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Article abstract

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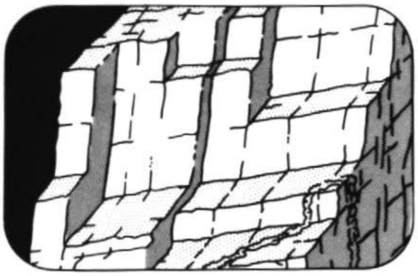

Fracture Patterns and Stresses in Granites

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Abstract
If granite bodies are to be used as receptacles for toxic waste materials, the presence or absence of barren fractures and the virgin stresses in the granite are of fundamental importance. Unfortunately, very little is known regarding the incidence of fractures, or stresses, which exist at depths (of about 1 km) in granite bodies. A simple analysis is presented of a hypothetical intrusion which indicates the magnitudes of stresses and the possible fracture development which may be expected in such bodies.

Introduction

Canadian and other authorities are currently concentrating on the use of major granitic bodies as "receptacles" for toxic waste material. It is of particular interest, therefore, to consider the fracture patterns and stress conditions which may obtain in such bodies at moderate depths (i.e., about 1 km.) below the present surface.

Studies of fractures which developed in major intrusions (Cloos, 1936; Balk, 1937, etc.) indicate the relationship between the geometry of an intrusion, its mode of intrusion and the fracture patterns which result. Such fractures are mainly concentrated in the zones of the intrusion adjacent to the country rock, where cooling of the magma progressed most rapidly. The semi-solid, crystalline "mush" which formed was the fractured in response to the continuing processes of emplacement of the still molten igneous material in the inner portions of the intrusion. The majority of the fractures formed at this time were forced open by magmatic pressure and acted as channels for the emplacement of "dykes" or "sills" within the intrusion. Thus, early fractures became completely welded and form visual discontinuities which now have little mechanical significance.

As the outer margins became cooler and stronger, the forces associated with the intrusion waned as even the central portions of the intrusion began to solidify. Fractures which developed at this later time may not be readily interpreted. Furthermore, granitic intrusions are often syn-tectonic features, so that these late fractures may often be related to adjacent tectonic events. Such late fractures are more likely to be barren and therefore of greater significance as regards toxic waste disposal. It is unfortunate, therefore, that barren fractures in granites and other major intrusions have received scant attention.

An exception to this statement is the exfoliation or "sheeting" type of fracture. Fine examples of these fractures, which are sub-parallel to the topography, are to be found in the granites of the Yosemite Park and New England. They have been studied by Jahn (1943), who has noted that the separation between fractures increases with depth of cover and that, at depths of a few hundred metres, such fractures probably cease to exist. These fractures are, therefore, of no concern when dealing with toxic waste disposal at greater depths. A similar conclusion can be reached regarding other fracture patterns (see Chapman and Rioux, 1958) which are also obviously related to topography.

Nevertheless, barren fractures in granites may exist at depth. So let us now consider how such fractures, which are not related to the mode of intrusion, to topography, or to tectonic processes, may develop at depths which are of concern to those involved with the disposal of toxic wastes in igneous intrusions.

Discussion

We shall consider the situation at point X (Figure 1) in a high level cupola of a completely hypothetical intrusion which initially had a temperature of 650°C. The country rock may consist of sediments, metasediments, or may form part of a batholith. The original depth (z) to point X is assumed to be 6 km. (This figure is, perhaps, rather small, but has been chosen because it permits one to take the ambient temperature after in situ cooling to be about 150°C. At this and lower temperatures one may, as a close approximation, regard granite and the country rock as elastic bodies.)

Let us now consider the stresses at point X which will exist 1) in the liquid state, 2) after in situ cooling and solidification and 3) during subsequent uplift and exhumation.

1) The pressure at X during the liquid magmatic stage of the intrusion will be hydrostatic and equal to the overburden pressure. Taking the average density of the cover-rock and magma to be 2.5, the magmatic pressure at X will be 1500 bars. This pressure is likely to be maintained during solidification, provided no strains are induced due to continuing intrusive activity.

