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WATER AND MAGMA GENESIS: THE ASSOCIATION HYPERSOLVUS GRANITE—SUBSOLVUS GRANITE

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ABSTRACT

Suites emplaced in environments of extensional tectonics are bimodal, characterized by the associations gabbro-granite or alkali gabbro-syenite (or volcanic equivalents). Felsic differentiates are commonly calcium-poor and have hypersolvus mineralogy, i.e., the alkali feldspars form by exsolution of one primary feldspar. This textural evidence and the common association with rhyolites and granophyres in specific complexes examined suggest that crystallization occurred at shallow levels, from melts relatively poor in dissolved water. Field studies also document the late appearance of subsolvus granites, in which the two feldspars form discrete grains, indicative of higher $P(H_2O)$. We propose that a late influx of water, possibly of meteoric origin, "soaked" the cooling hypersolvus granite once crystallized, inducing local near-complete fusion and remobilization of the early granite. No reheating need be implied as the "dry" solidus is even higher than the "wet" liquidus. At lower temperatures, the influx of water would be reflected in deuteric changes: alteration of mafic mineral assemblages, precipitation of late albite, replacement of pre-existing feldspars by albite, and local increase in degree of order of K-feldspar. The influence of surrounding supracrustal rocks is expressed by selective contaminations in elements carried by the convecting fluid phase. If the process occurs entirely below the "wet" solidus of the pertinent rocks, the protracted hydrothermal events can lead to economically valuable concentrations of incompatible elements.

SOMMAIRE

Les suites ignées typiques des zones de tectonique d'extension sont bimodales, caractérisées par l'association gabbro-granite ou gabbro alcalin-syénite (ou équivalents volcaniques). Les unités différenciées sont appreauvries en calcium et possèdent une minéralogie hypersolvus, i.e., les feldspaths alcalins sont formés par exsolution d'un feldspath primaire. Cet indice textural et l'association commune avec rhyolites et granophyres soulignent que la cristallization s'est déroulée à faibles profondeurs, à partir d'un magma relativement sec. A un stage tardif de l'évolution d'un complexe apparaissent des granites subsolvus, dans lesquels les deux feldspaths forment des grains séparés, ce qui indique des valeurs de $P(H_2O)$ plus grandes. Nous pensons que l'eau (météorique ?) est entrée dans le système sec, celui qui a donné les roches hypersolvus, et l'a humecté, ce qui a causé fusion presque totale et remobilisation des granites précoces. Un réchauffage n'est pas nécessaire, vu que le solidus "sec" est plus élevé encore que le liquidus "trempe". A des températures plus basses, cette addition d'eau se traduirait par des changements deutériques: altération des minéraux mafiques, précipitation d'albite tardive, albitisation de feldspaths pré-existants, et augmentation du degré d'ordre du feldspath potassique. L'influence des roches supracrustales environnantes s'exprime par la contamination sélective d'éléments apportés par la phase aqueuse en convection. Si ces événements se passent entièrement au-dessous du solidus "trempe" des roches différenciées, les phénomènes hydrothermaux échelonnés peuvent causer des concentrations importantes d'éléments incompatibles.

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INTRODUCTION

Modern igneous petrology has been undergoing a quiet revolution in recent years: what has emerged as being of prime importance in discussions bearing on the origin and evolution of terrestrial magmas is without doubt the question of availability of water. Also of vital importance is the evolutionary stage at which water becomes available. Clearly, different petrogenetic effects are to be expected in the two extreme cases, one in which water is plentiful at the site of partial melting, and the other in which water interacts only at a later stage, during the emplacement and cooling of an initially relatively dry magma. For example, Kushiro (1972) and Mysen & Boettcher (1975) have stressed the importance of having water available at the site of partial melting of mantle peridotites to explain the production of silica-oversaturated magmas. The hydrous, relatively calcic and aluminous basic liquids so formed appear to originate in the disturbed upper-mantle environments located directly above dipping Benioff zones of subduction; they can be considered parental to the orogenic (i.e., calc-alkaline) suites we find exposed on the earth's surface in loci of crustal shortening.

