Cataclysmic calderas catalogued

The centenary of the volcanic eruption of the island of Krakatoa has been an occasion for listing other such phenomena. There are (and have been) a lot of them.

ONLY volcanologists would think it proper, not macabre, to celebrate the centenary of a natural disaster, the eruption on Krakatoa in 1883, with a symposium. The event did, after all, put their subject on the map — but removed Krakatoa itself. The papers gathered for the fall meeting of the American Geophysical Union (AGU) last year, have now been published in an extra-thick issue of *J. Geophys. Res. B* (30 September, **89**, 8219-8842; 1984). The volume is, as it turns out, a kind of Baedeker of the known roughly circular pits called calderas, relics of "the most catastrophic geologic (*sic*) events that have occurred on the Earth's surface...".

Part of the trouble with extinct calderas is that they are often inconspicuous. Recognizing a nearly circular depression of 100 metres or so which may be 10 km or more across is easier from satellites than from the ground, especially when once-sharp edges have been eroded away. This is how R.L. Wunderman and W.I. Rose are able to describe for the first time (**89**, 8525) a still-active caldera just over 10 km south of Guatemala City.

Other calderas are more conspicuous, however. Carter Lake in Oregon is one, while California, Nevada, Utah and New Mexico are peppered with them, as is the East African Rift Valley. One of the neatest is Deception Island, a ring of barren rock in the South Atlantic. Olympus Mons on Mars (60 km across), splendidly photographed by the Viking orbiting spacecraft, may by now be one of the most familiar.

So this collection of articles is in part a kind of guidebook to known major calderas. The western United States are well worked over, but L.A. Morgan *et al.* (**89**, 8665) are able to make a case for three calderas in Idaho, which may have been the source of 1,500 km^3 of ash (now tuff) about 6.5 million years ago.

Further south, just across the Mexican border with California, D.L. Nielson and J.B. Hulen (**89**, 8695) have been able to use data gathered during geothermal drilling into the familiar now-domed Pliocene Valles caldera to construct a three-dimensional geological section through the structure. The 1,000 metres or more of tuff is interspersed with sandstone of irregular thickness — there was once a lake — and the section shows how the tuff has slumped along nearly vertical planes from time to time. But although the Valles caldera has now been converted into a domed structure by some 900 metres of recent uplift, even the deepest borehole (3,242 metres) has failed to intersect the rock responsible.

The richest caldera country in the world is the remarkable 65,000 km^2 of New Mexico, west of the Rio Grande, that seems to have suffered 20 million years of volcanism beginning in the late Eocene, 40 million years ago. W. E. Elston (**89**, 8733) lists 28 calderas so far recognized in the region, many of which have been put conveniently on display by erosion and faulting during the past 20 million years.

The sheer scale of this volcanism has evidently been a serious impediment to its interpretation. Elston writes wistfully of the early puzzle of the Black Range, 50 km west of the township of Truth or Consequences, a dome-shaped structure 55 km long, 2 km wide and 2 km high, now recognized as a 34-million-year caldera, whose central depression has been turned inside-out by the resurgence of magma. Can anyone now doubt that the Colorado Plateau, through which the Grand Canyon cuts, is a magmatic structure of the same kind?

The AGU symposium seems to have been generally agreed on the mechanism by which calderas are formed. A subterranean magma chamber contaminated with volatile components, water at the very least, breaks through the overburden, explosively to begin with. The volume of material ejected in one or more eruptions may be huge, but the characteristic of a caldera is the eventual collapse of the surface into the magma chamber beneath, at which stage there may be further eruptions through fissures or from the ring fracture around the subsiding plate.

Elston's catalogue of New Mexico includes all possible outcomes — calderas filled to the brim and beyond with the ash from post-collapse eruptions, others where resurgent doming has preceded roof collapse, and then vice versa. Individual calderas have been responsible for 2,000 km^3 of volcanic effluent. Halfway through the mid-Eocene volcanic episode, at least some magma chambers appear to have reached to within 2 or 3 km of the surface.

A few simple lessons stand out from the handful of attempts to account for these happenings. Simulations of the initial eruption of an over-pressurized magma chamber by calculations of what happens in a shock-tube (where the diaphragm between regions of high and low pressure gas is broken; K.H. Wohletz *et al.*, **89**, 8269) show that it is reasonable that the first ash-laden plume should reach to the stratosphere and that horizontal winds (laden with ash) may travel at 200 m s^{-1} or so at distances of 10 km or more from the vent. The mechanism by which caldera floors collapse is less clear, especially because many ring-shaped sunken floors seem to have fallen through downward-tapering apertures. Resurgence may be a precondition, and may itself arise from non-equilibrium processes in the magma chamber, compensation of over-expulsion of volcanic material or slow dissolution of volatiles from magma rendered metastable by an eruption (B.D. Marsh, **89**, 8245).

What stands out a mile, however, is that nobody has a clear idea of how the magma chambers have appeared within a few kilometres of the Earth's surface. It would be comforting if it turns out that magma chambers are not like subterranean caverns filled with molten mantle material from below but places within the crust in which ordinary material behaves so differently from its immediate surroundings that it seems qualitatively a liquid, not a solid.

The Long Valley caldera (with Mammoth Lake within its rim) due east of San Francisco may have the answer. The floor collapsed 720,000 years ago, but is now rising, at some places by 5 cm a year. Two underground magma chambers within 6 km of the surface have been mapped seismically (C.O. Sanders, **89**, 8287). Measurements on the spot do not indicate whether the outcome will be stasis or another eruption — but 5 cm a year is a lot.

In all this, the ubiquity of calderas is the big surprise. But most known calderas are young, suggesting that most of them do not leave permanent traces. Krakatoa, after all, has all but vanished.

So, too, has Minoan civilization. The spell-binding paper in this symposium is the reconstruction of the history of the caldera on Thera (Santorini) in the Aegean, whose eruption about 3,400 years ago put paid for a time to nearby Crete (G. Heiken and F. McCoy **89**, 8441). The eruption appears to have come from a volcano on dry land, to the east of a submarine caldera active during the previous million years. There were four distinct phases, perhaps separated by several years, but the first eruption that put Crete in trouble was preceded by minor ash-fall that would have given the people of Thera a chance to get away, which explains why no people have been found among the ashes. And volcanic activity continues, at the join of two submarine calderas.

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