a Mohr circle whose position is determined by the values of the principal stresses (σ_1 and σ_3). If a stress state, when plotted on the graph, does not touch or intersect the failure envelope, the stress state is stable, i.e., will not cause the rock to fail, e.g., stress field (i) Figure 7B. If, however, it does touch the envelope, failure will occur, either by tensile fracturing if the contact is with the tensile part of the envelope (Figure 7B (ii)), or shear fracturing if it is with the shear part (Figure 7B (iii)).

What Determines Whether Tensile or Shear Fractures Form?

It can be seen from Figure 7B that shear failure is associated with a large differential stress ($\sigma_1 - \sigma_3$) i.e., the Mohr's stress circle must be large in order to intersect the shear failure envelope, and that tensile failure is associated with a low differential stress, i.e., the Mohr's stress circle must be small in order to intersect the tensile failure envelope. The precise conditions necessary for the formation of the two types of fractures are:

For tensile failure to occur $(\sigma_1 - \sigma_3) < 4T$ [8a]

For shear failure to occur $(\sigma_1 - \sigma_3) > 4T$ [8b]

where T is the tensile strength of the material.

The geometrical relationships between the principal stresses and the fractures they produce (i.e., a conjugate set of shear fractures symmetrically about σ_1 and a single set of tensile fractures at right angles to σ_3) is shown in Figure 1 and, as noted below, the understanding of these relationships provides a powerful tool in fracture analysis.

It follows therefore that the orientation of the fractures that form in response to a stress field is determined by the orientation of the principal stresses (Figure 1), and the type of fracture (shear or tensile) by the magnitude of the differential stress.

The Effect of a Fluid Pressure on Fracturing

Fluid-Induced Failure

The state of stress in the crust is dominantly compressional. For example, in a nontectonic environment, the stress at any depth is generated by the overburden which produces a compressive vertical stress which induces a compressive horizontal stress. Thus, at any depth the Mohr stress circle will plot in the compressive regime in Figure 7B and there will be no possibility of tensile failure. Geologists were, therefore, perplexed to find that large numbers of tensional fractures occur in the crust. This paradox was resolved when the importance of fluid pressures within a rock was understood. Pore fluid pressure within a rock increases as the rock is buried. (*see* Tectonics: Hydrothermal Activity). The stress state within the pores is hydrostatic and the pressure acts so as to appose the lithostatic stress caused by the overburden. This effect can be shown diagrammatically by representing the lithostatic stress as an ellipse with the stress acting compressively and the fluid pressure as a circle with the pressure acting outwards (Figure 8A). The fluid pressure reduces all the lithostatic stresses by an amount P_{fluid} to give an effective stress. Thus, the principal stresses σ_1 and σ_3 become $(\sigma_1 - P_{fluid})$ and $(\sigma_3 - P_{fluid})$. This new stress field can be plotted as a Mohr stress circle (Figure 8B). It can be seen that the original lithostatic stress circle is moved towards the tensile regime but that the diameter of the circle, i.e., the differential stress, remains unchanged.

The amount of migration of the stress circle is determined by the magnitude of the fluid pressure. Thus, as the fluid pressure gradually increases during burial, the stress circle is pushed inexorably towards the failure envelope. When it hits the envelope, failure occurs. Such failure is termed fluid induced or hydraulic fracturing. In this way an originally compressional stress regime can be changed so that one or more of the principal stresses becomes effectively tensile and the conditions for tensile failure can be satisfied.

The Expression of Fluid-Induced Failure

In the example shown in Figure 8B the lithostatic stress had a small differential stress (i.e., less that 4T (see eqn [8]) and as a result the induced hydraulic fractures were tensile fractures. If it had been greater than 4T, shear fractures would have formed.

The Organization of Tensile Fractures

The Mohr circles shown on Figure 9 all intersect the failure envelope in the tensile regime, i.e., the differential stresses are all less than 4T and will all therefore result in tensile failure. Their differential stresses vary from just less than 4T (circle (i) Figure 9), to zero (circle (iv), Figure 9). Note that when the stress state is hydrostatic, the Mohr circle is reduced to a point.