It appears most unlikely that hydrous magmas will ascend from a mantle source without freezing (Cann 1970); none of the primary wet liquids formed in the mantle can be expected to be exposed now in orogenic belts, except perhaps in nascent island arc systems where oceanic crust is thin and highly fractured. This suggests in turn that the observed rocks in orogenic belts have been derived by a complex of processes that may have included fractionation of amphibole and magnetite (Boettcher 1973) from primitive basic liquids in the mantle, and successive refusions of magmatic precipitates at various levels above the zone of original partial melting. Martin & Piwinskii (1976) have proposed that the products of each freezing episode, as the magma crosses the "wet" solidus, are subjected to an on-going stream of hydrothermal fluids, largely released from the downgoing slab of metabasaltic oceanic crust. These fluids bring toward the surface a complement of solutes, largely Na, K, Si, Al, that can be expected to interact with the hot, crystalline products of "pressure"-quenched melts. There results a gradual metasomatic transformation of the hot plutonic rock into a bulk composition progressively more enriched in felsic constituents, and thus having a lower melting point. As the ascending fluid phase transfers heat as well as matter, and because the composition of the partial melt is becoming more and more granitic as lower and lower pressures are encountered (Piwinskii 1973), we expect that the magmas formed in this manner in the upper crust will have been through the greatest number of these cycles, and will consequently be more evolved and more water-rich (Martin & Piwinskii 1976). The ease with which water migrates along intercrystalline paths and the slow rates of diffusion of water through viscous melts of dioritic, granodioritic, or granitic composition (Shaw 1974), combine to support the suggestion that wet melts must freeze episodically during their diapiric ascent. The role of supracrustal continental rocks in the generation of calc–alkaline felsic liquids is viewed as purely accidental; most of the elements that make up calc–alkaline magmas here come from the mantle, though they ultimately may have entered the mantle in the dipping lithospheric plate. The role of crystal settling is largely conjectural, and is usually not supported by direct observations of accumulated crystalline phases.

In this paper, we focus on a different kind of suite, one which typically occurs in areas of crustal extension, and in which the appearance of water may occur only towards the end of crystallization history of mantle-derived basic liquids. Such non-orogenic suites (Martin & Piwinskii 1972) may or may not be differentiated. If differentiated, such as in central volcanic complexes, the basic rocks typically follow an iron-enrichment trend, and the felsic differentiates are also iron-enriched, magnesium-depleted. Compositional intermediates between gabbro and granite or syenite constitute but a minor volume of the total complex in most cases. Indices of hybridization can usually be found to account for some of the iron- and titanium-enriched intermediates. We address ourselves here specifically to the felsic members of differentiated non-orogenic complexes, in the hope of relating the observed development in time of textural and mineralogical variants to the important topic of availability of water and magma genesis. In particular, we wish to explain the common but unexpected close association in a single igneous complex of differentiates of hypersolvus *and* subsolvus character.

HYPERSOLVUS VS. SUBSOLVUS NON-OROGENIC DIFFERENTIATES

The felsic differentiates of non-orogenic suites are distinctly lime-poor and magnesium-deficient (Martin & Piwinskii 1972; Bowden 1974). What calcium there is in the rock is usually partitioned between hedenbergitic clinopyroxene, amphibole, fluorite and feldspar.

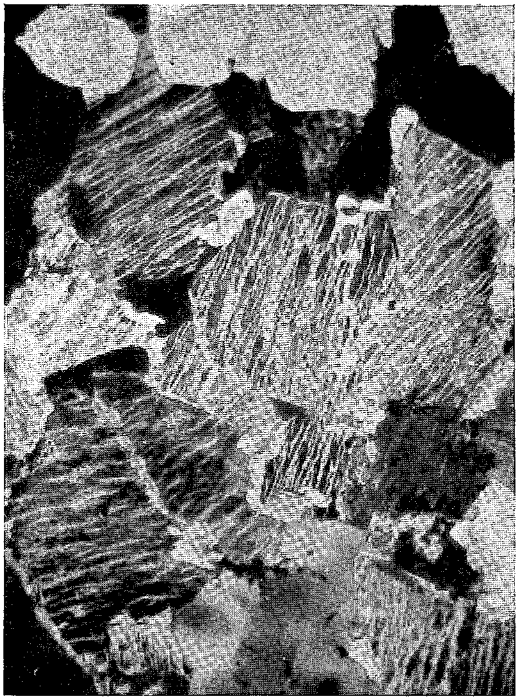


FIG. 1. Typical textural development of alkali feldspars in a hypersolvus granite from Corsica. Alkali feldspars consist of coarsely perthitic microcline (Bonin & Martin 1974b). The albite that borders perthite grains may be largely of hydrothermal origin. Other minerals include quartz, hastingsite, and fayalite. Average grain size: 7 mm. McGill petrology collection number IN8.

Because of this trait, the rocks can readily be interpreted and classified in terms of features in the systems $NaAlSi_3O_8$–$KAlSi_3O_8$–H_2O and $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O. Whether or not the solvus and the solidus were separated by a temperature interval in which a single feldspar was thermodynamically stable seems to be the central issue. Tuttle & Bowen (1958, p. 129) first proposed this scheme of classification for those nepheline syneites, syenites, and granites whose compositions place them in or near "petrogeny's residua system", the system $NaAlSiO_4$–$KAlSiO_4$–SiO_2.