2) After solidification, the cupola will cool until it reaches the assumed ambient temperature of 150°C. This cooling time will depend upon the size of the intrusion, but is unlikely to be less than 10^6 years. During this cooling phase , the potential, horizontal strains (e_c), i.e., thermal contractions, due to a temperature decrease (Θ) are given by $e_c = \Theta \alpha$, where α is the average coefficient of linear expansion. If such potential strains were realised in the

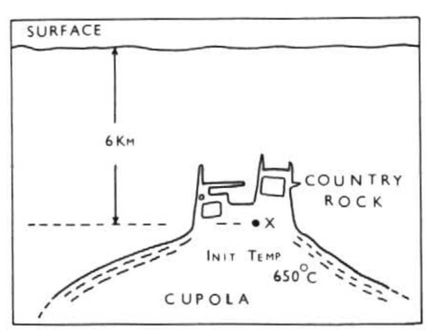

Figure 1.
Geometry of a hypothetical high level intrusion. Stress is considered for point X during cooling (see text).

elastic manner, a corresponding reduction in the horizontal stress due to cooling (σ_c) would be given by $\sigma_c = e_cE$, where E is the Young's Modulus of the solid igneous material. If we take Θ = 650° - 150° = 500°C, α = 5 x 10^{-6}°C and E = 8 x 10^5 bars, then the potential cooling strain e_c = 2.5 x 10^{-3} and the corresponding potential cooling stress is - 2000 bars. These potential cooling stresses are, of course, not realised.

It has been noted that the cooling time for the major igneous body would be at least 10^6 years (i.e., 3 x 10^{13} secs.). The potential cooling strains are 2.5 x 10^{-3}, so the average strain rate during this period of cooling would be ~ 10^{-16}/sec. One may infer from rock mechanics data (Fyfe, Price and Thompson, Chapter 8, 1978) that, in the temperature range 650° to 250°C, acid rock will flow or creep at strain rates of 10^{-16}/sec. at differential stresses of only a few tens of bars. Hence, the tendency for high differential stresses to develop will be nullified by creep and vertical strains. An element of lateral reduction in stress due to elasic strain will become progressivlely more important during cooling from 250°C to 150°C. Consequently, one may estimate that the decrease in the lateral stresses which will result from this total cooling phase is unlikely to exceed 400 bars. Thus, at this stage in the history of the igneous body, the vertical stress at X would still be 1500 bars, but the horizontal stresses could be reduced to 1100 bars.

It has also been noted that major igneous intrusions are often syntectonic. Hence, rather than experience a decrease in lateral stresses due to cooling, the lateral stresses in the igneous body may increase as a result of tectonic activity. It has been indicated (ibid) that the stronger sediments may be able to sustain differential stresses of a little over one kilobar. In general, however, it is likely that the *average* differential stress which the various rock types adjacent to an intrusion can sustain will not exceed 500 bars. Consequently, because the country rock and the intrusion will be in equilibrium, the differential stress at X is unlikely to exceed 500 bars: so that the horizontal stress will, in general, not exceed 2000 bars.

Hence, at this stage, depending upon the importance of tectonic activity, the horizontal stresses at X may be anywhere in the range between 1100 and 2000 bars. Let us now see how these stresses may be modified further during subsequent uplift and exhumation.

3) In this phase, the intrusion will experience strains and associated changes of stress due to further cooling as the cover is eroded and point X reaches higher levels in the crust, relative to the surface. Also, provided that the magnitude of the earth remains unchanged and the exhumation is accompanied by uplift, strains will also be induced at X by the changes in position of the igneous body.

The vertical stress at point X throughout uplift and exhumation is determined by gravitational loading, so that, if the cover is reduced from 6 km to (say) 1 km, the vertical stress decreases from 1500 bars to about 250 bars.

If the rock temperature decreases during this exhumation from 150°C to 25°C, the reduction in lateral stress due to cooling (125°C) during uplift is 500 bars (using α = 5 x 10^{-6} and E = 8 x 10^5 bars).

It has been shown (Price, 1966) that during simple parallel uplift (see Figure 2) there is also reduction in lateral stress (σ_u) which, as a close approximation is given by:

$$\sigma_u = \frac{-\sigma_z}{m-1} - \frac{dR}{R} E$$

where $-\sigma_z$ is the reduction in the vertical load during an uplift (dR): R is the radius of the earth, m is Poisson's Number and, as earlier, E is Young's Modulus. Given that $-\sigma_z$ is 1250 bars, dR = 5 km, R = 6400 km, E = 3 x 10^5 bars and m 6.0, then σ_u, during parallel uplift, would be 875 bars.

Hence, the total reduction in horizontal stress due to uplift and exhumation would be 500 + 875 = 1375 bars. It has been noted that the horizontal stresses after solidification and initial cooling from 650° to 150°C at 6 km., would probably be in the range 1100 to 2000 bars. So, after uplift and exhumation, the horizontal stresses should be in the range -275 to +625 bars.

