glasses. Note that the areas of glass that are brightest in the electron back-scatter SEM image are those which have the highest iron and calcium content (GL9 and GL11) and the darkest glass (GL10) has very little iron or calcium.

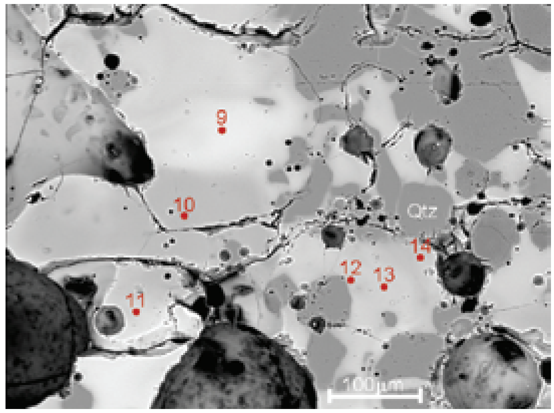

Fig. 7 (right). SEM BSE image of a glass fragment. The chemical composition of the individual glasses is found in Table 1.

Trinitite beads and dumbbells It was originally thought that much of the trinitite layer was formed in place by surface melting. However, further work now indicates that much of the material was entrained in the rising cloud of hot gases (see earlier description by Bethe) and subsequently rained down onto the surface as molten droplets. As this material was transported by the gas cloud, the molten droplets were formed into bead and dumbbell shapes (Fig. 8),

Fig. 8. Trinitite beads and dumbbells.

Table 1. Chemical data for trinitite fragment

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	CaO	MgO	Na_2O	K_2O	Total
GL9	56.75	1.89	13.47	4.29	0.10	12.53	2.28	1.22	4.54	97.07
GL10	63.46	0.27	18.82	n.d.	n.d.	0.96	0.21	2.08	11.70	97.50
GL11	60.21	0.51	15.40	1.86	n.d.	10.71	1.16	1.49	6.50	97.84
GL12	62.99	0.36	13.86	2.52	0.11	8.49	1.68	1.46	6.11	97.58
GL13	62.26	0.45	14.65	3.00	0.07	8.38	1.81	1.63	5.63	97.88
GL14	62.04	0.21	17.93	1.55	n.d.	6.89	1.05	1.97	6.16	97.80

morphologically similar to tektites which form when a meteorite impact melts surface material and splatters the melted material into the air. The molten droplets were transported downwind and deposited over a fairly wide area. The resulting glass particles are often concentrated around the tops of anthills, moved there by ants as they excavate their tunnels, and these glassy particles are sometimes referred to as 'anthill trinitite' (Fig. 9).

Fig. 9. Trinitite beads and fragments distributed around the top of an anthill.

At the microscopic scale the trinitite glasses show remarkable heterogeneity. A 2 mm glass sphere (Fig. 10) contains partly melted quartz grains (grey areas towards top right). A close up view of the top right part of the sphere shows the diffuse margins of these partly melted grains and 50 to 100 micrometre quartz grains that are embedded in the edge of the glass sphere. This sphere represents a droplet of melted sand that was transported through the air for some distance from the blast site. The small quartz grains were embedded in this droplet during transportation. The chemical variations even on this small a scale are significant (Table 2). TB1 is from the grey area of melted quartz and is almost totally SiO_2. TB4 is chemically similar to K-feldspar and the grey area surrounding the TB4 analysis is probably a melted K-feldspar grain. TB2, TB3, TB5 and TB6 (which are analyses of brighter parts of the glass) contain relatively high CaO. These concentrations exceed what can be contributed by the silicate minerals in the sand, and at least part of this calcium was derived from melted calcium carbonate grains.

A dumbbell shaped glass (Fig. 11) approximately 5 mm long contains a cluster of partly melted quartz grains. A close-up view of one edge of the dumbbell shows the irregular contact between the quartz grains and the surrounding glass indicating that the quartz was partially molten. If you look closely at this image you can see a diffuse grey region along the edge of the quartz grains, which is silica-rich. This represents the diffusion of the quartz melt into the surrounding melt. The bright band along the upper right of the dumbbell has the chemistry of a magnesium-rich amphibole.

