CASCADIA SUBDUCTION ZONE

# The calm before the quake?

*Thomas H. Heaton*

WITH the exception of Alaska, the Cascadia subduction zone, extending 1,200 km from northern California to Vancouver Island, is the largest tectonically active fault system in North America. Although it is widely accepted that the North American continental plate is converging at a rate of 2.5–4.5 cm $yr^{-1}$, modern seismic activity has been minimal along the Cascadia subduction zone. Are the Pacific oceanic plates sliding effortlessly below the continental margin? Or are the plates welded together, gradually accumulating elastic strain, to be released in another cataclysmic earthquake sometime in the coming centuries? There is geological evidence, much debated at a recent meeting*, that there have been six massive earthquakes (energy magnitude $M_w$ = 8.5–9.5; see box overleaf) in this region in the past 3,600 years, most recently sometime in 1680–90.

Several years ago, S. Hartzell and I argued that the Cascadia subduction zone might be locked, with slip occurring only during infrequent large earthquakes (*Science* **236**, 162–168; 1987). We concluded that the Cascadia subduction zone shares many characteristics with the Nankai Trough off southwestern Japan (convergence rate of 4 cm $yr^{-1}$), the site of $M_w$ = 8.1 earthquakes in 1944 and 1946, and the southern Chilean subduction zone (convergence rate 8 cm $yr^{-1}$), the source of the catastrophic $M_w$ = 9.5 earthquake in 1960.

But at the meeting, D. Byrne and L. Sykes (both at Lamont–Doherty Geological Observatory) argued that the accretionary wedge of the Cascadia subduction zone is too weak to support such large earthquakes. They suggested, rather, that the Cascadia subduction zone is similar to the Makran subduction zone of southern Iran which may be subducting by steady-state creep (no large earthquakes). Although an $M_w$ = 8.1 earthquake occurred in the Makran region in 1945, Byrne and Sykes presented seismological evidence that this was a normal faulting earthquake that did not occur along the main plate boundary. However, L. Kulm (Oregon State University) pointed out that there is significant variation in the apparent properties of the continental margin along the Cascadia subduction zone, and that Eocene crystalline rocks are common in the continental margin.

Nearly ten years ago J. Savage and others (*J. geophys. Res.* **86**, 4929–4940; 1981) reported evidence that strain is accumulating parallel to the direction of plate convergence. Additional studies since have corroborated this conclusion, with the largest strain rates (about 0.2 microstrain $yr^{-1}$) observed in coastal regions, including the area just north of the Mendocino triple junction (M. Lisowski and W. Prescott; US Geological Survey, Menlo Park). The relative rates of vertical deformation along the Oregon coast, over the past 50 years, as indicated by levelling data (M. Vincent and R. Weldon, University of Oregon; M. Richards, University of California, Berkeley), seems to be much greater than those inferred from the dating of uplifted Quaternary marine terraces. The observed historic strain and uplift data were independently interpreted by Vincent and others, Lisowski and others, and H. Melosh (University of Arizona) as evidence that these strains, that accumulate over centuries, are released in great subduction earthquakes.

The most compelling evidence that great subduction earthquakes have occurred comes from stratigraphic studies of Holocene coastal lowlands. Since the initial report by B. Atwater (US Geological Survey, Seattle; *Science* **236**, 942–944; 1987) that coastal lowlands in Washington have repeatedly subsided in the past several thousand years, many others have found buried, abruptly subsided lowlands at coastal sites ranging from Vancouver Island to Humboldt Bay, California. Atwater reported that many stratigraphic features seen along the Cascadia subduction zone are similar to those observed in a recent study (unpublished) of coastal deposits resulting from coastal subsidence during the 1960 $M_w$ = 9.5 Chilean earthquake. J. Bourgeois (University of Washington) reported that sand sheets deposited on lowlands of southern Chile by the tsunami wave from the 1960 earthquake resemble sand sheets that cover buried wetlands of coastal Washington and Oregon. The analysis by M. Reinhart (University of Washington) of the thickness distribution of these sand deposits from the last event in Washington is compatible with deposition associated with a 10-m tsunami, but not with a large storm surge.