As noted above, tensile fractures form normal to the minimum principal compressive stress σ_3 (Figure 1B), i.e., they open against the minimum compressive stress. The stress state represented by Mohr circle (i) in Figure 9, has a relatively large differential stress and there is, therefore, a definite direction of easy opening for the fractures. The fractures would

longest and most continuous runs approximately N–S. These are the oldest fractures and are crosscut by several younger sets which become progressively less continuous and less aligned as the regional stress fields responsible for their formation becomes progressively modified by the pre-existing fractures. The fracture set trending approximately NW–SE, the second set to form, shows a remarkable degree of continuity, being only affected by the N–S fractures; its orientation is related directly to the regional stress field.

However, as more fracture sets develop in the rock mass, modification of the stress orientation by the pre-existing fractures may result in there being a poor correlation between the fracture orientation and the regional stress field responsible for its formation. This is well illustrated in subarea A in Figure 15 which has been enlarged in the bottom left-hand corner of the figure. The influence of the pre-existing fractures on the orientation of the late fracturing is so marked that the later fractures display a polygonal organization and cannot be linked directly to the regional stress field responsible for their formation.

Fracture Analysis

A fracture analysis is the study of a fractured rock mass in order to: (i) establish the detailed geometry of the fracture network; (ii) determine the sequence of superposition of the different fracture sets that make up the fracture network; and (iii) deduce the stress regime associated with the formation of each fracture set. The reason why a detailed knowledge of the geometry of the fracture network is so important is that the bulk properties (e.g., strength, permeability) of a fractured rock mass (and most natural rocks are fractured) are generally determined by the fractures they contain rather than by the intrinsic rock properties.

Stages (ii) and (iii) of a fracture analysis are carried out using the principals outlined above relating to the interaction of fractures and the relationship between the stress field and fracture orientation (Figure 1).

Types of Faults a Plate Margins

The 'type' of plate margin is controlled by the relative motion of the two adjacent plates. They can be subdivided into three classes, convergent, divergent, and strike-slip. Convergent margins lead to compressional regimes at the plate margins which results in the formation of mountain belts. The stress regime is that appropriate for thrusts to form, namely a horizontal maximum principal compressive stress and a vertical minimum stress (Figure 5C). Divergent plate margins result in the formation of oceans and the separation of plates. The initial stage of this process is the fracturing of the lithosphere and the formation in the upper crust of major rift systems such as the East African Rift (*see* Tectonics: Rift Valleys). The stress regime of a horizontal minimum principal compressive stress and a vertical maximum stress is appropriate for the formation of normal faults (Figure 5A). When plates move parallel to each other at different velocities, conditions are appropriate for the formation of major wrench (strike-slip) faults (Figure 5B) such as the San Andreas Fault zone of California which separates the Pacific and North American plates.

Thus it can be seen that each of the three types of plate margins is characterized by a different types of fault.

Scale of Fracturing

Fractures occur on all scales within the Earth's crust, ranging from major faults that define plate margins, through faults that can be seen on seismic sections (*see* Tectonics: Seismic Structure At Mid-Ocean Ridges), down to faults that can be observed directly in the field, e.g, Figure 4, to microscopic fractures only visible under the microscope. Detailed studies of the microfractures in rocks at different stages of the evolution of tensile fractures show, as predicted by Griffith's theory of stress magnification (1925) outlined above, that the microfractures grow by tensile failure at the crack tips and that suitably located microfractures link to form larger fractures oriented normal to σ_3, the minimum compressive stress (*see* Tectonics: Faults).

More remarkably, when the growth of shear fractures are studied in the same way, it is found that

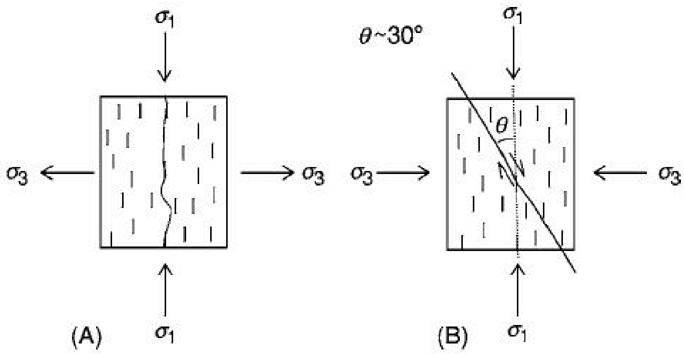

Figure 16 Randomly oriented micro fractures within a material and their growth by tensile failure and subsequent linkage to form (A) macroscopic tensile fractures and (B) macroscopic shear fractures.