WHAT CAUSES EARTHQUAKES?

BY ANDREW ROBINSON

They've devastated cities throughout human history, but have proved to be one of the most difficult of natural phenomena to understand

NOT LONG AFTER midnight on an ordinary evening in 2008, I had an uncanny seismic experience. I had just finished drafting a review of a book called *Apocalypse: Earthquakes, Archaeology, And The Wrath Of God* when I felt the floor of my upstairs flat in London shift almost imperceptibly for a second or two. Perhaps the vibration had been caused by a London Underground train, so I forgot about it and went to bed.

The following morning, however, the BBC radio news bulletin announced that there had been an earthquake, at 12.56am. The British Geological Survey had monitored the event as having occurred at a depth of 5km, with its epicentre in Lincolnshire, roughly north of London around 200km away, and with a potentially destructive magnitude of 5.2. One serious injury was reported and many houses close to the epicentre – where the intensity of an earthquake is greatest – suffered damage. This was the biggest earthquake in the UK since 1984.

Every year in Britain, some 200 minor tremors are recorded by seismographs. A magnitude-4 earthquake occurs every two or three years on average; a magnitude-5 quake every 10 years. In 1931, there was a quake of magnitude 6.1 – the largest British earthquake measured to date.

As a rule, 90 per cent of these tremors go undetected by the public. Those that are noticed – like the magnitude-5.2 earthquake on 27 February 2008 – are nevertheless rapidly forgotten. To most people, earthquakes and England would appear to have little connection with the almost apocalyptic earthquakes that have shaped society in countries like China, Japan, Iran and Pakistan, where violent shaking of the earth has killed millions of people in modern times. Yet, it was in Britain that seismology emerged as a science.

The first attempts to account for earthquakes in other than divine terms come from ancient Greece and Rome. Rather than imagining the god Poseidon striking his trident on the ground in anger, some Greek philosophers proposed natural explanations. Aristotle, during the 4th Century BC, believed in a 'central fire' inside caverns in the Earth. As the subterranean fires burned away the rocks, the underground caverns collapsed, generating earthquakes.

Aristotle even classified earthquakes into types according to whether they shook structures and people in mainly a vertical or a diagonal direction, and whether or not they were associated with escaping vapours. Much later, the Roman philosopher Seneca, inspired in part by an Italian earthquake in AD 62 or 63 that devastated Pompeii, proposed that the movement of air – rather than smoky vapours – trapped and compressed within the Earth, was responsible for both violent storms and destructive rock movements.

MADE IN CHINA

The first measurement of an earthquake comes from ancient China, however. The earliest known seismometer was invented in AD 132 by Zhang Heng. It consisted

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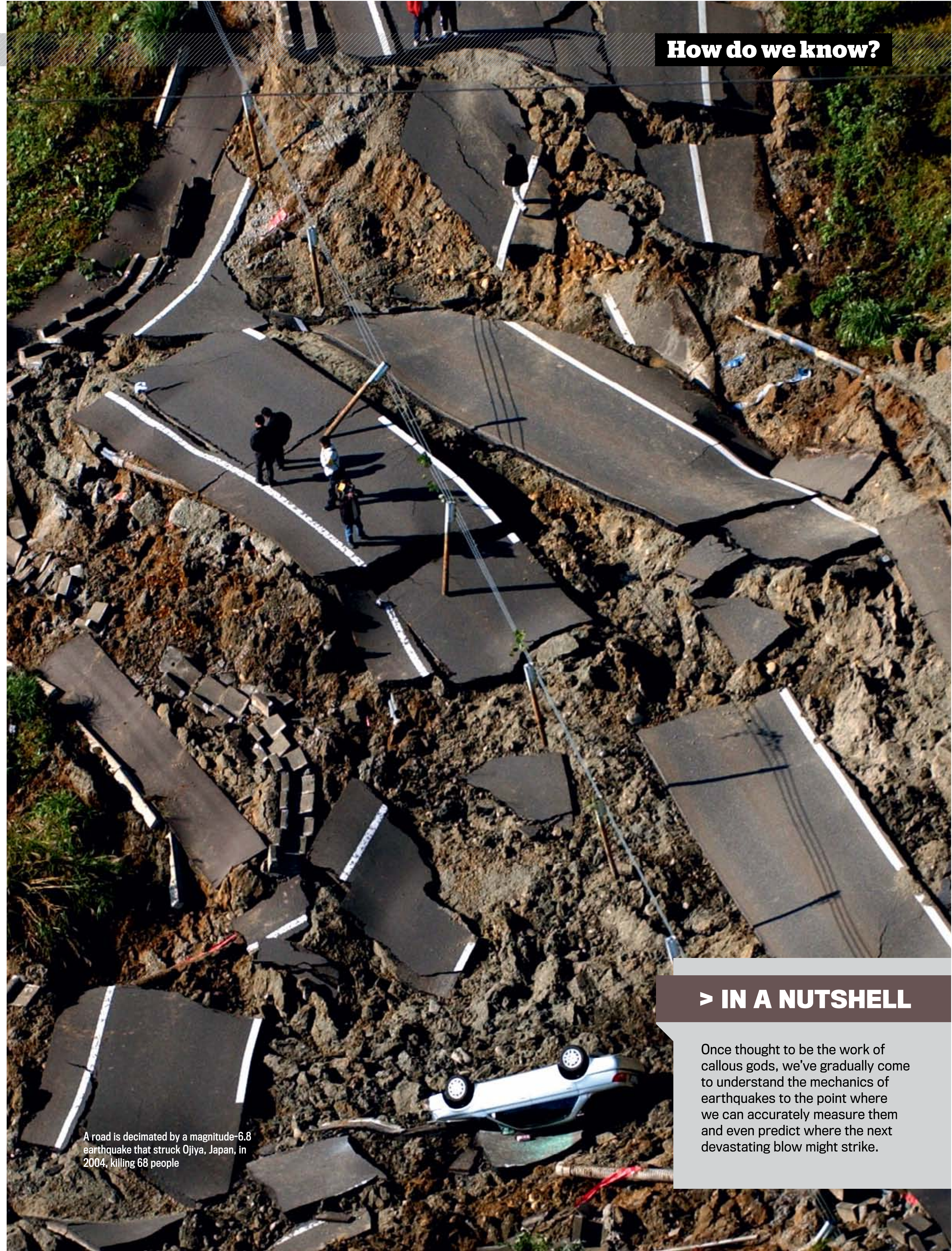


