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EARTHQUAKES

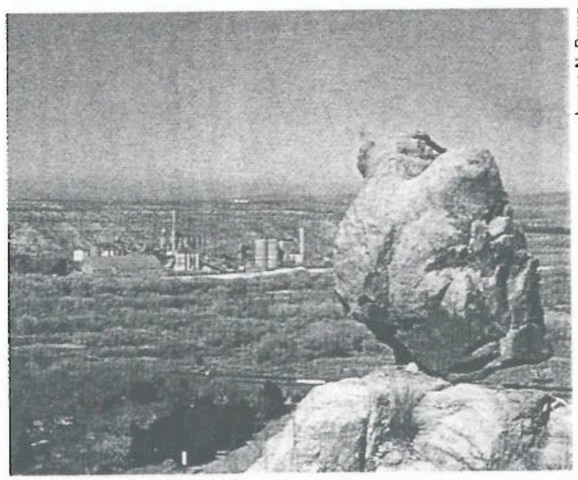
Being struck by a balance

Ross S. Stein

HIKING down windswept Solitario Canyon, ground zero of the proposed US nuclear waste repository in Nevada, James N. Brune was struck by the beauty of a huge, precariously balanced boulder. "But why hasn't an earthquake knocked that thing off?" he thought. Or could the rock have been poised to fall for only a short time? Brune got his answer a few days later at the annual meeting of the Geological Society of America, where evidence was presented that the weathered pavement of Yucca Mountain had survived for 30,000 years, long enough to have experienced whatever shaking the local earthquakes had to offer[1].

Brune soon found that such 'precarious rocks' could be dislodged by ground shaking with just 10 to 20 per cent of the peak motions recorded during the recent Landers, Northridge, or Kobe earthquakes. With these insights, Brune transformed a stone of beauty into a stone of witness, extending one aspect of the record of earthquake shaking in the United States by a hundredfold over our brief history, and in the process challenging theoretical ground-motion predictions in closely watched southern California[2].

Precarious rocks form underground when joints — or sets of cracks — in granite or welded volcanic rocks (or 'tuffs') slowly widen, isolating the interior core-stones. Erosion eventually washes away all but the core-stones, and occasionally one stone remains piggybacked on another. Stones smaller than about 0.3 m get knocked down by the wind, leaving the large ones to await nearby earthquakes or errant teenagers for the *coup de grâce*. Of the 18 fields of precarious boulders in California and Nevada that Brune has found by cruising the highways with binoculars in hand, none is in a site that has sustained ground accelerations of more than about $0.2g$ from historical earthquakes or underground nuclear blasts.



James N. Brune

Does the boulder in the foreground ensure the safety of the buildings in the background? Just 40 km from the southern San Andreas fault, near Victorville, California, a field of precariously balanced rocks testifies to 10,000 years of seismic sleep.

Brune and his students developed techniques to estimate the acceleration needed to topple precarious rocks by subjecting styrofoam rock models to recorded earthquake accelerations, and by dynamic two-dimensional computer modelling[3]. They also felled rocks in the field by static loading (a geologist's version of killing animals in the service of human medicine?). They found that precarious rocks fall when horizontal acceleration exceeds $0.1–0.2g$, in accord with studies of earthquake-induced rockfalls[4]. Semi-precarious boulder fields, with less spectacularly poised boulders, can sustain motions of $0.3–0.4g$ (ref. 3). They also found a dependence of rocking frequency on the square root of height, with dominant frequencies in the range 1–5 Hz. This is the range for one- to twelve-storey buildings, so serendipitously the boulders stand in quite well for human edifices threatened by shocks.

With help from other geologists, Brune found that most rocks have held their balance for at least 10,000 years, ensuring that they are unlikely to have escaped the largest events that occur at a site. The trick to divining the antiquity of the rocks is to measure not the time a boulder has been on the ground, but the time it has been poised to fall. For that, one must work at the fulcrum. Most boulders are coated by rock 'varnish' layers of manganese and iron oxides. Existing radiocarbon dating and new techniques that associate the varnish layers with climatic events yield a range of 10,500–22,000 years for the periods over which different rocks have been perched.

Because granite and volcanic tuffs only cover a minority of the surface in the western United States, and boulders disintegrate rapidly in all but arid climates, it is difficult to make a systematic survey of precarious rock sites. Brune and his entourage have yet to canvass park rangers, drive country backroads, or take to the air in ultralight aircraft to search for new sites. But even with these limitations, the impact of the rocks promises to be heavy.

If the 1995 working group report on earthquake probabilities[5] is correct, all boulder fields in southern California should have been flattened during the past 3,300 years of shaking. Instead, most fields have survived at least three times as long. The report, a seminal document for the incorporation of palaeoseismic, seismic and geodetic data, postulates random, large, rare earthquakes throughout the region to reconcile earthquake occurrence with plate-tectonic motion, which requires a rate of large earthquakes (of magnitude 6 or above) twice that observed during our scant 150-year record. Between the major faults, the accelerations predicted by this model are nearly twice as high as the limits implied by precarious rocks. If instead the 'wildcard' earthquakes are confined to the major faults, quiet zones emerge in between to accommodate Brune's rock sentinels.

Because our historical record is far too brief to reflect the richness of earthquake occurrence, a 10-millennium record of shaking, no matter how faintly etched on the landscape, is invaluable. "Why didn't I think of that?" is the question that comes to one's lips. Brune not only thought of it, but pursued its many consequences until he could use the rocks to test, if not topple, our best models. □

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