The full value of -275 bars would probably not develop because a limit is set by the tensile strength of granite, which is usually in the neighbourhood of -200 bars. The probable horizontal stress range, therefore, is -200 to +625 bars.

If one assumes a further uplift and exhumation of 1 km, with the attendant temperature changes and strains, one can show that there would be a further decrease in lateral stress of approximately -225 bars. Hence, below the zone of weathering, the horizontal stress near the surface could still be as high as +400 bars. Indeed, although the mechanism is not well understood, it is the release of these high lateral stresses during the processes of weathering which are thought to give rise to the formation of exfoliation and other topography-related fractures mentioned earlier.

It is emphasized that horizontal stresses of +400 bars near the surface and +625 bars at depths of 1 km are geologically realistic, or even conservative. Thus, near Elliot Lake, Ontario, at depths of between 300 and 700 metres, horizontal stresses between 210 and 370 bars have been recorded. At Timmins the horizontal stresses at 700 to 850 metres were in the range 530 to 725 bars (Herget, 1976); while at the depths of 1200 to 1700 metres in the Sudbury Basin, the near horizontal stresses attained values between 800 and almost 1300 bars. (See Eisbacher and Bielstein, 1971, Herget, 1976, Herget *et al.* 1975; and Miles and Herget, 1976.) Some of the principal stresses

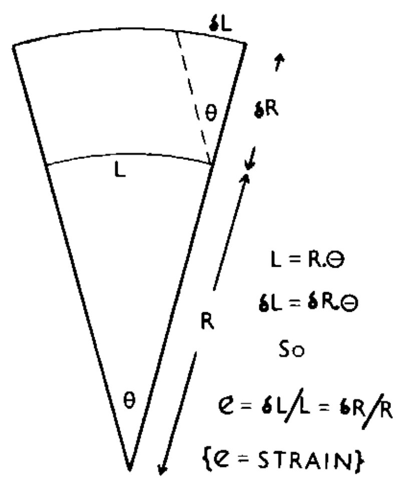

Figure 2.
Diagram illustrating stress generated by vertical uplift (see text for explanation).

determined in the measurements cited above are not horizontal and vertical, but plunge. Although these stress measurements were not obtained in granites, the rock types concerned have physical properties comparable with those of granite. It has also been noted that intrusions and country rocks are in equilibrium. Hence, when the physical properties of the various rock types are comparable, the stress too will be similar.

It will be realised that the model on which the calculations are predicted represents an extremely simple strain history, resultant upon cooling and simple parallel uplift. However, more complex forms of crustal deformation can be considered which indicate why principle stresses plunge. For example, it is known that large areas of Canada (including those in which sites for toxic waste disposal may be contemplated) are currently under-going differential uplift due to glacial rebound. Such differential uplift results in a shear strain (ϕ) and the associated shear stresses (τ) (see Figure 3), which are related by:

$$\tau / \phi = G$$

where G is the elastic shear modulus.

The shear modulus is not readily determined by direct measurement but, from linear elasticity theory, it can be expressed in terms of other elastic moduli, so that:

$$G = \frac{mE}{2(m-1)}$$

Using the values of $E = 8 \times 10^5$ bars and $m = 6.0$, it follows that $G = 4.8 \times 10^5$ bars.

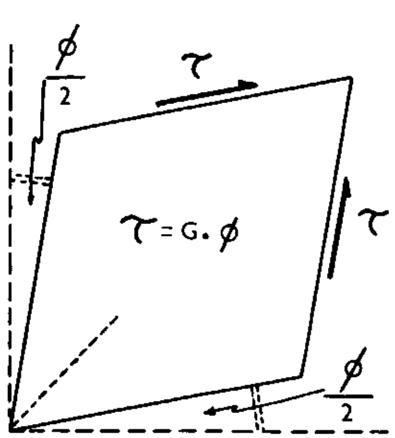

Figure 3.
Diagram showing main stress-strain terms during glacial rebound (see text).

The tilt induced by glacial rebound may reach 1/1500, i.e., ϕ is about 10^{-3} radians. Consequently, shear stresses will tend to develop as a result of this rebound with the magnitude:

$$\tau = 10^{-3} \times 4.8.\ 10^5 = 480 \text{ bars.}$$

It has been noted that, at a depth of 1 km, the vertical stress is 250 bars and the horizontal stress may fall in the range -200 to +625 bars. Using these end values, it can be seen from the stress circles A and B, Figure 4, how a shear stress of 480 bars would tend to modify the orientation and magnitude of the prinicipal stresses.

