The upward intrusion of magma from deeper to shallower levels beneath volcanoes obviously plays an important role in their surface deformation. This chapter will examine less obvious roles that hydrothermal processes might play in volcanic deformation. Emphasis will be placed on the effect that the transition from brittle to plastic behavior of rocks is likely to have on magma degassing and hydrothermal processes, and on the likely chemical variations in brine and gas compositions that occur as a result of movement of aqueous-rich fluids from plastic into brittle rock at different depths. To a great extent, the model of hydrothermal processes in sub-volcanic systems that is presented here is inferential, based in part on information obtained from deep drilling for geothermal resources, and in part on the study of ore deposits that are thought to have formed in volcanic and shallow plutonic environments.

The material presented here is adapted from an article that I had published in the journal Economic Geology (Fournier, 1999). That article emphasized ore-forming processes that are likely to occur as a result of emplacement and degassing of magmatic bodies at relatively shallow depths in volcanic systems. Here I emphasize the deformation resulting from these hydrothermal processes and the expected variations in compositions of discharged gases. I will begin by reviewing the factors that influence the brittle–plastic transition in the Earth’s crust, emphasizing sub-volcanic or shallow plutonic conditions. I will then discuss the accumulation of exsolved magmatic fluids in plastic rock and tie together various coupled physical and chemical phenomena that result from a decrease in fluid pressure from near lithostatic to near hydrostatic in an environment of transition from plastic to brittle behavior.

10.1 THE HYDROLOGIC IMPORTANCE OF BRITTLE–PLASTIC PHENOMENA

The maximum depth of occurrence of earthquakes that result from shear failure in the crust marks the transition from brittle to plastic behavior in the lithosphere (e.g., MacElwane, 1936; Byerlee, 1968). Because the onset of plastic flow of rocks is highly dependent on temperature, it is not surprising that the bottoming of seismicity occurs at very shallow depths beneath large, hot, and presently active geothermal fields, such as The Geysers and Clearlake Highlands (California, USA) (Majer and McEvilly, 1979; Sibson, 1982), the Imperial Valley (California, USA) (Gilpin and Lee, 1978), and Yellowstone National Park (Wyoming, USA) (Smith and Braile, 1984, 1994; Miller and Smith, 1999). In addition to limiting seismic activity, the onset of plastic flow closes pre-existing interconnected pore spaces and fractures (Brace, 1972), thereby restricting the depth of circulation of meteoric water into the crust at hydrostatic pressure (pressure imparted by the weight of an overlying column of water). On the other hand, there is evidence from fluid inclusions that aqueous liquids are found deep in the crust at temperatures sufficient for rocks to behave plastically (Roedder, 1984). Petrologists and geochemists generally have assumed that, in these deep, hot environments, pore-fluid pressure ($P_f$) equals the lithostatic load or vertical stress ($S_v$) (e.g., Turner, 1981).

Many deep geothermal exploration wells in
continental crystalline rocks have encountered meteoric-derived fluids at hydrostatic pressure at temperatures up to about 350–360°C. To date, the few deep wells drilled to temperatures greater than 370–400°C either have produced gas-rich brines at greater than hydrostatic pressures or have encountered little permeability (e.g., wells discussed in Fournier, 1991). These observations indicate that the brittle-plastic transition commonly occurs at about 370–400°C within presently active continental hydrothermal systems. The well data also show that fluids at greater than hydrostatic pressure may accumulate in quasi-plastic rock, and that a narrow zone or shell of relatively impermeable material commonly separates two very different hydrologic domains.

10.2 THE BRITTLE-PLASTIC TRANSITION

10.2.1 General considerations

Figure 10.1 schematically shows the general relations for initiating failure of materials in the brittle and plastic regions of the Earth’s crust. In the brittle region, the stress difference required to cause shear failure of a pre-existing open crack increases with increasing depth, and is relatively independent of temperature, rock type, and strain rate. It is, however, highly dependent on the coefficient of friction, on the orientation of the fracture with respect to the stress field, and on pore-fluid pressure $P_f$. Commonly, $P_f$ in the crust is expressed relative to the vertical stress $S_v$ by the relation $\lambda = P_f/S_v$. For an average fluid density of 1 g cm$^{-3}$ and average rock density of 2.6 g cm$^{-3}$, $\lambda = 0.38$ for hydrostatic $P_f$ conditions. Most rocks have a coefficient of friction of about 0.6 to 0.8, according to measurements by Byerlee (1978).

In Figure 10.1, the line from the origin at zero depth through point $A$ shows the stress difference $(\sigma_1 - \sigma_3)$ required to activate fault movement on an existing open crack (a crack having no cohesive strength) that is oriented at an optimum angle of about 26 degrees to the direction of application of the maximum principal stress, when $P_f$ is assumed to equal the hydrostatic pressure. Here $\sigma_1$ is the maximum principal stress and $\sigma_3$ is the least principal stress. The stress difference required to cause shear failure increases dramatically when the direction of the maximum principal stress, with respect to the plane of the fracture, departs by more than 5 to 10 degrees from an optimum angle of about 26 degrees (Sibson, 1985, 1990). When all the existing fractures are unfavorably oriented with respect to the direction of the maximum principal stress, increasing the stress difference may overcome the cohesive strength of the rock and cause a new crack to develop at an optimum angle before the stress difference becomes great enough to cause shear failure along any of the unfavorably oriented pre-existing open fractures (Sibson, 1985). Also, in the event that an optimally oriented fracture regains cohesive strength as a result of cementation by vein formation, a greater stress difference is required to cause shear failure than would have been required before cementation. For example, in Figure 10.1 the dashed line from point $N$ through point $A'$ shows the stress differences versus depth required to renew shear failure when $\lambda = 0.38$ along a fracture that has cohesive strength given by point $N$.

In contrast to the conditions for brittle failure, the stress difference required to initiate plastic deformation is highly dependent on temperature, strain rate, and rock type (material constants), and it is little affected by confining pressure. However, the presence of water allows plastic behavior at lower temperatures compared with the behavior of dry rock (Carter and Tsenn, 1986).