Tuttle & Bowen (1958) proposed two broadly different categories of low-calcium felsic plutonic rocks; these are usually, but not necessarily, non-orogenic in character. *Hypersolvus* rocks are characterized by the absence of an albitic plagioclase except as a component of perthite. *Subsolvus* rocks are characterized by discrete grains of K-feldspar and quartz. Figures 1 and 2, taken at the same magnification and showing genetically related rocks, demonstrate well the characteristic contrast in texture and grain size: subsolvus rocks are commonly finer grained than related hypersolvus rocks. Intermediates, called *transsolvus* by Bonin (1972), are recognized between the two extremes. They imply an interruption in crystallization history, to be discussed in a later section.

A combination of experimental and field evidence, to be reviewed herein, has suggested to most users of this classification that hypersolvus rocks are expected from relatively dry liquids in near-surface environments, whereas subsolvus felsic plutonic rocks formed from wetter liquids crystallizing at deeper crustal levels. Yet, granites of hypersolvus and subsolvus character are commonly associated in the same non-orogenic complex; specific examples follow.

SELECTED EXAMPLES OF THE ASSOCIATION

The Cape Ann plutonic series, Massachusetts, of late Ordovician age (Zartman & Marvin 1971)

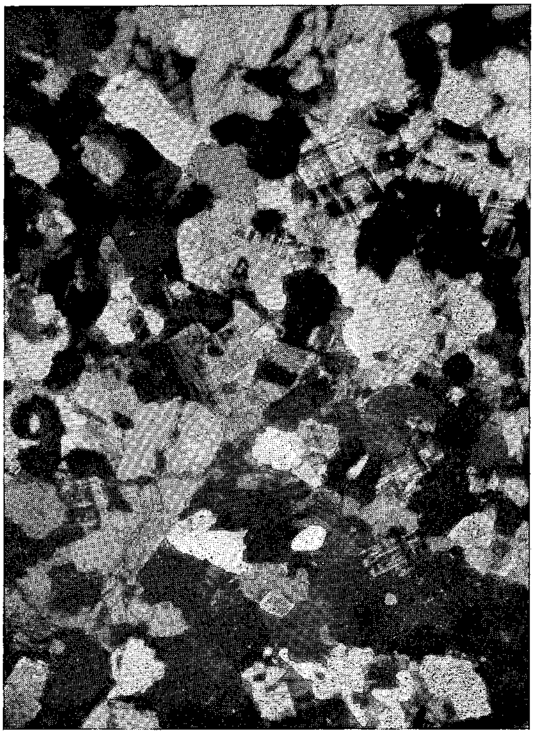


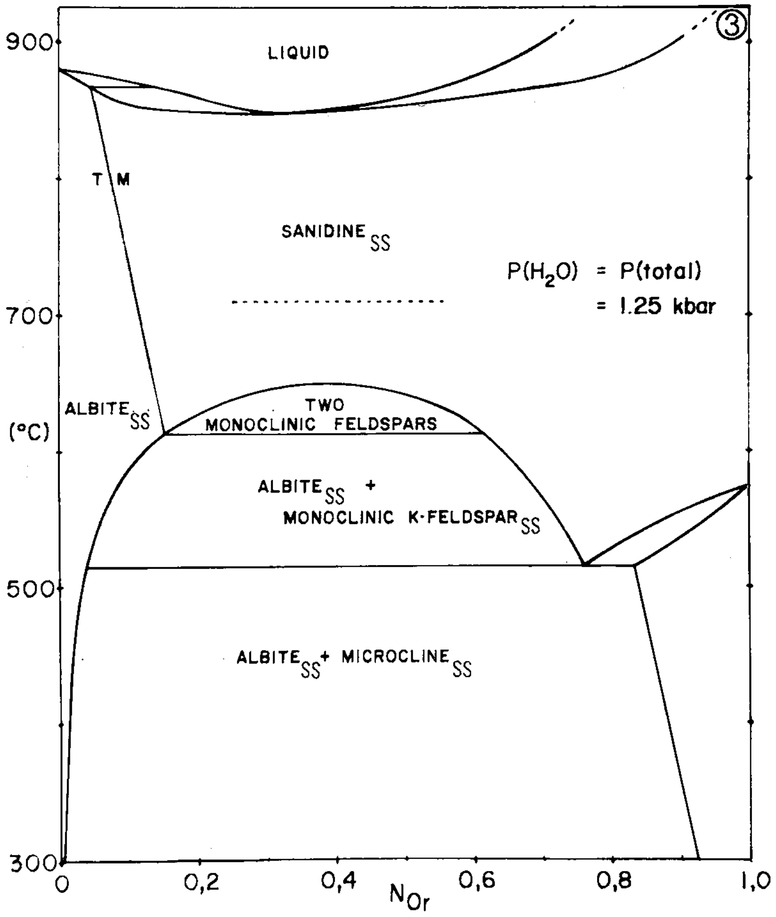
FIG. 2. Typical textural development of alkali feldspars in a subsolvus granite from Corsica. Alkali feldspars consist of non-perthitic microcline showing excellent cross-hatch pattern, and albite as discrete grains. Bulk composition of this biotite-bearing granite is very similar to that of rock in Figure 1. Average grain size 1 mm. McGill petrology collection number IN13.

