Parental Magmas for all Plutonic Bodies Were and Must Have Been Wet!

Rais Latypov

Geological Institute, Kola Science Centre, Apatity, 184200, Russia (Present address: Institute of Geosciences, P.O. Box 3000, FIN – 90014, University of Oulu, Finland)
; e-mail: Rais.Latypov@oulu.fi

It is widely believed that crystallization of natural magmas mostly occurs under anhydrous conditions; fluid-saturated conditions are considered to only be significant during the latest stages of magmatic differentiation. There is, however, an opposing opinion that nearly all plutonic bodies start to form in conditions close to fluid phase saturation (Cann, 1970; Fife, 1970; Dubrovskii, 1984, 1993; Latypov and Chistyakova, 2001). The idea comes from topology of anhydrous and water-saturated solidus-liquidus lines of the natural silicate systems on the P-T diagram (Fig. 1A). Anhydrous silicate melts always have solidus-liquidus lines with positive slopes. Water-bearing silicate melts have solidus-liquidus lines with negative slopes at low pressure when the system contains enough water to saturate the liquid. When all available water in the system has dissolved in the liquid, the solidus-liquidus lines adopt positive slopes. The behavior of dry, low and high water-content parental magmas during ascent towards the earth's surface is distinctly different. A dry melt X^1 will reach the surface and erupt as lava at Z well above its solidus and clearly without volatile exsolution during ascent (Fig. 1B). A melt X^2 with low water content, say, 0.5 wt. % (Fig. 1C) will rise and begin to lose water near Y where it crosses a vesiculation isopleth of the melt and will erupt at Z with volatile exsolution. A melt X^3 with a relatively high amount of water, say, 4 wt. % (Fig. 1D) will rise and begin to lose water near Y where it crosses a vesiculation isopleth of the melt and will start to crystallize on a liquidus-solidus line at Z (Fife, 1970). If the densities of the host rocks and the magma at Z prove to be similar, the latter will cease to rise and start to form a plutonic body. It is widely accepted that dissolved volatiles, dominated generally by H_2O, are present in nearly all terrestrial magmas (Johnson et al., 1994). Therefore it seems inevitable that all types of magmas giving rise to plutonic bodies must exsolve water as a separate phase during ascent and will begin to crystallize as water-saturated melts when reaching their liquidus-solidus. There is only one possibility for magma to escape water-saturated conditions of crystallization. The rising superheated magma must be arrested physically during ascent, say, at point K (Fig. 1D) and then slowly cooled to point M on the solidus (an interval of cooling of about 100^oC) where it starts to crystallize with the absence of a separate fluid phase. However, one can hardly observe a plutonic body that is formed from such magma because it will remain at considerable depth.

Another important inference, which can be drawn from the P-T diagram, regards the relationship between lithostatic pressure (or dry, P_{dry}) and water pressure (P_{H2O}) (Fig. 2A). It is demonstrated (Dubrovskii, 1984) that P_{H2O} can be either equal or higher than P_{dry} but it can never be less than P_{dry}. The latter is related to the dissolubility of volatiles in silicate melts that is dependent on P_{dry}. One cannot speak about P_{H2O} if all volatiles dissolved in the melt are under a certain value of P_{H2O}. In this situation corresponding to the ascent of magma from the place of generation up to the vesiculation isopleth, magma is under lithostatic pressure. Upon reaching the vesiculation isopleth, where a melt becomes water-saturated and fluid exsolves in the form of a separate phase, P_{dry} becomes equal to P_{H2O} ($P_{dry} = P_{H2O}$). An increase in the amount of fluid phase during the magma's ascent towards the earth's surface will provide the rise in fluid pressure P_{H2O}. The fluid pressure during magma ascent will increase in contrast to the lithostatic pressure that will decrease. The isochoric crystallization of magma that starts upon its reaching the liquidus-solidus line will bring a further increase in P_{H2O}. Only the loss of volatiles from a magmatic chamber can change the situation when fluid pressure is higher than lithostatic pressure. There are abundant examples in petrological literature which indicate that crystallization of magma in the chamber occurred, say, at $P_{dry} = 4kbar$ and $P_{H2O} = 0.5$ kbar. It follows from the above that such inferences make no sense. Magma can be either under lithostatic pressure when subjected to the external pressure of overlying rocks, or under fluid pressure when subjected to the internal pressure of gas bubbles (Fig. 2B). There is no intermediate position between these two extreme cases.

