EARTHQUAKE PREDICTION

Precursory V_p/V_s Changes

from our Geomagnetism Correspondent

MORE than a decade ago, Kondratenko and Nersesov (*Trudy Inst. Fiz. Zemli*, **25**, 130; 1962) reported that the velocity of crustal P waves increases after moderately large earthquakes in the Tadjikistan region of southern central Asia. They had analysed more than 800 travel-time curves from foreshocks and aftershocks of earthquakes with magnitudes 5 or greater and occurring during the period 1958–1961, and had concluded that the average P wave velocity was 5.3 km s^{-1} prior to main shocks and 6.3 km s^{-1} afterwards. This was the first report of a variation in seismic velocity associated with earthquakes; but unfortunately it was not translated from the Russian and so apparently remained unknown in the west (and even more surprisingly in Japan) until Savarensky (*Tectonophysics*, **6**, 17; 1968) reviewed the data in English.

There can be little doubt that had this discovery been made known at the time outside the Soviet Union, it would have attracted considerable attention, especially in Japan where earthquake prediction research had long been a subject of great concern. The sheer magnitude (more than 15%) of the reported velocity change of the P waves would have ensured attempts to repeat the analysis elsewhere. Rikitake (*Earth Sci. Rev.*, **4**, 245; 1968), for example, was later to imply doubt about the validity of the Russian data on the grounds that a P wave velocity change of 15% would correspond to a 30% change in elasticity. As it was, the delay in the communication of the Russian results was compounded by the fact that, throughout the 1960s, seismic velocity was not apparently among the many parameters independently studied from the point of view of earthquake prediction.

Following Savarensky's report and other reports of Russian work (see, for example, Nersesov *et al.* in *The Physical Basis of Foreshocks*, Moscow, 1969), the subject was taken up by United States seismologists. In 1969, Semenov (*Izv. Acad. Sci. USSR Phys. Solid Earth*, **4**, 245; 1969) had shown that prior to earthquakes in the magnitude range 3–5, the P wave–S wave velocity ratio (V_p/V_s) decreased by about 6% and then increased again to about its normal value just before the onset of the main event. Aggarwal *et al.* (*Nature*, **241**, 101; 1973) then reported a similar phenomenon involving V_p/V_s) decreases of up to 13% for earthquakes in New York in the magnitude range 1–3. But these changes all involved relatively small events; and it was clearly desirable to determine whether similar precursors apply to larger earthquakes. Proof that they do has now been supplied by Whitcomb *et al.* (*Science*, **180**, 632; 1973) in respect of the 1971 San Fernando earthquake (magnitude 6.4). This report from Whitcomb and his colleagues, coming at a time when many people have become discouraged by the apparent lack of progress in the highly intractable problem of earthquake prediction, is likely to become a landmark in the subject, for not only does it present convincing evidence for the phenomenon concerned, but it has also been possible to view an earthquake precursor in terms of a realistic physical model.

The facts are easily stated. Whitcomb *et al.* have used P and S waves from nineteen earthquake sources during 1961–1970 to show that the V_p/V_s ratio in the San Fernando epicentral region had an average value of 1.75 up to 1967 but decreased suddenly by 10% in the middle of that year and then gradually increased to about its normal value at the time of the 1971 shock. When the P and S wave velocities are examined individually both are found to change in the same sense as the V_p/V_s ratio, but the V_p variation is the greater and the variation in V_s is little greater than the uncertainties of measurement. Thus, contrary to some previously stated beliefs, it is V_p which accounts for the change in V_p/V_s. This is an important result, not only because it leads directly to a possible physical explanation of the precursory variation but because of its practical consequences. Man-made explosions produce chiefly P waves, any S waves generated being difficult to measure. The new result thus opens the way to the use of artificial sources to detect precursory V_p/V_s changes, rather than having to depend on the vagaries of earthquakes.

The second important result concerns the interval between the sudden V_p/V_s decrease and the onset of the earthquake, which in the San Fernando case is 3.5 yr. Combining this result with data from previous studies, Whitcomb *et al.* show that, over the magnitude range 0–6.4 at least, the precursory interval increases logarithmically with earthquake magnitude. Extrapolation of this variation (the validity of which will need testing by future studies) suggests that a magnitude 7 event would have a precursory interval of 8 yr and that a magnitude 8 event would have an interval of 40 yr. Clearly no great reliance should be placed on these absolute figures at this stage; but what is quite certain is that the precursory interval increases with magnitude. By contrast, the precursory V_p/V_s decrease is independent of magnitude.

Whitcomb and his colleagues then go on to show that all of these results may be accommodated, both qualitatively and quantitatively, by a physical model derived from the known behaviour of fluid-filled, porous media—in particular, the phenomenon of rock dilatancy, or the increase of volume resulting from a change in shape. In the field, the change in shape is thought to be caused by shear stresses associated with regional tectonic strain. Assuming the pores and cracks in the rock to be initially saturated with fluid, the dilatant volume increase will lead to a decrease in pore fluid pressure, and if the dilatancy is large enough the pore and crack volume will ultimately exceed the fluid volume. In this undersaturated stage the enlarged rock voids will partially contain vapour, resulting in a reduction of the overall bulk modulus. This produces a decrease in V_p, but little change in V_s and thus accounts for the drop in V_p/V_s.

The effect of the reduction in pore fluid pressure is to increase the fracture strength of the rock and thus delay the onset of the earthquake. Fluid flow from outside the dilatant volume, however, gradually returns the permeable rock to its saturated state, producing a gradual increase of V_p/V_s and a gradual decrease in fracture strength until an earthquake occurs. The actual variations in V_p and V_s during these processes depend on the range of velocities in the rock between the saturated and undersaturated states. This range is independent of earthquake magnitude, and so the drop in V_p/V_s must also be independent of earthquake magnitude. On the other hand, the rate at which the rock returns to the saturated state depends partly on the permeability of the rock and the availability of fluids but also on the dilatant volume. The dilatant volume, in turn, must depend on the amount of stored mechanical energy which presumably determines the magnitude of the final earthquake. The precursory interval—the time taken for V_p/V_s to return to its normal value—should thus depend on the earthquake magnitude, the greater the magnitude the longer being the interval.

It is this marriage of observation and physical theory which makes the report from Whitcomb and his colleagues particularly important. Thus, in spite of the historical accident which delayed the wider communication of the original discovery, the V_p/V_s precursor now emerges as probably the most promising of all possible earthquake precursors. As Whitcomb *et al.* point out, however, there are other phenomena (such as electrical conductivity) associated with dilatancy. Some of these have already been studied with a view to earthquake prediction, but such studies may now become more significant.