Table 2. Chemical data for trinitite bead

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	CaO	MgO	Na_2O	K_2O	Total
TB1	96.80	0.10	0.35	0.17	n.d.	1.40	0.10	0.10	0.53	99.59
TB2	64.31	0.31	14.57	2.18	0.13	12.70	1.10	0.95	1.44	97.68
TB3	51.53	0.26	11.49	3.20	0.11	27.33	1.78	0.73	2.66	99.09
TB4	63.56	0.08	18.46	0.13	n.d.	0.52	0.29	1.83	13.47	98.33
TB5	62.60	0.37	15.19	2.39	n.d.	12.81	1.27	0.74	1.43	96.80
TB6	64.02	0.27	14.67	2.37	0.09	12.91	1.10	0.74	1.44	97.62

Many of the glass beads show a 'swirly' texture (Fig. 12), reminiscent of marble cake. This texture illustrates the intimate mixing of very viscous melts of different compositions at the 10 to 100 micrometre scale. The element maps (Fig. 12) show the distribution of different elements in the glass. The brightness of the colour indicates the relative amount of the element, brighter areas represent higher concentrations. Note the very fine layering shown in the Al map. The brighter areas in the Si map most likely represent blobs of melted quartz. K is generally abundant indicating that melted K-feldspar (microcline) is a major component of this glass. The region of high Ca content corresponds to the bright area on the back-scatter image and probably represents a melted carbonate grain.

The complexity of the glasses at the 10s to 100s of micrometre scale is a delightful challenge. What we are looking at are micromelts of individual mineral components. Given the high viscosity of

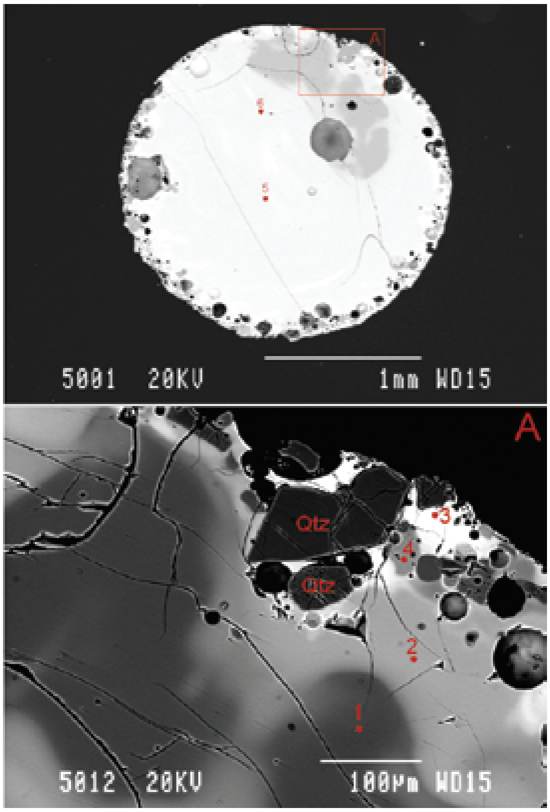

Fig. 10. BSE images of a trinitite bead. Note the dark areas of the images, which are partially melted quartz grains. Also note the small quartz grains embedded along the outer rim of the bead. These grains were picked up during atmospheric transport of the melted material. Chemical compositions for the various glasses are found in Table 2.