consists of comagmatic gabbro, syenite, and granite that define a bimodal distribution of basic and felsic rock types characteristic of non-orogenic suites. Superb coastal exposures have led to detailed descriptions of textural variants and their mutual intrusive relationships. They have also afforded valuable insight into the intricate chain of events attending the cooling of a typical non-orogenic plutonic suite. At Andrew's Point, the predominant Cape Ann grey to yellowish hypersolvus granite (Fig. 1) contains large rafts of nordmarkitic granite (Warren & McKinstry 1924, Plate II), that locally had been cut by basic dykes. The medium- to coarse-grained Cape Ann granite and its compound inclusions are cut by fine-grained subsolvus granite (Fig. 2) and associated pegmatites and aplites. Warren & McKinstry (1924, p. 320) suggested that a facies of this late fine-grained granite was itself cut by basic dykes, now dismembered by movement of the partly solidified host rock. Bonin & Martin (1974a) suggested that the basic dykes may have locally remelted their host rocks upon emplacement. Both fine-grained host and broken-up portions of the basic dykes are cut by a 1.5 m wide coarse hypersolvus granite (Warren & McKinstry 1924). That the emplacement of subsolvus granite is bracketed by two episodes of compositionally equivalent hypersolvus granites suggests that the two types of melts, one presumably wetter than the other, crystallized at the same depth during the same intrusive cycle. The water-enriched magma followed the dry magma, but emplacement evidently occurred before complete crystallization of the batch of relatively dry granitic melt. The availability of an aqueous fluid phase during the cooling of both subsolvus and hypersolvus members of the Cape Ann plutonic series led to serious disturbances in K-Ar and Rb-Sr systems (Zartman & Marvin 1971), pluton-wide efficient ordering of alkali feldspars, and localized fenitization in cataclastic zones (R. F. Martin, in press). Warren & McKinstry (1924), seem to have been aware of the control on textural development that a variable like $P(H_2O)$ could have: "The (textural) difference must after all be brought about by some rather slight differences in physical conditions at the time of crystallization".

A second example is provided by occurrences in Corsica. Plutonic rocks abound in Corsica, but only recently has it become clear that not all granitoid rocks there are related to the Variscan orogeny. Bonin (1972) noted the significance of younger ring complexes of peralkaline and subalkaline non-orogenic granites, dated as Permo–Triassic (236±5 and 196±14 m.y.; Bonin *et al.* 1972). This group of "younger granites" is characterized by a common intrusive sequence of (1) hypersolvus granite, then (2) subsolvus granite, along with transsolvus intermediates. These suites intrude the Hercynian basement and cut genetically related volcanic edifices made of rhyolites, ignimbrites, rare basalts and lahars. The remains of these near-surface structures occur either as typical calderas (e.g. Monte Cinto, Scandola complexes) or as screens in ring complexes (e.g. Cauro-Bastelica, Tana-Peloso complexes). The intrusive sequence of hypersolvus granite followed by subsolvus granite has been demonstrated in the Cauro-Bastelica complex (Bonin 1972) as well as in the Tana-Peloso and Bavella-Sambucco complexes (Bonin 1973). However, the sequence is locally incomplete: only hypersolvus granites occur in the Evisa and Monte Cinto complexes (Quin 1969; Vellutini, 1973), whereas only subsolvus granites are found in the Porto, Monte Peloso, and Ospedale complexes (Bonin 1973; Vellutini 1975). The common association of these rocks with granophyres in ring or radial dykes further demonstrates the near-surface, essentially contemporaneous emplacement of relatively dry and wet granitic melts. The association of these ring dykes with occurrences of graphic granite, pegmatite and aplite, and with minor albitization further suggests the availability of water at the magmatic and post-magmatic stages.

An X-ray diffraction study of alkali feldspars in the five major intrusive units of the Cauro-Bastelica complex, including peralkaline and subalkaline hypersolvus granites, fine-grained subsolvus granites, and rhyolites (Bonin & Martin 1974b) shows that all component feldspars have recrystallized thoroughly in the presence of an aqueous fluid phase. The very well-ordered nature of the alkali feldspars still in coarse perthitic intergrowth in hypersolvus members of the complex is an indication of a short-lived interaction with a hydrothermal fluid. We have proposed as a source for this hydrothermal fluid the crystallization of the late, wet granitic liquids that yielded the subsolvus granites. The water released during crystallization also disturbed the K-Ar systematics of biotite in the adjacent basement rocks (Bonin *et al.* 1972).