The acceptance of the idea that nearly all plutonic bodies start to crystallize under conditions close to fluid saturation has a critical significance for the estimation of P-T conditions of crystallization of basic plutonic bodies (Fig. 3). The point is that the approximate value of fluid pressure (P_{H2O}) under which crystallization of magma in plutonic bodies takes place can safely be estimated by the use of amphibole. The coexistence of amphibole with a silicate melt requires that there is a considerable amount of dissolved water in the melt. The solubility of water in a silicate melt is strongly pressure-dependent. The existence of amphibole can therefore constrain the pressure of crystallization of magmatic bodies (Hanski, 1992; Dubrovskii, 1993). The minimum fluid pressure at which amphibole appears on the liquidus in a basaltic system has yet to be determined accurately,

but the most reasonable estimate is no more than 1-1.5 kbar (Yoder and Tilly, 1962; Condliffe, 1976; Spulber and Rutherford, 1983, Dubrovskii, 1993). Thus, the rare occurrence of cumulus amphibole in the most basic intrusions can be used to indicate that they crystallized at a fluid pressure of less than 1-1.5 kbar that, in turn, constrains the temperature range to 950-1050°C (Fig. 3).

Thus, three principle conclusions can be drawn from the presented P-T diagrams (Figs. 1-3): 1. Nearly all plutonic bodies start to crystallize under fluid (water) pressure and with the presence of a separate fluid phase. 2. Magma can be either under external lithostatic (dry) or internal fluid pressure. There is no intermediate position between these two extremes. 3. Basic intrusions lacking cumulus amphibole crystallized at a fluid pressure of less than 1-1.5 kbar.
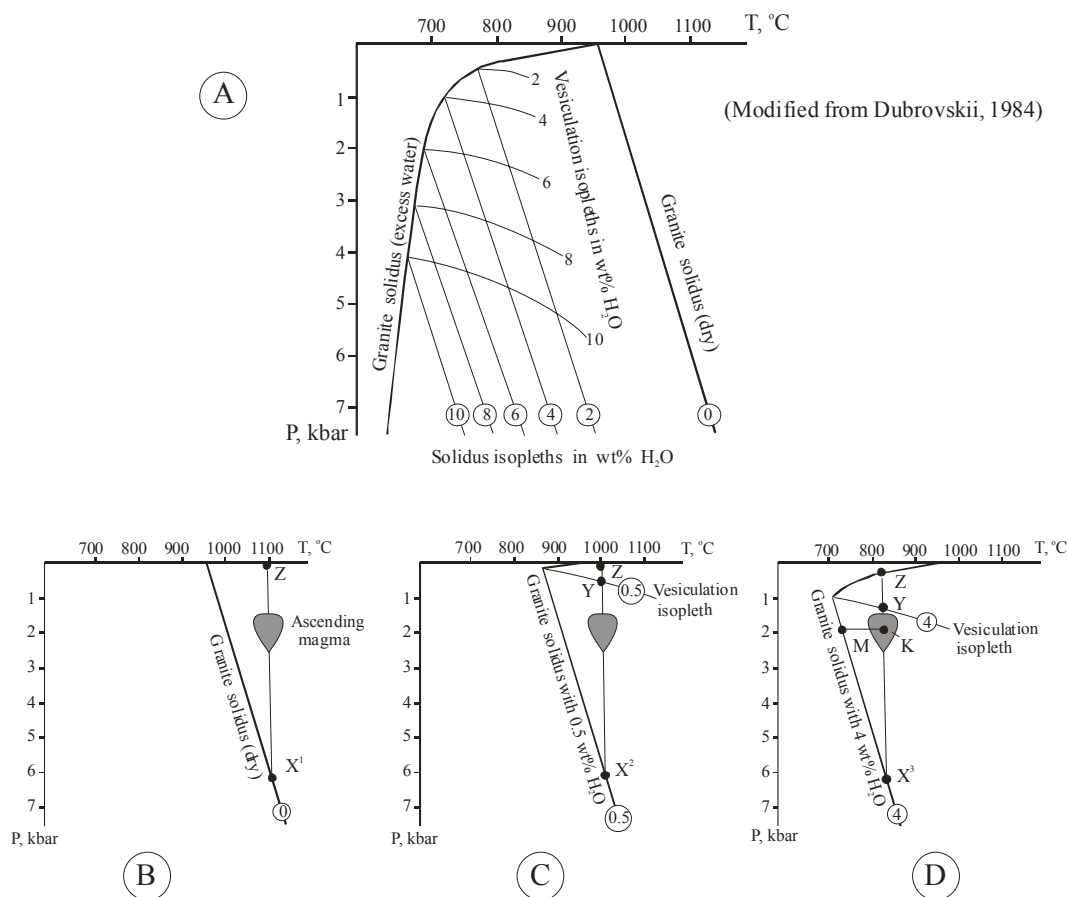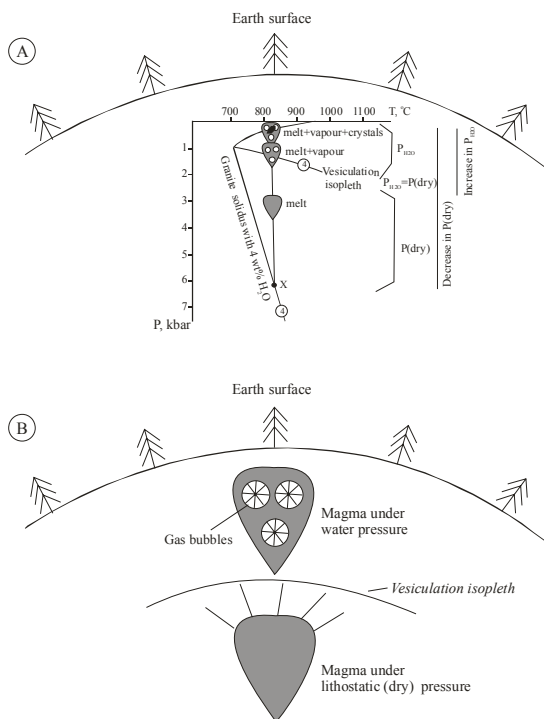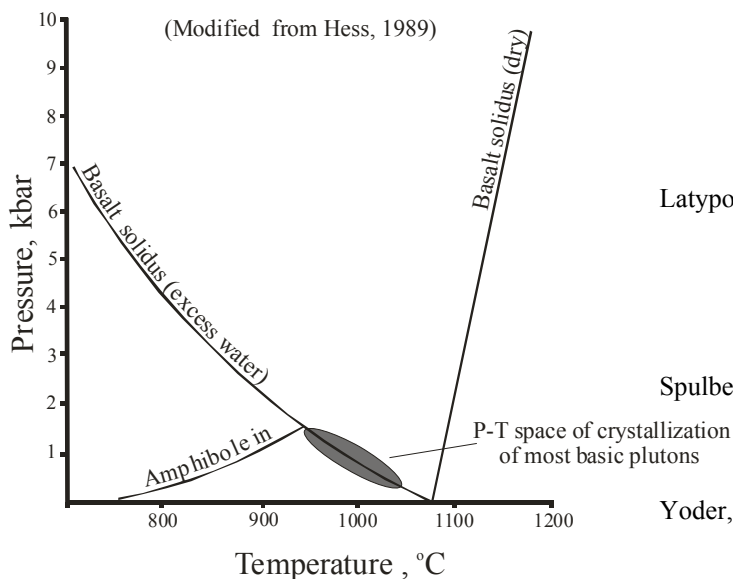

