

in New Hampshire and in the southeast Scottish Highlands. It would not be observed if the metamorphism resulted from deep burial in a region in which the geothermal gradient was everywhere the same and was "normal" in the sense that its curvature was as shown in figure 3. Horizontal gradients of temperature, pressure, or both during metamorphism are required to account for this distribution of kyanite and sillimanite. The existence of such horizontal gradients has previously been deduced from field studies (Harker, 1939, p. 185).

Field studies have revealed a "complete absence of kyanite from aureoles of thermal metamorphism" (Harker, 1939, p. 151), although sillimanite and andalusite are often found near the contacts of intrusive rocks. It appears that there is no known example of an igneous rock emplaced at sufficiently high pressure (and sufficiently low chemical potential of water) to make kyanite stable at the temperature prevailing in the wall rock. Once this temperature is better known, an upper limit to the pressure at which igneous rocks are known to solidify can be determined from the kyanite-sillimanite curve.

Syntectonic granites occurring in rocks in which kyanite had previously been formed through regional metamorphism are of special interest. Kyanite is never observed to persist up to the contacts, although sillimanite is characteristically present. This implies that a region of relatively high temperature or relatively low pressure existed near the contacts; the first alternative is a natural consequence of the emplacement of magma. The second alternative, which would be preferred by transformists, may require unlikely stress distributions.

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REFERENCES

- Eitel, Wilhelm, 1954, *The physical chemistry of the silicates*: Chicago, Univ. of Chicago Press.
- Gibbs, R. E., 1926, Structure of α -quartz: *Royal Soc. London Proc., Ser. A*, v. 110, p. 443-455.
- Griggs, D. T., and Kennedy, G. C., 1956, A simple apparatus for high pressures and temperatures: *AM. JOUR. SCI.*, v. 254, p. 722-735.
- Harker, Alfred, 1939, *Metamorphism*: London, Methuen & Co. Ltd.
- Heitanen, Anna, 1956, Kyanite, andalusite, and sillimanite in the schist in Boehls Butte Quadrangle, Idaho: *Am. Mineralogist*, v. 41, p. 1-27.
- Hey, J. S., and Taylor, W. H., 1931, The coordination number of aluminum in the aluminosilicates: *Zeits. Krist.*, v. 80, p. 428-441.

- Kelley, K. K., 1949, Contributions to the data on theoretical metallurgy. X. High-temperature heat-content, heat-capacity, and entropy data for inorganic compounds: U. S. Bur. Mines Bull. 476.
- , 1950, Contributions to the data on theoretical metallurgy. XI. Entropies of inorganic substances: U. S. Bur. Mines Bull. 477.
- Kennedy, G. C., 1955, Pyrophyllite-sillimanite-mullite equilibrium relations to 20,000 bars and 800°C: *Geol. Soc. America Bull.*, v. 66, p. 1584.
- Kerr, E. G., Johnston, H. L., and Hallett, N., 1950, Low temperature heat capacities of inorganic solids. III. Heat capacity of aluminum oxide (synthetic sapphire) from 19° to 300° K: *Am. Chem. Soc. Jour.*, v. 72, p. 4740-4742.
- Kubaschewski, O., and Evans, E., 1956, *Metallurgical thermochemistry*: London, Pergamon Press.
- MacDonald, G. A., and Merriam, R., 1938, Andalusite in pegmatite from Fresno County, California: *Am. Mineralogist*, v. 23, p. 588-594.
- Miyashiro, Akiho, 1949, The stability relation of kyanite, sillimanite and andalusite, and the physical condition of metamorphic processes: *Geol. Soc. Japan Jour.*, v. 55, p. 218-223.
- Naray-Szabo, St., Taylor, W. H., and Jackson, W. W., 1929, The structure of cyanite: *Zeits. Krist.*, v. 71, p. 117-130.
- Palache, Charles, Berman, Harry, and Frondel, Clifford, 1944, *Dana's system of mineralogy*, vol. 1: New York, John Wiley & Sons.
- Robertson, E. C., Birch, F., and MacDonald, G. J. F., 1957, Experimental determination of jadeite stability relations to 25,000 bars: *AM. JOUR. SCI.*, v. 255, p. 115-137.
- Roy, D. M., 1954, Hydrothermal synthesis of andalusite: *Am. Mineralogist*, v. 39, p. 140-143.
- Taylor, W. H., 1928, The structure of sillimanite and mullite: *Zeits. Krist.*, v. 68, p. 503-143.
- , 1929, The structure of andalusite: *Zeits. Krist.*, v. 71, p. 205-218.
- Thompson, J. B., 1955, The thermodynamic basis for the mineral facies concept: *AM. JOUR. SCI.*, v. 253, p. 65-103.
- Todd, S. S., 1950, Heat capacities at low temperatures and entropies at 298.16° K of andalusite, kyanite, and sillimanite: *Am. Chem. Soc. Jour.*, v. 72, p. 4742-4747.
- Wyckoff, R. W. G., 1926, The crystal structure of the high temperature (β) modification of quartz: *AM. JOUR. SCI.*, 5th ser., v. 11, p. 101-112.

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