the spoil with a layer of soil. This should be of neutral or alkaline reaction, otherwise its leachate would dissolve more chromium from the underlying spoil. Upward diffusion of chromium would remain a problem; this has been shown to occur through 15 cm layers of soil. An impermeable layer between the spoil and the soil would lead to erosion of the upper soil. It seems, therefore, that chemical reduction of chromate is the best hope for a long-term solution to the problem of reclamation of chromium waste heaps.

EARTHQUAKES

Predicting Locations

from our Geomagnetism Correspondent

EARTHQUAKE prediction must obviously involve both the times and locations of impending events. But having acknowledged that, it is possible to visualize two rather different approaches to the prediction problem with rather different emphases on time and place. It is probably true to say that prediction has most often been perceived as the problem of determining in advance the times of events likely to occur in regions known to be seismic, and in such cases the seismic regions may be regarded as essentially local even though some may have similar characteristics (similar fault types or similar earthquake depth ranges, for example). Thus attempts to predict earthquakes by seeking, for example, premonitory geodetic, geomagnetic or seismic velocity changes have been carried out in specific areas, certainly in the hope that any conclusions emerging may be applicable to other seismic zones, but more realistically in the expectation that the results may be applied at least within the particular region concerned.

Clearly this approach is possible even in the absence of any general framework linking all, or most, seismic zones. Japan, for instance, has long been known to be seismically active, and attempts have been made to predict the times of occurrence of earthquakes since the last century. But the advent of the new global tectonics has opened up a new approach which may be expressed as attempting to deduce, not so much the times of impending events in a particular area, but rather the likely locations of events within a particular time interval. This possibility first became apparent in a general way with the discovery that seismic zones are not randomly scattered about the world but form a series of linked belts now known to correspond to plate boundaries (although some earthquakes also occur outside these belts). At this point it became possible to make a statistical statement to the effect that future events are much more likely to take place along the defined belts than in the interiors of the plates. Moreover, more detailed work on the nature of plate boundaries led to more detailed predictions about where particular types of earthquake would occur—for example, that very large earthquakes are much more likely to occur along subduction zones and along transform faults than along oceanic ridges.

But can this approach be refined? In other words, given that future earthquakes are more likely to occur along the defined belts, can the belts themselves now be subdivided into segments in which the chances of an earthquake occurring during a specified period differ? For although this may not lead to precise prediction in the sense of being able to forecast the exact time and place of a future event, it would nevertheless be of some social importance to be able to predict whether, say, the San Francisco area is very likely or highly unlikely to experience a significant seismic event during the next few decades.

In a long and detailed analysis of the Pacific plate margins, Kelleher *et al.* (*J. Geophys. Res.*, **78**, 2547; 1973) have now shown that it is indeed possible to subdivide the circum-Pacific seismic belt in this way, although they admit that this first systematic attempt is "crude" and that "profound social changes" are therefore not warranted. Their chief aim was to predict the locations of large (magnitude $\geqslant 7$) shallow earthquakes due to take place over the next few decades around the Pacific; and they have done this by successively applying two sets of criteria to give a three-fold classification of marginal segments.

The initial set of criteria was designed to exclude all segments which are not part of a major shallow seismic belt characterized predominantly by thrust or strike slip faulting, and all segments which have ruptured during the past 30 years as a result of large earthquakes. The object of the first of these criteria was largely to remove from consideration those regions not relevant to the principal aim and thus to exclude intermediate and deep earthquakes, large shallow earthquakes within plates and earthquakes associated with normal faulting. Spreading ridges were also eliminated because large shocks rarely occur along them, and a few other areas were removed because of tectonic complexity. The point of the second criterion is that there is now considerable theoretical and observational evidence to suggest that large earthquakes are least likely to occur in the immediate future in zones which have experienced such events in the recent past. In short, there is a tendency for large earthquakes to fill in the "seismic gaps" which have not been subject to rupture for some considerable time. This was first appreciated by Fedotov (*Tr. Inst. Fiz. Zemli Akad. Nauk SSSR*, No. 36, 66; 1965) and was used by him and others to predict earthquake locations in limited areas. Thus Kelleher *et al.* do not claim that their initial criteria are new, although this is the first time they have been systematically applied over such an extended region.

To the areas of "special seismic potential" defined by the initial criteria, Kelleher and his colleagues then applied a supplementary set of three criteria in an attempt to pick out the zones most at risk to large earthquakes during the next few decades. According to the first supplementary criterion, a historical record of one or more large events along a segment is regarded as evidence that similar events can occur there again. If no such record exists, it may be that the strain is being released by aseismic creep or small to moderate earthquakes, and the risk of a large earthquake will be low. On the other hand, it could also be either that the historical record is incomplete or that the recurrence time for large earthquakes is longer than the historical record. This criterion is therefore not foolproof.

The point about the recurrence interval is taken up again in the second criterion, for an area is considered to be particularly at risk in the near future if historical data and relative plate motions suggest that the recurrence time is comparable to the time since the last large earthquake occurred. But although this is straightforward enough in principle, calculated recurrence times are particularly vulnerable to defects in the past record of events and variations in relative plate motions and will thus be subject to large uncertainties. Finally, an area is designated as one of high risk if it appears to be the site of the next event in a series of earthquakes progressing regularly in time and space. There are now several recorded examples of regular progressions of events along extensive sections of plate boundaries, suggesting that many earthquakes are causally related.

By systematically applying the various criteria in detail to each segment of the Pacific belt, Kelleher and his colleagues end up with a map defining three degrees of risk with respect to large shallow earthquakes. The low risk areas are those excluded by the initial set of criteria. The risk in those areas not so excluded is higher, and is higher still in those regions selected by one or more of the supplementary criteria. But as the authors point out, the uncertainties are large. They thus regard their results not as the last word but rather as "working hypotheses to be tested, modified, and discarded if necessary".