A road is decimated by a magnitude-6.8 earthquake that struck Ojiya, Japan, in 2004, killing 68 people

> IN A NUTSHELL

Once thought to be the work of callous gods, we've gradually come to understand the mechanics of earthquakes to the point where we can accurately measure them and even predict where the next devastating blow might strike.

of eight dragon-heads facing the eight principal directions of the compass. They were mounted on the outside of an ornamented vessel said to resemble a wine jar with an approximate diameter of 2m. Around the base, directly beneath the dragon-heads, were eight squatting toads with open mouths. In the event of an earthquake, a bronze ball would drop from a dragon-head into a toad's mouth with a resonant clang. The direction of the earthquake was probably indicated by which dragon-head dropped its ball, unless more than one ball dropped, indicating a more complex shaking. The device must have comprised a pendulum as the primary sensing element, somehow connected to levers that caused the bronze balls to drop.

According to Chinese history, in AD 138 the seismometer enabled Zhang Heng to announce the occurrence of a major earthquake at Rosei, 650km to the northwest of the Chinese capital Loyang – two or three days before news of the devastation arrived by messengers. This prediction restored the faith of court officials in the seismometer, and led the imperial government to appoint a secretary to monitor the instrument, which remained in existence for four centuries.

But scientific understanding of how earthquakes form had to await the destruction of Lisbon in 1755 by an extremely powerful earthquake followed by a tsunami and fires. In Britain, data on the effects of the Portuguese earthquake were collected from all over the country and abroad by the Royal Society, supplementing that collected after a series of British earthquakes in 1750. John Michell, an astronomer at Cambridge University, took up the challenge of analysing the eyewitness reports, and accounting for earthquake motions in terms of Newtonian mechanics. Michell eventually published an important, if flawed, geological paper, 'Conjectures concerning the cause and observations upon the phaenomena of earthquakes', in the Royal Society's *Philosophical Transactions* for 1760.

He correctly concluded that earthquakes were 'waves set up by shifting masses of rock miles below the surface'. However, his explanation for this shifting relied wrongly on explosions of steam when underground water encountered underground fires.

When the shifting occurred beneath the seabed, Michell also rightly concluded that it would produce a sea wave (a tsunami), as well as an earthquake. There were two types of earthquake wave, he said, once again coming close to the truth: the first was a 'tremulous' vibration within the Earth, followed shortly by an undulation of the Earth's surface.

From this he argued that the speed of an earthquake wave could be determined by its arrival times at different points on the surface. Such times were approximately known from eyewitness reports for far-flung places affected by the Lisbon earthquake, which enabled Michell to calculate a speed for its wave of 1,930km/h.

He was the first scientist to attempt such a calculation – unaware though he was that the speed of seismic waves varies with the types of rock through which they pass. He then went further, by theorising that the surface origin of an earthquake, what we now call the epicentre, could be located by combining the same data on arrival times. Although he curiously chose a different – and inaccurate – way to calculate the epicentre of the Lisbon earthquake (relying instead on reports of the direction of the tsunami), his theoretical principle is the basis of today's method for locating an epicentre.