Figure 1.

Figure 2.

(Modified from Hess, 1989)

Figure 3.

References

Cann, J. R., 1970, Upward movement of granitic magma: Geological Magazine, v. 107, p. 335-340.

Condliffe, E., 1976, Melting relationships of selected rocks of dioritic mineralogy: Progress in Experimental Petrology, v. 3, p. 54-55.

Dubrovskii, M. I., 1984, Granite systems and granites. St. Petersburg, Nauka, 352 pp. (in Russian).

Dubrovskii, M. I., 1993, Physicochemical (P (H2O) - T – X) Models for the Crystallization of Magmatic Olivine-normative Rocks with a Standard Alkalinity: St.-Petersburg, Nauka, 215 pp. (in Russian).

Fife, W. S., 1970, Some thoughts on granitic magmas: In Newall, G., Rast, N. (Eds.), Mechanism of Igneous Intrusion. Liverpool, Gallery Press, pp. 201-216.

Hanski, E. J., 1992, Petrology of the Pechenga ferropicrites and cogenetic, Ni-bearing gabbro-wehrlite intrusions at Pechenga, Kola Peninsula, Russia: Geological Survey of Finland Bulletin 367, 192 pp.

Hess, P. C., 1989, Origin of igneous rocks: Harvard University Press. Cambridge, Massachusetts.

Johnson, M. C., Anderson, A. T., Jr., and Rutherford, M. J., 1994, Pre-eruptive volatile contents of magmas: In Carroll M. R., Holloway J. R. (Eds.), Volatiles in Magmas. Mineralogical Society of America, Reviews in Mineralogy 30, p. 281-330.

Latypov R. M., and Chistyakova S. Yu, 2001, Physico-chemical aspects of magnetite gabbro formation in the layered intrusion of the Western Pansky Tundra, Kola Peninsula, Russia: Petrology, v. 9, p. 25-45.

Spulber, S. D. and Rutherford, M. J., 1983, The origin of rhyolite and plagiogranite in oceanic crust: An experimental study: Journal of Petrology, v. 24, p. 1-25.

Yoder, H. S. and Tilley, C. E. (1962). Origin of basalt magmas: an experimental study of natural and synthetic rock systems: Journal of Petrology, v. 3, p. 342-532.