GRANITE MELT FORMING REACTIONS

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Partial melting within the crust is widely accepted for the production of at least some, if not most granite magmas. It is considered that partial melting is not a response to increasing temperatures in rocks containing haplogranite components but is a result of melt-forming reactions as temperature and possibly pressure increases (White et al. 2003, and refs therein). Melt-forming reactions are mainly dehydration reactions. The process has been called "vapour-absent melting".

At low temperatures, melt reactions involving dehydration of muscovite in the presence of quartz and plagioclase produces a granite melt that is strongly peraluminous because Al_2SiO_5, a bi-product of the reaction, dissolves in the melt. On cooling this melt crystallises to muscovite granite. Crystallization involves a back reaction to new muscovite.

At temperatures near 800 to 850°C and pressures near 500 to 600 MPa (5 – 6 Kb), there are reactions in a protolith containing quartz + feldspars + biotite which produces melt and orthopyroxene as a bi-product. In this case only a small amount of the orthopyroxene is soluble in the melt. The remainder appears as residual crystals or restite. Orthopyroxene is the first mafic phase to crystallise from this melt whether it is separated from the restite or not. Consistent with this model, S-type volcanic rocks of the Lachlan Fold belt contain large crystals ("phenocrysts") of orthopyroxene most of which are considered to be restite. On the other hand, granites having the same composition as these S-type volcanics, contain no orthopyroxene because there has been a back reaction of orthopyroxene to form biotite. The magma is quenched.

Experiments (e.g. Johannes & Koepke 2001) have shown that dehydration melting of the assemblage hornblende + plagioclase produces a tonalite melt (I-type) with residual clinopyroxene and lesser orthopyroxene both of which are only partly soluble in the melt. I-type dacites contain crystals of both pyroxenes. Crystallisation of a magma of this sort to tonalite, results in back reactions (peritectics) to generate hornblende and biotite respectively. Experiments also show that many or most of the solid products of melt-forming reactions appear as perfectly-shaped crystals e.g. orthopyroxene (Johannes & Koepke 2001 fig. 8). Crystals produced by melt-forming reactions if carried along with the magma as restite crystals are indistinguishable from phenocrysts.

Plagioclase may completely dissolve in the melt phase if the protolith is low in Ca and Na. In protoliths containing more Ca and Na (e.g. metamorphic plagioclase), plagioclase reacts. Johannes (1989) showed that partial melting of plagioclase (An_{60}) in the system Qz-Ab-An-H_2O at 200 MPa (2 Kb) and 850°C produces new plagioclase crystals $An_{82–85}$ as well as a more sodic plagioclase component in the melt. It is suggested that new plagioclases resulting from melt reactions in the Earth's crust will be in local equilibrium because reaction occurs with rising temperatures. The relicts of calcic plagioclase (near An_{80}) in the Jindabyne tonalite are interpreted as new plagioclases produced during the melt-forming reaction that produced the tonalite magma. Near uniformity of core compositions indicate local equilibrium during formation of the calcic plagioclase but the corrosion of cores and complex zoning of the outer parts seen in the rocks, indicates disequilibrium. The plagioclase was not completely "made over", to use Bowen's (1922) term, as crystallisation proceeded with falling temperatures. The corroded calcic plagioclase cores are all that remain of restite plagioclase.

Johannes and Holtz (1991 showed that, at least at low pressures, the plagioclase loop is very flat in the haplogranite system when the activity of H_2O is well below 1. A similar explanation is therefore likely for the corroded calcic cores common in many low temperature granites. In volcanic rocks with the same chemical composition as those low temperature granites, plagioclase "phenocrysts" with the same calcic compositions as in the granites but without the complex, outer more sodic zones, are mostly restite plagioclase. These have not re-equilibrated because the rock has cooled rapidly.

The phenocrysts, we contend, may not have crystallized from the melt but may be restite phases carried along by the magma from the source of partial melting – the new uniform plagioclases like those produced in the experiments of Johannes (1989). The partial "making over" as Bowen (1922) put it, of the equilibrium plagioclase of the partial melt during cooling and crystallization, is a type of back reaction.

Bowen, N.L. 1922, The reaction principle in petrogenesis. *Journal Geology* **30**, 177-198

Johannes W. 1989, Melting of plagioclase - quartz assemblages at 2Kb water pressure. *Contributions Mineralogy Petrology* **103**, 270-276.

Johannes W. & Holtz, F. 1991, Transactions Royal Society Edininburg Earth Science **83**, 417-422.

Johannes W. & Koepke J. 2001, Incomplete reaction of plagioclase in experimental dehdration melting of amphibolite. *Australian Journal Science* **48**, 581-590.