Karner & Bertram (1972) also discussed the intimate occurrence of hypersolvus and subsolvus granites in a preliminary study of granitic rock types found in individual complexes in the non-orogenic White Mountain series, New Hampshire; these suites were emplaced during an episode of Mesozoic rifting in North America that appears to correlate with that active in Corsica during emplacement of the suites just described. Hypersolvus rocks are believed to



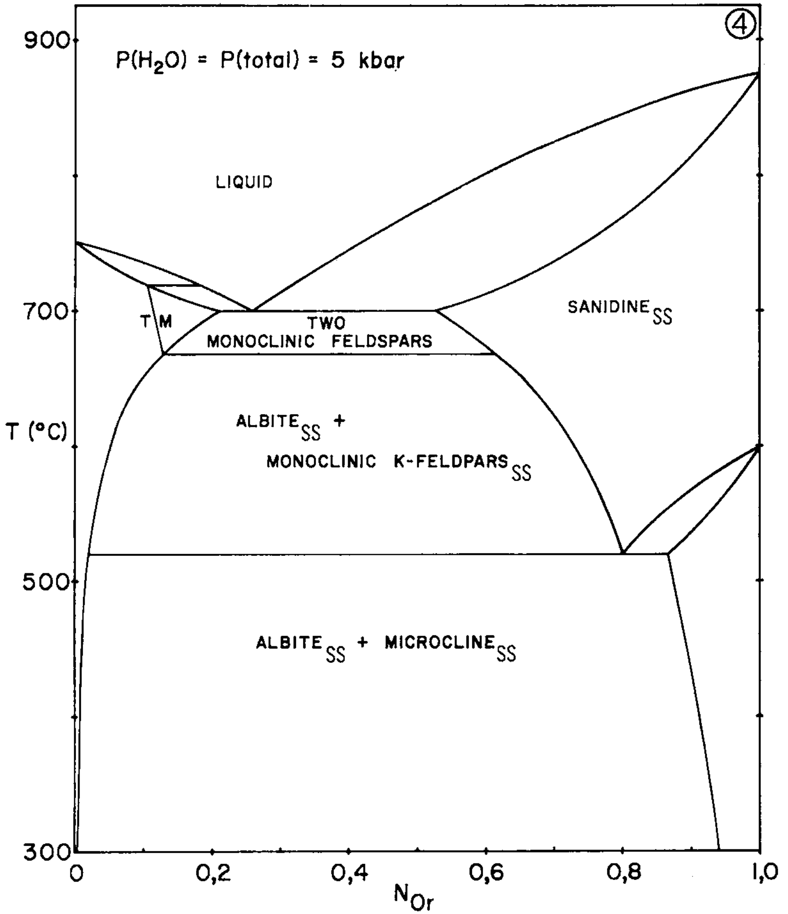


FIG. 3. Possible phase relations in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-H_2O at 1.25 kilobars $P(H_2O)=P(\text{total})$. Data from Kroll (1971), Luth *et al.* (1964, 1973), Martin (1974), and Tuttle & Bowen (1958). It has been assumed here that pure albite disorders gradually with increasing temperature.

FIG. 4. Possible phase relations in the system $NaAlSi_3O_8$–$KAlSi_3O_8$-H_2O at 5 kilobars $P(H_2O) = P(\text{total})$. Data from Kroll (1971), Luth *et al.* (1964, 1973), Martin (1974), Morse (1970), Tuttle & Bowen (1958), and Yoder *et al.* (1957).

represent the lower and marginal parts of magma reservoirs, whereas subsolvus types are located in central and upper portions, where water-enriched granitic liquids should accumulate in a convecting fractionating system. Karner & Bertram's (1972) model may be criticized for assuming that crystal fractionation and convection are efficient in such melts, but their descriptions emphasize the common occurrence of cogenetic hypersolvus and subsolvus granites.

EXPERIMENTAL BASIS OF THE CLASSIFICATION

Considering first the case of $P(H_2O)=P(\text{total})$, data on the relevant systems indicate that only at low confining pressures are the solidus and the crestal region of the solvus separated by a field of stability of one alkali feldspar. Figure 3 shows the configuration of the solvus and solidus in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–H_2O at $P(H_2O)=P(\text{total})=1.25$ kbars. The solvus is that obtained with peralkaline starting materials, so selected to speed up the attainment of equilibrium. The resultant solvus in Figure 3 approaches the equilibrium solvus more closely than when stoichiometric or peraluminous mixes are used (Luth *et al.* 1973; Martin 1974). Syenitic liquids that would plot in Figure 3 would thus be expected to precipitate one feldspar, sanidine, which would remain within its stability field for at least 200°C[1]. Only upon intersection with the solvus would exsolution occur and the perthitic texture develop. Note that granitic liquids at the same pressure would persist to at least 710°C, the minimum in the quarternary system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O (dashed horizontal line in Fig. 3). At this minimum, a single feldspar would coexist isothermally with quartz and an aqueous fluid; however, the temperature interval over which one sanidine is stable is reduced to 60°C at this low pressure. This interval may be reduced even further if the effects of supercooling needed for effective crystal growth are taken into account and if equilibrium had not been attained in determinations of the "wet" solidus in the pertinent systems.

