of at least 8-10 km. Support for this interpretation also comes from gravity data, for to explain the steep gradient in the Bouguer gravity profile near the San Andreas fault zone it is apparently necessary to invoke the presence of a slab of low density (~2.6 g cm^{-3}) extending to a depth of 8-10 km. A density of 2.6 g cm^{-3} is typical of fault gouge.

Wang and his coworkers go no further with their experiments; but they have gone far enough to show that fault gouge as a possible modifier must not be ignored when it comes to considering the causes of shallow earthquakes. □

Phase transitions in spin glasses

from a Correspondent

If the temperature of a supercooled liquid is lowered sufficiently, it may form a glass. For twenty years or more there has been an inconclusive debate as to whether this change is of purely kinetic origin, occurring when the relaxation times of the liquid become longer than the patience of the experimenter, whereupon the liquid appears to have solid properties, or whether the change reflects an underlying phase transition. It looks as though the debate on the causes of the similar phenomena found in spin glasses may be just as lengthy and inconclusive.

A spin glass is typically a substitutional alloy of a few percentage of a transition metal such as iron or manganese in a host metal such as copper or gold. The transition metal impurities—the spins of the spin glass—can be taken as being approximately randomly distributed throughout the alloy. They interact with each other through the conduction electrons of the host metal to give a long-range coupling between the spins whose sign depends on the distance between the spins. This means that the interaction between some spins is ferromagnetic in sign which favours their parallel alignment while that between other pairs of spins is antiferromagnetic which favours their antiparallel alignment. The net effect of such a mixture of competing interactions is to produce a ground state in which the orientation of the spins is chaotic and which has no resultant magnetic moment.

When cooled below its freezing temperature T_F, the properties of a spin glass are radically altered in much the same way as the properties of a supercooled liquid are altered below the glass transition temperature T_g. Above T_F an induced magnetic moment rapidly decays away on a microscopic time scale when the magnetic field which induced it is switched off. Below T_F an induced moment can take hours to decay away. One can immediately deduce that some relaxation processes in a spin glass take place very slowly. Another characteristic is the 'cusp' in the magnetic susceptibility at the freezing temperature. The susceptibility as a function of temperature rises at T_F to a maximum which is quite sharp, especially when the susceptibility is measured using small applied fields.

Non-analytic behaviour such as a cusp usually indicates that a phase transition must be taking place. In 1975, Edwards and Anderson (*J. Phys.* **F6,** 1927; 1975) proposed a phase transition theory for spin glasses which gave a seemingly satisfactory explanation of the cusp. The order parameter q of their theory is the probability that any given spin is still pointing after an infinitely long time in the same direction as it was at some initial time. Above T_F, q is zero, but below T_F, which is identified as the phase transition temperature, it is non-zero and increases to unity as the temperature approaches absolute zero.

Although we live in a three-dimensional world, it is both interesting and useful to examine (theoretically!) the nature of a phase transition in worlds of different dimensionality. There is always a 'lower critical dimension' below which the phase transition will not take place. Thus the Heisenberg type of ferromagnet does not have a phase transition in two dimensions for its lower critical dimension is two. The lower critical dimension for the spin glass transition is controversial, with arguments being advanced for two, three and four dimensions. Numerical evidence derived from high-temperature series expansions seems to favour four (Reed, *Phys. Lett.* **A68,** 473; 1978). If that really is the case, then the phase transition theory of spin glass behaviour fails and an alternate explanation must be sought.

An explanation which actually predates the phase transition theory is that spin glass behaviour is entirely a non-equilibrium effect resulting from the long relaxation times which exist within spin glasses at low temperatures. The relaxation modes probably involve activation processes in which a potential barrier separating two easy orientations of a spin has to be surmounted. This will produce relaxation times which follow an Arrhenius law and so rapidly increase at low temperatures. The 'cusp' in the susceptibility is explained on this hypothesis by observing that at temperatures below T_F only a fraction of the total spins present will contribute to the susceptibility, namely those spins or groups of spins which can relax on a time scale shorter than the time scale of the experiment. The other spins are effectively frozen in fixed orientations and do not contribute. For a given experimental time scale, the further the temperature is lowered below T_F the larger the fraction of frozen spins becomes and hence the smaller will be the observed susceptibility. A corollary of this hypothesis is that the freezing temperature T_F should alter with the experimental time scale. Lengthening the time scale should enable more spins to contribute to the susceptibility and so depress the apparent freezing temperature. A similar effect occurs at the glass transition in ordinary glasses where T_g falls when the liquid is allowed a longer time to come to equilibrium.

A recent experiment of Murani and Heidmann (*Phys. Rev. Lett.* **41,** 1402; 1978) clearly indicates that lengthening the time scale depresses T_F. They have carried out neutron inelastic scattering measurements on a Cu–8 at % Mn alloy at three different energy resolutions. The temperature dependence of the elastic magnetic cross section can be extracted from the data. It is related to the Edwards-Anderson order parameter q on a phase transition hypothesis and to the number of frozen spins on a relaxation time hypothesis. The elastic cross section increases below a certain temperature but the temperature at which this happens, the nominal freezing temperature, varies with the energy resolution employed. They argue that the time scale in their experiment is proportional to the inverse of the energy resolution. For a time scale of 10^{-11} s, T_F is 75 K, whereas T_F is about 40 K on a time scale of 10^{-2} s (this latter data is from separate experiments on the a.c. susceptibility). At first sight this appears to be strong evidence against a phase transition (since a phase transition should take place at a unique temperature) and in good accord with the explanation of spin glass behaviour in terms of long relaxation times and frozen out spins.

Unfortunately it is not as simple as this. A phase transition could be accompanied by long relaxation times which would produce an apparent freezing temperature that decreased with increasing experimental time scale, but which eventually saturates at the true transition temperature T_F for a hypothetical experiment with an infinitely long time scale. There is just a hint of such a possibility within their data but it is not sufficiently strong to be compelling evidence. It is clearly going to be very difficult to decide from experiments of this kind whether spin glass behaviour is or is not due to a phase transition. A new idea is needed for a conclusive experimental test to distinguish the rival approaches.