FINDING THE EPICENTRE

The next major development came in the mid-19th Century from a brilliant Irish civil engineer, Robert Mallet, who had spent two decades collecting data about historical quakes. His catalogue of world seismicity contained 6,831 listings, giving the date, location, number of shocks, probable direction and duration of the seismic waves, along with notes on related effects. In 1858, he travelled to Naples to investigate the destruction wrought by a recent major earthquake.

THE KEY DISCOVERY

The movement of roads, fences and streams crossing the San Andreas Fault enabled Harry Fielding Reid to develop a theory of how earthquakes are triggered

IN 1906, THE San Francisco earthquake produced a surface rupture 435km (270 miles) in length, and wide enough to swallow a cow, according to a famous folk tale of the time. The rupture happened in an area named the San Andreas Fault. To explain it, geophysicist Harry Fielding Reid published his mechanism of 'elastic rebound'.

Reid had noticed that in the years before 1906, roads, fences and streams crossing the fault had been deformed by its movement, and how after the earthquake they were displaced or offset by up to 6.4m. He proposed that before the earthquake, friction between the two sides of the fault had locked part of it, deforming it as the sides moved past each other – until finally the fault snapped. The sides sprang away from each other and they elastically rebounded, creating the surface rupture.

The lower the friction, the weaker the fault and the more easily it would slip, suggested Reid. In places where the friction was of medium size, the fault would slip frequently, producing many small earthquakes. But where friction was high and the fault strong, it would slip only occasionally: there would be few, but large, earthquakes. While Reid's model suffers from serious difficulties, it's still the best that seismologists have.

Around 3,000 people were killed and 80 per cent of the city destroyed as a result of the 1906 San Francisco earthquake

CAST OF CHARACTERS

Masters of destruction: the minds who unlocked the mystery of earthquakes

Zhang Heng (AD 78-139) designed the earliest recorded seismometer. He was a Chinese astronomer and mathematician. In 138, the seismometer measured a major earthquake far from the Chinese capital, two or three days before news of the earthquake's damage arrived by messenger.

Robert Mallet (1810-81) was an Irish civil engineer and inventor who became interested in earthquakes during the 1830s. He created experimental earthquakes with dynamite, investigated the 1857 Neapolitan earthquake through detailed analysis of its damage to buildings, and compiled world maps that showed earthquakes clustering in mysterious belts.

John Milne (1850-1913), a British geologist and mining engineer, was a professor in Japan from 1876-95. His teaching, the seismographs he designed and his investigation of the 1891 Mino-Owari earthquake established Japanese seismology, while the international earthquake bulletin he issued after his return to Britain led to the International Seismological Summary started in 1918.

Harry Fielding Reid (1859-1944) served on California's state commission to investigate the 1906 San Francisco earthquake. An American geophysicist, he closely examined land movements due to earthquakes over the course of the previous half-century. He then proposed that earthquakes were the result of the 'elastic rebound' of geological faults such as the San Andreas Fault.

Charles Richter (1900-85), like Reid, was an American physicist-turned-seismologist. Working with Beno Gutenberg at the California Institute of Technology, Richter devised a magnitude scale for Californian earthquakes in 1935. Until the 1980s, 'Richter magnitude' was used internationally, but it has now been replaced by a more accurate 'moment magnitude' scale.

TIMELINE

The key discoveries that have enabled us to understand the mechanism of earthquakes and detect them

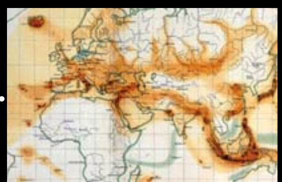
AD 132

The world's first seismometer (pictured), invented by Zhang Heng, establishes the principle that an earthquake can be scientifically measured with an instrument located far from the epicentre.

1755

A catastrophic earthquake in Lisbon leads John Michell, a British clergyman and astronomer, to conclude, in the Royal Society's *Philosophical Transactions* in 1760, that earthquakes are 'waves set up by shifting masses of rock'.

1862



Robert Mallet publishes his two-volume study, *Great Neapolitan Earthquake*, and maps of world seismic intensity demonstrating that earthquakes cluster in certain belts around the Earth.

1906

An earthquake in San Francisco and a subsequent fire destroy the city but establish the discipline of seismology in California. Harry Fielding Reid proposes the 'elastic rebound' theory of earthquakes, which is still influential, if flawed.

1935

Charles Richter, following the 1933 Long Beach earthquake near Los Angeles, creates a magnitude scale, which enables seismologists to allot a size to each Californian earthquake, regardless of its varying intensities.