The effect of increasing $P(H_2O)$ is to lower the granite solidus (Luth *et al.* 1964); Luth *et al.* (1973) showed that the crest of the solvus increases in response to increasing $P(\text{total})$. At a unique pressure, the tie-line linking a granitic liquid with its products of crystallization will touch the solvus, though not exactly at its crest. As contact occurs, a melt will coprecipitate two feldspars, one sodic and the other potassic, and the minimum in the granite system is transformed into a eutectic. The resultant igneous rock would clearly be subsolvus if formed at a $P(H_2O)$ of 5 kbars from a melt of either syenitic *or* granitic bulk composition (Fig. 4).

Given that $P(H_2O) = P(\text{total})$, one important question concerns the water pressure at which a change occurs from hypersolvus to subsolvus-type crystallization from the melt. Tuttle & Bowen (1958, Fig. 38) suggest that this change occurs between 3 kbar, where the granite system appears to have a minimum, and 4 kbar, where it features a true eutectic point. Recent data on the configuration of the alkali feldspar solvus allow calculation of the critical feldspar curve, as projected on a *P-T* diagram (Luth *et al.* 1973). The intersection of the straight line, T_c (°C) = 626.4+0.0183 (*P* bars), with the "wet" solidus in the granite system (Fig. 5) provides one means of estimating the water pressure at which this change occurs. A maximum $P(H_2O)$ of 2.5 kbar is proposed; granitic liquids will not yield a hypersolvus mineralogy at water pressures above 2.5 kbar, according to Figure 5. This limit could be lowered if the wet granite "solidus" moves to the left for reasons of disequilibrium mentioned above. For "wet" syenitic liquids, the analogous cross-over in Figure 5 would be expected to occur approximately 2 kbar higher than for granitic liquids.

COMPLICATING FACTORS

Important variables complicate the direct application of this simple modal classification as it stands. The first is the likelihood that the condition $P(H_2O)<P(\text{total})$ applied to many primitive non-orogenic felsic liquids as they reach the surface. It is considered likely that a hypersolvus mineralogy (Fig. 3) can form at total pressures well above 2.5 kbar if $P(H_2O)$ is maintained at a low value. The striking increase in solidus temperature as $P(H_2O)$ decreases ensures that a broad temperature interval would separate the solidus from the solvus even at $P(\text{total})>2.5$ kbar is $P(H_2O)<P(\text{total})$. Relatively dry granitic liquids will evidently give hypersolvus products at high pressures.

A second important variable is calcium content of the feldspar assemblage. As fully recognized by Tuttle & Bowen (1958, Fig. 64, p. 131), the addition of the component $CaAl_2Si_2O_8$ to the

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[1] In the presence of a (Na,K)Cl-bearing aqueous fluid, J. T. Iiyama (pers. comm. 1975) has found that the minimum is shifted down-temperature, perhaps by as much as 50°C. As chlorine partitions very strongly into the fluid, this lowering of the solidus probably reflects a closer approach to equilibrium than in previous experimental studies done with distilled water.