Dating of the coastal subsidence is important not only for determining recurrence intervals for the inferred earthquakes, but also for learning the maximum coastal extent of individual events, as a guide to rupture length and earthquake magnitude. W. Grant (US Geological Survey, Seattle) cited 200 radiocarbon ages for buried lowlands in Washington, Oregon and northern California as evidence of episodic, sudden deformation of regional extent. Known episodes in the past 2,000 years occurred about 1,700 years ago (two episodes within several hundred years of one another, known for southern Washington and northern Oregon), 1,100 years ago (known for northern Oregon and northernmost Washington) and 300 years ago (known for northern California, Oregon and southern Washington).

The radiocarbon ages have too much error to show whether these episodes each consisted of a single great earthquake, or whether each episode comprises several lesser earthquakes. D. Yamaguchi (University of Colorado) obtained better precision by using ring-width patterns to date trees that died from subsiding into the intertidal zone during the most recent episode (about 300 years ago; see figure). The trees come from six sites scattered along a 90-km stretch of the southern Washington coast. Although most of the trees have lost their outermost rings to weathering, dates for the outermost preserved rings cluster in the 1670s and 1680s. The most recent great earthquake on the Washington part of the Cascadia subduction zone therefore seems to have occurred about 1690 — more than half a century after the founding of the Massachusetts colony.

Extraordinary geological events, perhaps coeval with great Cascadia earthquakes, have also occurred inland. R. Buckman (US Geological Survey) described a marine terrace 10 km west of Seattle that underwent 7 m of rapid uplift sometime in the past 1,700 years. A map by H. Gower and others (*US Geol. Surv. Misc. Invest. Map I–1613*, 1985) shows that the probable structure on which this uplift occurred extends through the centre of Seattle. P. Williams (Lawrence Berke-



Brian F. Atwater

Ghost forest of western red cedar (*Thuja plicata* Donn.) protruding through a tidal marsh in coastal Washington state. The man to the left at the waterfront stands on roots that mark the present level of ghost-forest floor. According to recent geological and dendrochronological studies, the forest subsided into the intertidal zone during a great earthquake on the Cascadia subduction zone in about 1690.

*American Geophysical Union fall meeting, San Francisco, 4–8 December 1989.

ley Laboratory) reported that three huge landslides fell into Lake Washington, just east of Seattle, about 1,100 years ago, and that two others occurred there about 1,700 years ago. He suggested that the slides were triggered by great earthquakes on the Cascadia subduction zone.

The suggestion that great Cascadia subduction earthquakes occur has evolved in the past decade from hypothetical conjecture to a widely discussed model that seems to provide the best explanation for many observations. Yet, with the subduction zone quiet since Europeans arrived in northwestern America about 200 years ago, few of the region's 10 million people have become prepared for the minutes of strong ground shaking and the devastating tsunami that a great Cascadia earthquake would produce. Although basic scientific questions remain about the earthquake potential of the Cascadia subduction zone, many researchers feel that the evidence is sufficient to warrant updating building codes (particularly in Oregon) and tsunami evacuation plans to reflect the potential for great subduction earthquakes. □

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## Earthquake magnitude scales

**Charles Richter's original magnitude scale (usually called the local magnitude $M_L$), developed in the 1930s, was designed to measure the size of waves recorded in southern California for local earthquakes. To generalize the restrictive range of seismograms and earthquakes that could be quantified with the local magnitude scale, many other magnitude scales have been developed in the past 50 years. Surface-wave magnitude ($M_s$) measures the size of long-period surface waves recorded at large distances from earthquakes and it is one of the most popular magnitude scales in use today. It became clear in the 1970s that existing magnitude scales did not adequately represent the total energy of very large earthquakes. $M_w$ is an energy magnitude scale obtained from estimates of the total kinetic energy radiated by an earthquake (H. Kanamori *J. geophys. Res.* 82, 2981 – 2987; 1977). It is defined to give values comparable to Richter's original magnitude scale for earthquakes as large as magnitude 6. For each unit increase in $M_w$, the total kinetic energy increases by a factor of 31.6. Therefore an earthquake of $M_w$=9.0 radiates about 1,000 times as much kinetic energy as the recent 17 October 1989 $M_w$=7.0 Loma Prieta earthquake in California. Unfortunately, the many different existing magnitude scales are generally all included together in the maddeningly vague term 'Richter Scale', which is popular with the press, but meaningless to a seismologist.** T.H.H.