White R W., Powell Roger,, & Clarke, G L. 2003, Prograde metamorphic assemblage evolution during partial melting of metasedimentary rocks at low pressures: migmatites from Mt Stafford, central Australia. *Journal Petrology* (in press).

Wyborn D. & Chappell, BW. 1986, The petrogenetic significance of chemically related plutonic and volcanic rock units. *Geological Magazine*, **123**, 619 - 628.

GRANITE MELT FORMING REACTIONS

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PARTIAL MELTING IN THE CRUST

Partial melting is widely accepted for the production of at least some, if not most granite magmas.
Less widely appreciated is that there are melt-forming reactions. (see Dick White et al. 2003, J. Petrol. And refs therein).

Of the four haplogranite melt-forming components Qz, Ab, Or and H_2O, only the first is likely occur in the source rocks in any abundance. Ab will occur in plagioclase, Or mainly in biotite and less commonly muscovite, and H_2O in biotite or hornblende and less commonly muscovite.

GRANITE MELT-FORMING REACTIONS

1. DEHYDRATION MELTING OF MUSCOVITE

At low temperatures (upper amphibolite facies) and moderate pressures (> about 350 MPa (3.5 Kb)), the melting reaction involving muscovite is something like:-

muscovite + quartz + (albite)
= $\underline{\text{ qtz + albite + K-feldspar + }H_2O\text{+ }Al_2SiO_5}$
(hydrous granite melt components)

This has been the subject of various studies. The most comprehensive discussion is that by Johannes & Holtz (1996)

1. DEHYDRATION MELTING INVOLVING MUSCOVITE CTD

Note. Aluminosilicate produced is dissolved in the melt which is therefore strongly peraluminous.

muscovite + quartz + (albite) =

qtz + albite + K-feldspar + H_2O+ Al_2SiO_5

(hydrous granite melt components)

This has been the subject of various studies. The most comprehensive discussion is that by Johannes & Holtz (1996)

1. DEHYDRATION MELTING INVOLVING MUSCOVITE CTD

Crystallisation of melt

Separation of this strongly peraluminous melt, accumulation and crystallisation produces a muscovite granite.

Crystallisation is essentially a back reaction

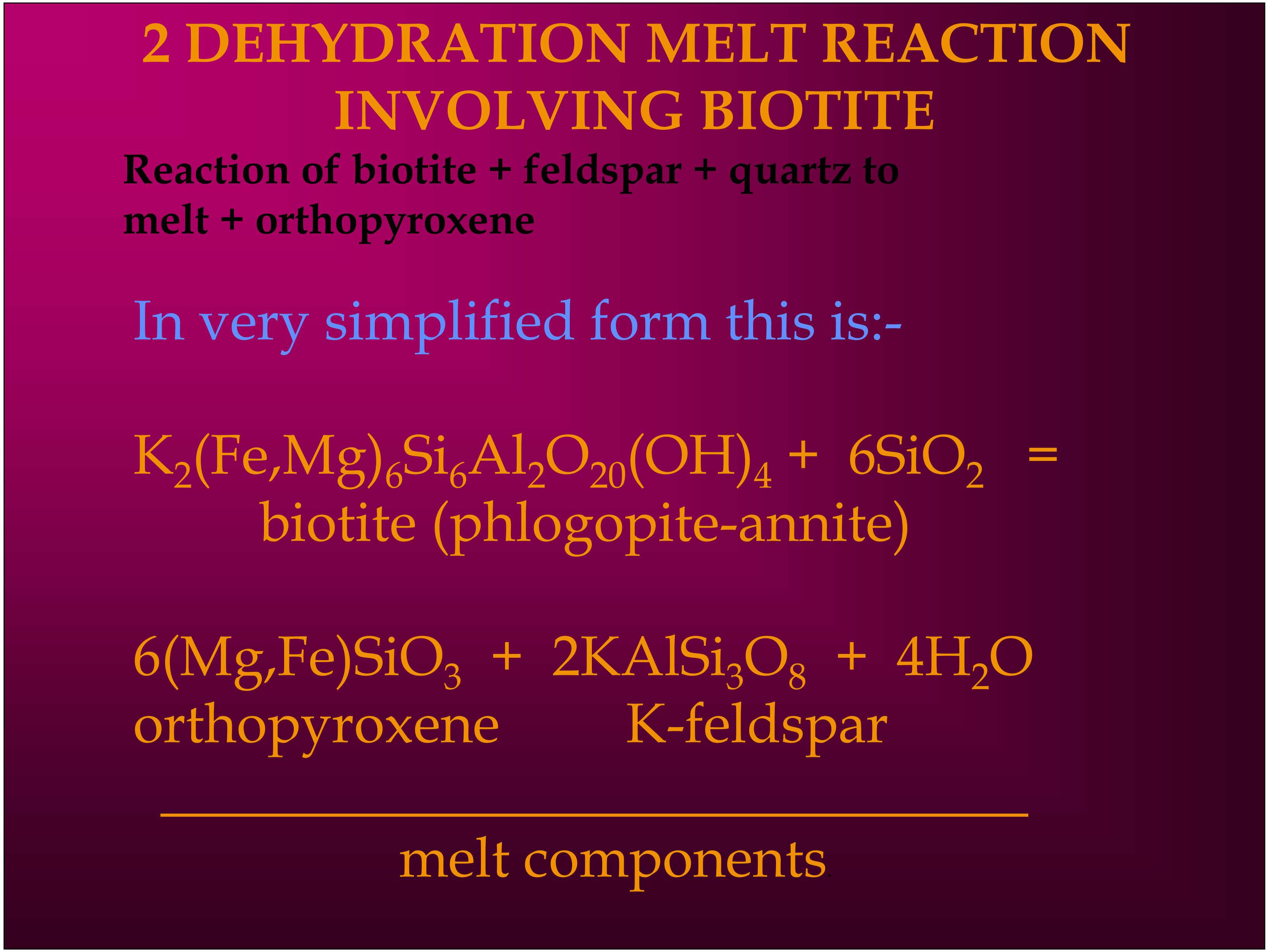
$$\underline{\text{qtz + albite + K-feldspar + } H_2O + Al_2SiO_5} =$$