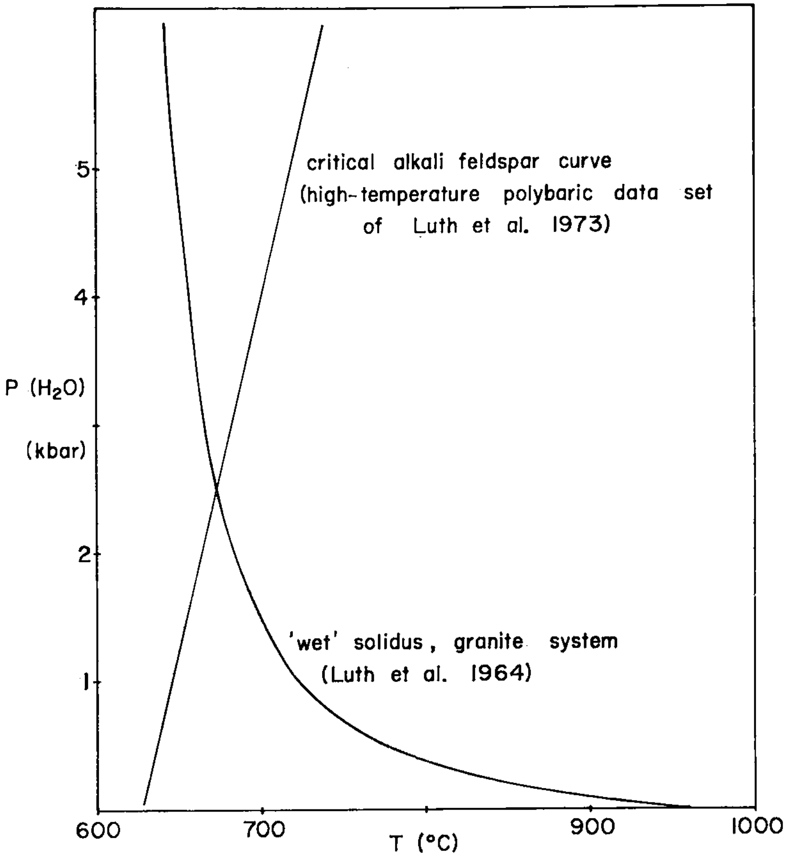

FIG. 5. Relationship between the critical alkali feldspar curve (the maximum on the solvus) and the water–saturated granite minimum or eutectic, as projected onto a $P(H_2O) = P(\text{total})$ vs T plot.

system $NaAlSi_3O_8$–$KAlSi_3O_8$–H_2O causes the gap between solvus and solidus at low water pressures to narrow and eventually to close. Here, the response is more profound in the solvus than in the solidus, though both are increased in temperature by the addition of $CaAl_2Si_2O_8$ to the system. On the basis of two subliquidus experiments, James & Hamilton (1969) suggest that at $P(H_2O)=1$ kbar, granitic liquids containing 3 wt. % normative An do precipitate 2 separate feldspars. If correct, their suggestion would relegate hypersolvus granites containing 3 wt. % anorthite to total and water pressures of less than 1 kbar, again if $P(H_2O)=P(\text{total})$. The early coprecipitation of two feldspars from a batch of relatively calcic magma may give way, however, to end-stage precipitation in the rock of sanidine as overgrowths on both the plagioclase and K-feldspar (Tuttle & Bowen 1958, p. 134). This might be an indication of crystallization at low $P(H_2O)$ that would want to be confirmed in the mineralogy of associated low-Ca granites and syenites.

The extent to which the calcium present in a melt partitions into the feldspar depends on the availability of H_2O, F, P, and Ti. Fluorine is usually enriched in differentiates of non-orogenic suites, and may appear as fluorite or as an important substituent for hydroxyl in amphiboles and micas. The amphibole will also contain some of the available calcium. Elements like fluorine, phosphorus (Wyllie & Tuttle 1961; 1964) and boron (Chorlton 1973) are also important in lowering the solidus, i.e., lowering further the threshold confining pressure at which a primary subsolvus mineralogy will form.

Finally, the user must be aware of possibilities of a metamorphic or metasomatic overprint on the igneous rock. As a hypersolvus igneous rock cools, perthitic exsolution, short-range migration of the albitic component beyond the borders of the original grain, and Si-Al ordering are attempts to re-establish equilibrium. An aqueous fluid will probably be required for any migration or Si-Al ordering. Theoretically, a subsolvus mineralogy involving fully ordered albite and microcline can originate by such thorough subsolidus recrystallization, as proposed by Tuttle & Bowen (1958). In practice, these cases may be rare, as transitional assemblages have not been documented. A subsolvus mineralogy could also be expected when albite and K-feldspar precipitate directly from an aqueous fluid at relatively low temperatures. In a similar way, at higher temperatures, an aqueous fluid could precipitate a single, calcium-poor feldspar that subsequently intersects the solvus; such phenomena occur in metasomatic 'syenites' as described by Denaeyer (1959); they occur mainly in aureoles of fenitization about alkaline and carbonatitic bodies. Despite these complications, most subsolvus rocks associated with hypersolvus granites and syenites, the association that we are trying to explain here, occur in dykes or small plutons intrusive into earlier members of the plutonic series; thus they represent products of crystallization of melts rather than of hot aqueous fluids.

A Model to Explain the Association

From our previous discussion, hypersolvus granites and syenites should be confined to the epizone (Buddington 1959), there to merge with subvolcanic members of the same complex. This is the association stressed by Tuttle *et al.* (1964), who suggested that, in contrast, most subsolvus granites and associated pegmatites "are regarded as products of more volatile-rich magmas crystallizing at lower temperatures under deep-seated conditions." The two groups of rocks thus should not be associated in the same igneous complex. Yet the close association of hypersolvus and subsolvus granites is common in many non-orogenic complexes; selected examples have been reviewed above.

