GEOLOGICAL IMPLICATIONS

The high pressures required to form kyanite stably, which were an unexpected result of the previous work (Clark, Robertson, and Birch, 1957), are substantiated by the present study. Temperatures of a few hundred degrees seem to be required to produce regional metamorphism, which means that a pressure of 7 to 10 kilobars is roughly the minimum compatible with stable formation of kyanite in nature.

Depths of burial are commonly related to pressure by $P = \bar{\rho}\, gh$, where $\bar{\rho}$ is the mean density between the surface and depth h, and g is the gravitational acceleration. The scale at the top of figure 3 has been calculated for $\bar{\rho}$ equal to 2.67 gm/cm^3 in the crust and 3.33 gm/cm^3 in the mantle. A depth of more than 35 km is required to reach a pressure of 10 kilobars; this implies that kyanite schists formed at depths equivalent to those towards the base of the "normal" sea-level crust, on this model. This conclusion does not follow if the phase boundary has appreciable curvature at high temperatures, but such behavior, although not impossible, is certainly improbable.

If kyanite-bearing rocks are to be formed at depths in excess of 20 km, large vertical movements must have taken place in the past. Such large amplitudes of motion might accompany the formation of a major mountain root, but they seem unlikely to result from less extreme orogenic episodes. The depth required for the stable formation of kyanite in a mountain root may be greater than that required elsewhere because of the high temperatures that may exist in a thickened crust (Birch, 1950; Clark and Niblett, 1956). This could lead to the formation of zones of kyanite-bearing rocks near the margins of the root, with sillimanite in the central, hot portion. This is the spatial distribution of the aluminosilicates found in New Hampshire, for example (Billings, 1956).

These great depths of burial can be escaped, or at least lessened, if pressures in the crust are sustained by the strength as well as the weight of the overlying rock. The mere existence of deformation in metamorphic terrains implies that stress differences exceeded the strength of the rocks, and the nature of the deformation suggests that the stresses causing it were compressive relative to $\bar{\rho}\, gh$ rather than tensile. This implies that the mean of the principal stresses at times exceeds $\bar{\rho}\, gh$. The magnitude of this "tectonic overpressure" is set by the strength of the rocks that support it.

A rough notion of how large the overpressure may become may be obtained from a simple model. Consider a small spherical cavity in the Earth inside which the pressure is P, and suppose that the stress due to the weight of the overlying rock is simply a hydrostatic pressure. In this case the stress difference in the rock surrounding the cavity is zero when $P = \bar{\rho}\, gh$. We now calculate the largest value of $P_E = P - \bar{\rho}\, gh$ allowed by the strength of the wall rock. P_E can be identified with the maximum tectonic overpressure in that it is the maximum mean stress that can be contained. No account of the origin of this pressure is given. It is assumed that tectonic forces do in fact build up the maximum tolerable pressures, and that they are relieved by yielding of the rocks, probably mainly in the vertical direction.

If the wall rock behaves as a perfectly plastic material obeying the Tresca yield criterion (which in this case states that the maximum stress difference cannot exceed Y, the yield point in simple tension), the maximum permissible value of P_E is (Hill, 1950, p. 104):

$$P_E = 2/3\ Y \ln\ (E/3(1-\sigma)Y).$$

If Poisson's ratio, σ, is set equal to 1/3, and Young's modulus, E, is taken to be 500 kilobars (Birch, Schairer, and Spicer, 1942), P_E is found to be 3.7 kilobars if $Y = 1$ kilobar and 0.52 kilobars if $Y = 0.1$ kilobar. If plastic flow is not allowed in the wall rock, $P_E = 2/3\ Y$, a result which is identical to that obtained by Birch (1955) from a different argument.

Griggs, Turner, and Heard (1960) have observed tensile strengths greater than 1 kilobar in several rocks at 5 kilobars confining pressure and 800°C. As these authors are careful to point out, however, the experimental results refer to rates of strain that may exceed those occurring in nature by a factor as large as 10^{12}. This implies that the strengths of rocks may be substantially smaller under natural conditions than under the conditions of these laboratory tests. This problem is complicated by recrystallization. The strength of a rock under natural conditions may be determined by the relative rates of deformation and recrystallization.

An overpressure persisting for only a few thousand years, a time that is short geologically speaking, could significantly affect the mineralogy of the rock. A value of Y of a few hundred bars might persist for short times during active deformation; this leads to overpressures of 1 kilobar or more. Since 1 kilobar corresponds to the weight of nearly 4 km of overburden in the crust, the reduction in the depth of burial required may be considerable.

Evidence of the existence of tectonic overpressures in rocks, other than the fact that deformation takes place, is usually indefinite. No clearcut distinction between tectonic pressure and deep burial can be made in most regionally metamorphosed terrains, because no way of determining depth independently of pressure has been found. Estimates based on thickness of strata are vitiated by tectonic thickenings and thinnings of unknown magnitude. Although distorted crystals of kyanite are common, they only show that deformation followed growth. It may also have accompanied it, but there is no proof of this. An unusual local occurrence of kyanite is in the contact aureoles of granitic bodies in SW Ankole. Combe (1932) noted that kyanite occurs in the schists only where they have been strongly deformed by the forceful emplacement of the granites.

The hypothesis of tectonic overpressures represents a return to the stress mineral concept of Harker but in modified form. Harker supposed that the fields of stability of minerals were influenced by shear. This idea has fallen into disrepute in recent years, both on theoretical grounds (Verhoogen, 1951; Macdonald, 1957) and because of the occurrence of stress minerals in rocks that show little or no evidence of deformation (Miyashiro, 1949, 1951). Tectonic overpressures provide a different reason for "stress minerals" (most of which are in reality high-pressure minerals) to be associated with shear. In the present view, shearing stresses make possible an increased mean principal