Stress circle A relates to the condition when the horizontal stress is -200 bars. If shear stresses of 480 bars were to develop, the least principal stress would attain a value of about -500 bars. As we have noted, this is far in excess of the tensile strength of about -200 bars, which would set a limit to the value of the least prinicipal stress. Consequently, one can conclude that the shear stresses would not attain a magnitude of 480 bars, but would be dissipated by the development of new fractures or the rejuvenation of existing fractures. The orientation of the maximum principal stress (σ_1) cannot, then, be uniquely defined.

Stress circle B relates to the condition when the horizontal stress in the plane of the shear strain is +625 bars. For a shear stress of 480 bars, the principal stresses would be -150 and +820 bars respectively. Thus, differential stresses of almost 1 kb. could exist in dry granite at a depth of 1 km. Moreover, the maximum principal stress will plunge at 40°. ($2\vartheta = 80°$, Fig. 4).

Fluids, and hence fluid pressures, introduced into the system by drilling or permitted to enter as a result of "cracking", which could result from the thermal effects of some toxic wastes, would certainly enhance the possibility of rock failure. For the stress situation represented by circle B, the differential stress is approximately five times the tensile strength of the rock. For such stress conditions (see Price, 1977), the resulting fracture would be a hybrid extension-shear fracture: a type of fracture which, on its development is capable of generating high energy earthquake, with its attendant dangers.

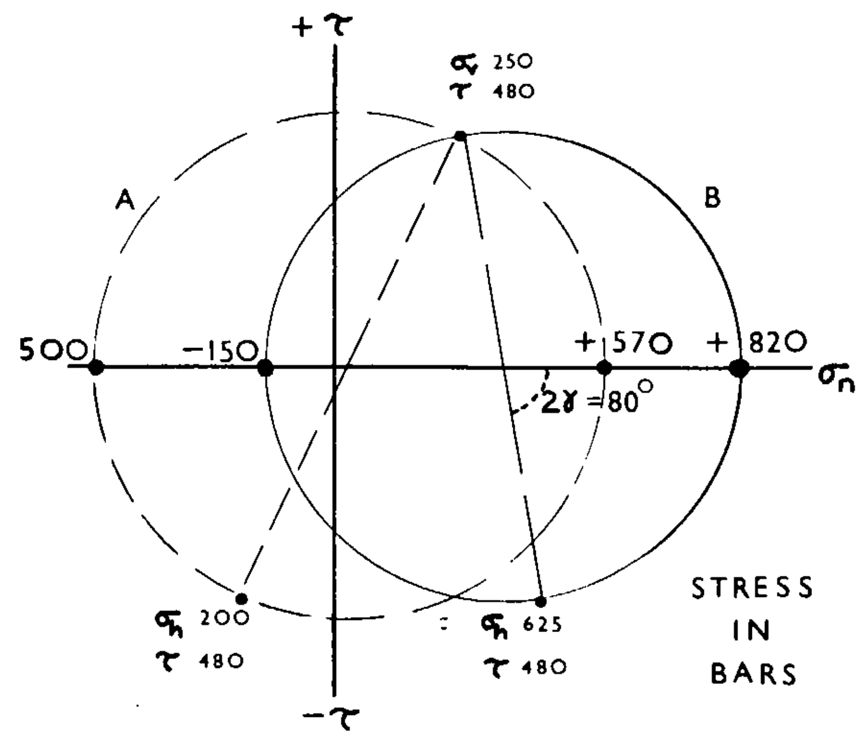

Figure 4.
Stress analysis and stress magnitude during glacial rebound (see text).

Conclusion

The arguments presented here have been extremely simplistic. The geometrical models used and the sequence of events assumed have been restricted. The single values used in the calculations for the elastic moduli have been representative; but they must vary from situation to situation depending upon exact composition, grain size etc. of specific rock types. Nevertheless, the predicted levels of stress are in agreement with those already measured in areas of Canada. From these arguments one may conclude, therefore, that sites for toxic wastes disposal in large igneous bodies could be intrinsically dangerous. In addition to current exploratory techniques, the problem requires an extensive in situ stress measurement programme and attendant studies of rock properties. Because the toxic wastes may be required to be safely contained for thousands of years in situations which involve quite large volumes of rock, relative to those normally studied in the laboratory, the rock studies should give particular emphasis to time-dependent failure and the effects of size of rock domain.

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