The association of hypersolvus and subsolvus granites in non–orogenic complexes can best be explained by proposing that the hot, relatively dry, fluorine-bearing differentiates of gabbroic melts are remelted locally due to the influx of water, possibly of meteoric origin. The cooling parental gabbroic rocks that accompany the granitic liquids are viewed as the efficient heat engine that will set in motion ground-water and magmatic water in convection patterns through supracrustal host rocks into the hot intrusive body. As diffusion of water through granitic liquids is very sluggish (Shaw 1974), we prefer to think of refusion, probably complete, of the hot *crystalline* hypersolvus differentiates in the presence of a free fluid phase that migrated in along grain boundaries. Refusion must go on at a sufficiently high value of $P(H_2O)$ and P(total) that the resultant mineralogy will be subsolvus. The proposed sequence of events is possible without reheating because the temperature of the "wet" liquidus could well be less than that of the "dry" solidus. Whereas the primary hypersolvus differentiates commonly are peralkaline, liquids obtained by melting these rocks in the presence of water are likely to be subalkaline; their products of crystallization will be subalkaline and subsolvus.

The crystallization of hypersolvus rocks in several complexes appears to be followed without transitional rock types by subsolvus granites; influx of meteoric water can explain this abrupt change. The relatively rare intermediates here called "transsolvus" contain perthite in a subsolvus matrix. They can be attributed to cases of incomplete fusion of hypersolvus parent material. If water content of the granitic liquid were to build up more gradually, as by crystallization and separation of anhydrous minerals from the original granitic liquid, a gradational transition from hypersolvus to subsolvus products would be expected. Such a gradation is not found.

Of course, the proposed influx of an aqueous fluid may occur at a temperature too low for refusion of the differentiates. In this case, the hypersolvus rocks will show clear signs that a hydrothermal fluid has entered the system. These lower-temperature effects include ordering of feldspars, slight but pervasive alteration leading to turbidity in the feldspars and degradation in the mafic minerals, and disturbances in hydrogen, oxygen, strontium, and lead isotopic systems (Taylor & Forester 1971; Taylor 1974). The incipient development of these features in most hypersolvus granites and syenites points to common influx of water into the system once crystallization is complete. The subsolvus granites themselves give evidence of crystallization from hydrous melts. In addition to the occurrence of pegmatites, missing in hypersolvus granites, Lameyre (1973) has recognized kaolinization, greisen formation, and muscovitization as telltale signs of the availability of water upon crystallization of subsolvus granites from the Massif Central, France. The K-feldspar of subsolvus granites is microcline, which is evidence of the availability of water at the temperature of the monoclinic-triclinic inversion. In contrast, the K-feldspar in hypersolvus granites and syenites is generally less well ordered, unless interaction with aqueous fluids has persisted below the monoclinic-triclinic inversion.

Occurrences in Western Africa provide examples in which influx of water occurred mainly at subsolidus temperatures. In the Aïr, Faabriès & Rocci (1965) have described a type of late-stage interstitial crystallization of quartz, albite and microcline. In the Jos Plateau, Nigeria, most non-orogenic granites are truly hypersolvus. However, the albite-riebeckite and albite-biotite granites there are not true subsolvus granites, as the albite is secondary, related to rare-earth and tin mineralization and greisen formation. The extensive hydrothermal alteration phenomena encountered in these subvolcanic and epizonal plutonic complexes, and the absence of late subsolvus granites and accompanying pegmatitic complexes, suggest that fluids had definitely become available after crystallization of the hypersolvus granites, but possibly at too low a temperature to effect significant or widespread remelting. The resulting metasomatic effects have considerable economic importance, as they may lead to economically important enrichment of elements like Sn, W, Mo, Be, rare earths, and fluorine. It is interesting to speculate whether hypersolvus granite—hydrothermal fluid interaction would be as extensive if a local melting event had occurred, providing an efficient means of removing water from the system.

CONCLUSIONS

The availability of water controls directly the textural development of low-calcium granite and syenitic rocks. Where water becomes available at relatively high temperatures, and at pressures perhaps even below the 2.5 kbar limiting value for granitic systems, complete refusion of early-formed, commonly peralkaline, relatively dry hypersolvus granites can be expected during their cooling history. The ubiquitous distribution of meteoric water at shallow crustal depths and well-documented cases of plutonic rock—meteoric water interaction by oxygen isotope geochemistry suggest this source of water. Furthermore, transfer of water is most efficient once a plutonic rock has crystallized, but unrealistically slow if diffusion is involved at the magmatic stage. This refusion does not imply a second thermal event. It would appear to provide a temporary sink for water, which is later released upon crystallization of the resulting subsolvus granites. Where influx of relatively cool fluid occurs, or where the heat engine is smaller or more remote, temperatures may be too low to allow refusion to occur. However, the resultant metasomatic changes are likely to lead to economically important enrichment of incompatible elements in part brought in from the host rocks by the fluid phase. The association hypersolvus granite-subsolvus granite (or syenitic equivalents) is a common one in differentiated non-orogenic intrusive complexes; it provides an excellent example of the critical role of water in genesis of non-orogenic felsic derivative magmas and associated alteration phenomena.

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