1960s

The theory of plate tectonics explains why the vast majority of earthquakes cluster in belts, at plate boundaries such as the 'Ring of Fire' around the Pacific Ocean; but it fails to explain intra-plate earthquakes, for example in Missouri.

Assessing every crack with a trained eye, Mallet compiled isoseismal maps: that is, maps with contours of equal earthquake damage/intensity. It's a method employed today, albeit with refinements, to map seismic hazard. Mallet placed too much reliance on the direction of fallen objects and the type of cracks in buildings as indicators of earthquake motion (cracking is in fact mainly a function of the type of building construction). But his maps did allow him to estimate the centre of the earthquake and its size relative to other earthquakes.

Using the new technique of photography, he documented the damage. He then reported to the Royal Society in a two-volume study, *Great Neapolitan Earthquake Of 1857: The First Principles Of Observational Seismology*, published in 1862. Elsewhere, he published maps of world seismic intensity, providing the first indication that earthquakes cluster in certain belts around the Earth. An explanation of this fact would have to wait another century, but in the meantime Mallet's map focused scientific attention on these patterns.

GLOBAL NETWORK

Over the next half-century seismology became a truly international science, as measuring instruments improved in sensitivity to the point where they were able to monitor, and record, earthquakes all over the planet from a single location. A British geologist and mining engineer, John Milne, having designed more than one such seismograph while living for two decades in Japan, returned to Britain in 1895 and established a central earthquake observatory at his house on the Isle of Wight. It had inputs from a worldwide network of seismographic stations. Although Milne's theoretical contributions were small, he has a considerable claim to be considered the founder of seismology.

With the vast increase in seismic data, theoretical understanding advanced in the first decade of the 20th Century. The theory that volcanic action might be related to earthquakes – believed by Aristotle and lent credence by the contiguous volcanoes and earthquakes of southern Italy and Japan – was largely abandoned when it became clear that active volcanoes were often free from earthquakes.

NEED TO KNOW

Key terms that will help you understand earthquakes

1 EPICENTRE
The area of origin of an earthquake underground is its hypocentre or focus. The point on the Earth's surface immediately above the hypocentre is the epicentre, where there is often visible movement and cracking of the Earth, as surface waves radiate from the epicentre.

2 FAULT
At its simplest, a geological fault is a joint between two rock planes. The fault is usually not exactly vertical and so one plane of the fault overhangs the other. Fault movements and earthquakes are intimately connected, but their precise relationship is controversial.

3 INTENSITY
The intensity of an earthquake measures its effects on objects, humans and animals. Intensity generally increases the closer the observer is to the epicentre. It's also higher for a poorly constructed building than for a well-built one, given the same shaking.

4 MAGNITUDE
Unlike intensity, magnitude is independent of the observer's distance from the epicentre. It is, so to speak, the amount of explosive in a bomb, as opposed to the bomb's effects. An earthquake can have only one magnitude, fundamentally; but it always has many intensities.

Charles Richter studies earthquake tremors in his laboratory in Pasadena, California – he developed the Richter scale in 1935

Instead, the tectonic movement of geological faults came to be seen as the chief origin of earthquakes. Known as the 'elastic rebound' model, abrupt fault movement was first proposed by the American geophysicist Harry Fielding Reid in 1906 to account for the surface rupture of the San Andreas Fault in the San Francisco earthquake (see 'The Key Discovery', p98).

But while the model was plausible enough, it offered no explanation as to why the sides of certain geological faults should be grinding past each other in a regular fashion, causing periodic earthquakes. What force was driving them? Not until the 1960s, with the advent of plate tectonic theory, did seismologists appreciate that the San Andreas Fault was the boundary between two tectonic plates, the Pacific plate and the North American plate, which were moving in opposite directions. Some other plate boundaries, for example near Japan, were also seismically active. Hence the fact, first noted by Mallet, that earthquakes clustered in bands, which were now understood to coincide with plate boundaries.

Yet, despite progress, seismologists remain far from fully understanding earthquakes. Plate tectonics do not really explain British earthquakes, far from the mid-Atlantic plate boundary. What's more, geological faults such as the San Andreas have turned out to be very much weaker than would be expected from the elastic rebound model for large earthquakes.

As for earthquake prediction, which was touted by many seismologists as achievable during the last few decades of the 20th Century, all seismologists now admit it's currently impossible. The scale of the task was outlined by Charles Richter, who devised the 'Richter' magnitude scale for measuring earthquakes in the 1930s. The seismologist said: "One may compare it to the situation of a man who is bending a board across his knee and attempts to determine in advance just where and when the cracks will appear." ■

Andrew Robinson is the author of *Earthquake: Nature And Culture* and *Earthshock*

Find out more

BBC WORLD SERVICE *Forecasting Earthquakes* reveals the past, present and future of earthquake detection. www.bbc.co.uk/programmes/p01c4qgt