# Colour consciousness in archaeology

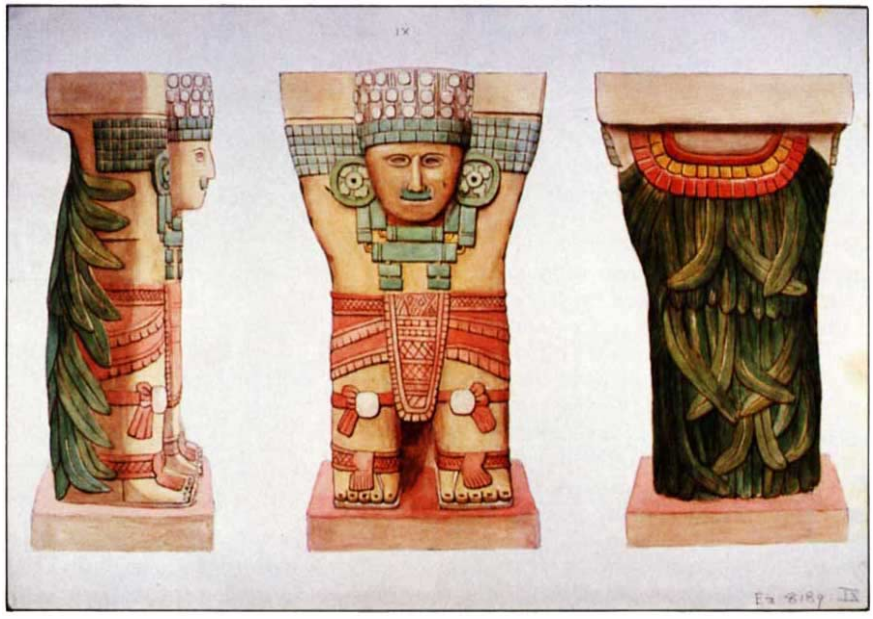
**Adela Catherine Breton (1849–1923), the painter of the picture reproduced below, has a special place in the history of Maya archaeology. In 13 visits to Mexico and Central America around the turn of the century, she photographed and painted the major prehispanic ruins and, at her death, bequeathed her collections to Bristol City Museum. The Museum has, for the first time, put the best of this material on display*.**

**What excites professional mayanists is the series of watercolour copies Breton made of wall paintings and architectural details, many of which are now damaged beyond repair. Her diaries describe how she searched out traces of pigment in cracks and crannies in order to produce original-colour renderings of sculptured monuments. The example illustrated here (a caryatid from the Upper Temple of the Jaguars at Chichén Itzá) may disconcert tourists used to the beauty of plain stone, but this colour is what the Maya artist meant us to see. Without it, one would not realize that the cape was made of green quetzal feathers and the necklace of jade.**

**To a Maya observer, details of costume and insignia gave precise information about a personage's nature (human or divine) and about his rank and status in the world. A decorated Maya facade was designed to be 'read' for its message as well as appreciated for its beauty, and in this system of visual communication colour-coding played a vital part. Red, for instance, was used for human figures; blue was reserved for gods and for things sacred or precious, pertaining to worship and to the divine rights of kings.**

**In her lifetime Adela Breton was highly regarded by the founding fathers of Maya research, but her work was largely neglected in the 1960s and 1970s, when archaeology was attempting to be a science and its practitioners were barely speaking to the art historians. Today there is a happier relationship between dirt archaeologists, epigraphers and art historians, and I predict that many specialists will make their way to Bristol.**

**At the time when the Breton exhibition was opening, a disquieting report appeared in Vol. 11 of *The Pre-Columbian Art Research Institute Newsletter* on the damage done to Maya monuments by acid rain, algae, windblown dust and the ravages of mass tourism. This survey draws on a three-year investigation by Merle Robertson on behalf of the National Geographic Society. To quote from the summary: "there is not going to be any visible sculpture or painted buildings or any kind of buildings for that matter a 100 years from now. The paint will be gone long before that, in fact, it is almost all gone NOW". Already the world-famous Bonampak murals, after a generation of mistreatment, can be better appreciated in museum replicas than in the original temple, and Palenque was documented just in time. Meanwhile, Adela Breton's fine watercolours become increasingly precious records of Maya culture.**



Warwick Bray

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**The Art of Ruins: Miss Adela Breton and the Temples of Mexico* is at the City of Bristol Museum and Art Gallery, Queen's Road, Bristol, until 10 March.