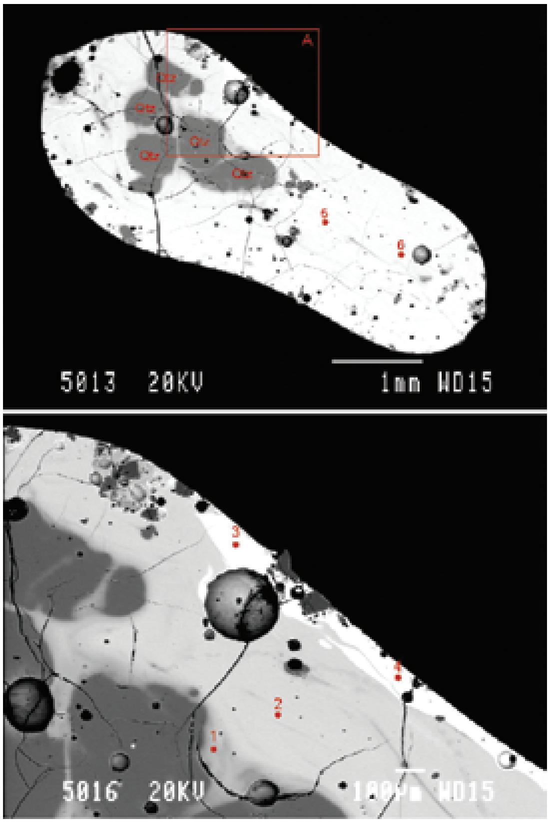

Fig. 11. BSE image of dumbbell shaped trinitite. The close-up view illustrates the diffuse margins around the quartz grains where the melted quartz is mixing with the surrounding melt. The brightest part of the image, along the edge of the grain, probably represents melted Mg-rich amphibole.

these melts and the short duration of the heating, the glasses were not homogenized but rather show a very heterogeneous texture. Chemical analyses show us that the glass components consist of individual minerals that melted and the melts partly mingled. Because of its high melting point (~1670 °C) quartz was the only crystalline phase that did not totally melt in the fireball.

Nuclear forensics

Contained within the trinity glasses is a record of the first atomic bomb. The radioactive elements distributed throughout the glasses reflect the nature of the atomic blast. Actual bits of the bomb and the surrounding material are found in the metallic chondrules from the red trinitite. In any nuclear test similar glasses will be formed. Hence we can use the chemistry and radioactivity of these glasses to infer the type of device that was detonated and to estimate its explosive power—nuclear forensics.

Suggestions for further reading

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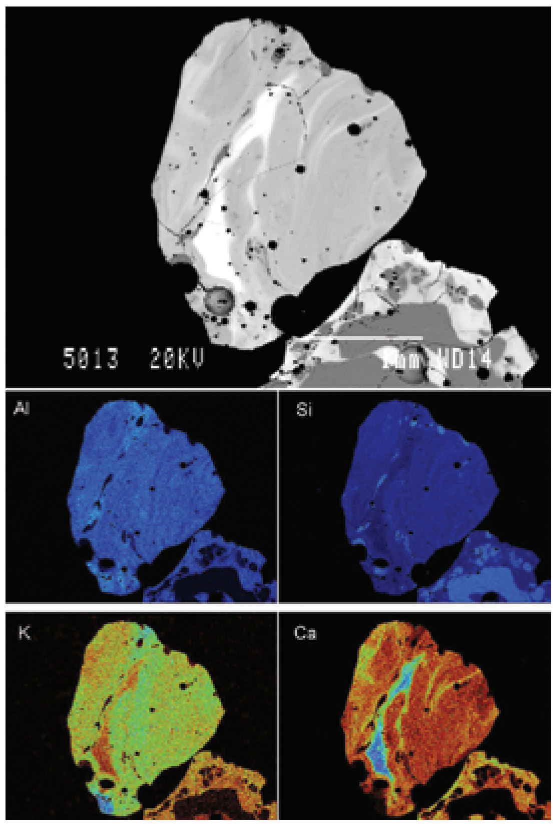

Fig. 12. BSE image and element maps showing intimate layering at the 10 to 100 micrometre scale. The brighter areas are Ca-rich. Note the fine banding shown by the Al map and spot silica concentrations (probably remnant quartz grains) shown on the Si map. The relatively high potassium concentrations indicated by the K map suggest that K-feldspar was an important component in the formation of this bead.