(hydrous granite melt components)

muscovite + quartz + albite

(muscovite granite)

An example of a muscovite granite of this type is given by Kemp et al.. 2002. *Aust. Earth Sci* **49**, p 202.



2 DEHYDRATION MELT REACTION INVOLVING BIOTITE

Reaction of biotite + feldspar + quartz to melt + orthopyroxene

In very simplified form this is:-

$K_2(Fe,Mg)_6Si_6Al_2O_{20}(OH)_4 + 6SiO_2 =$

biotite (phlogopite-annite)

$6(Mg,Fe)SiO_3 + 2KAlSi_3O_8 + 4H_2O$

orthopyroxene K-feldspar

melt components

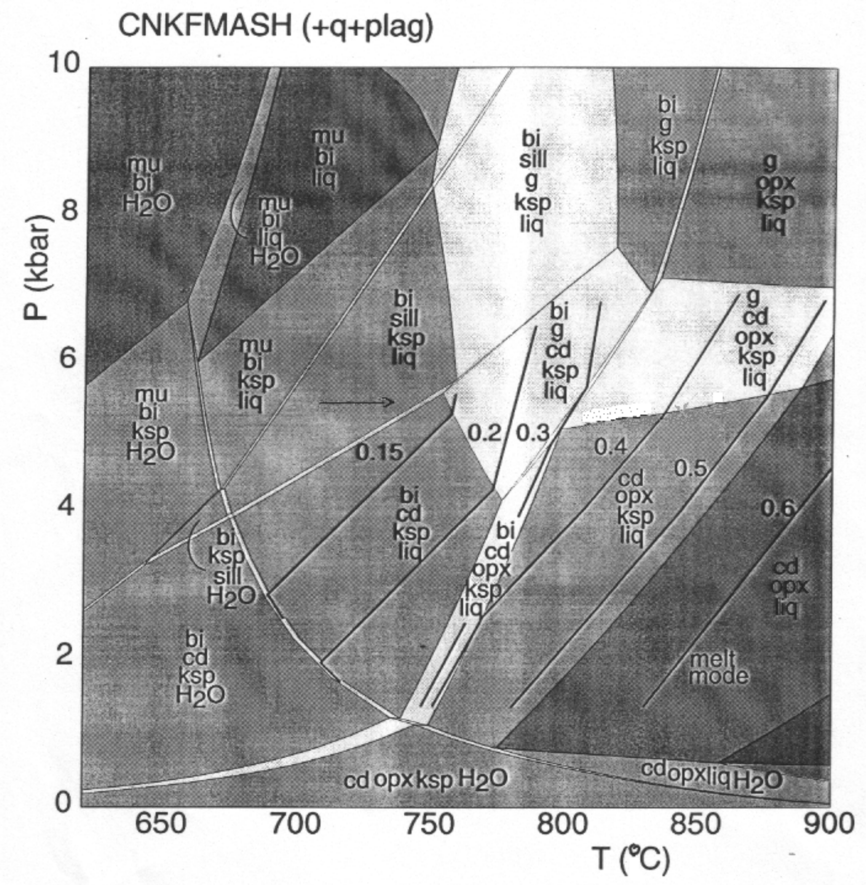
2 DEHYDRATION MELT REACTION INVOLVING BIOTITE

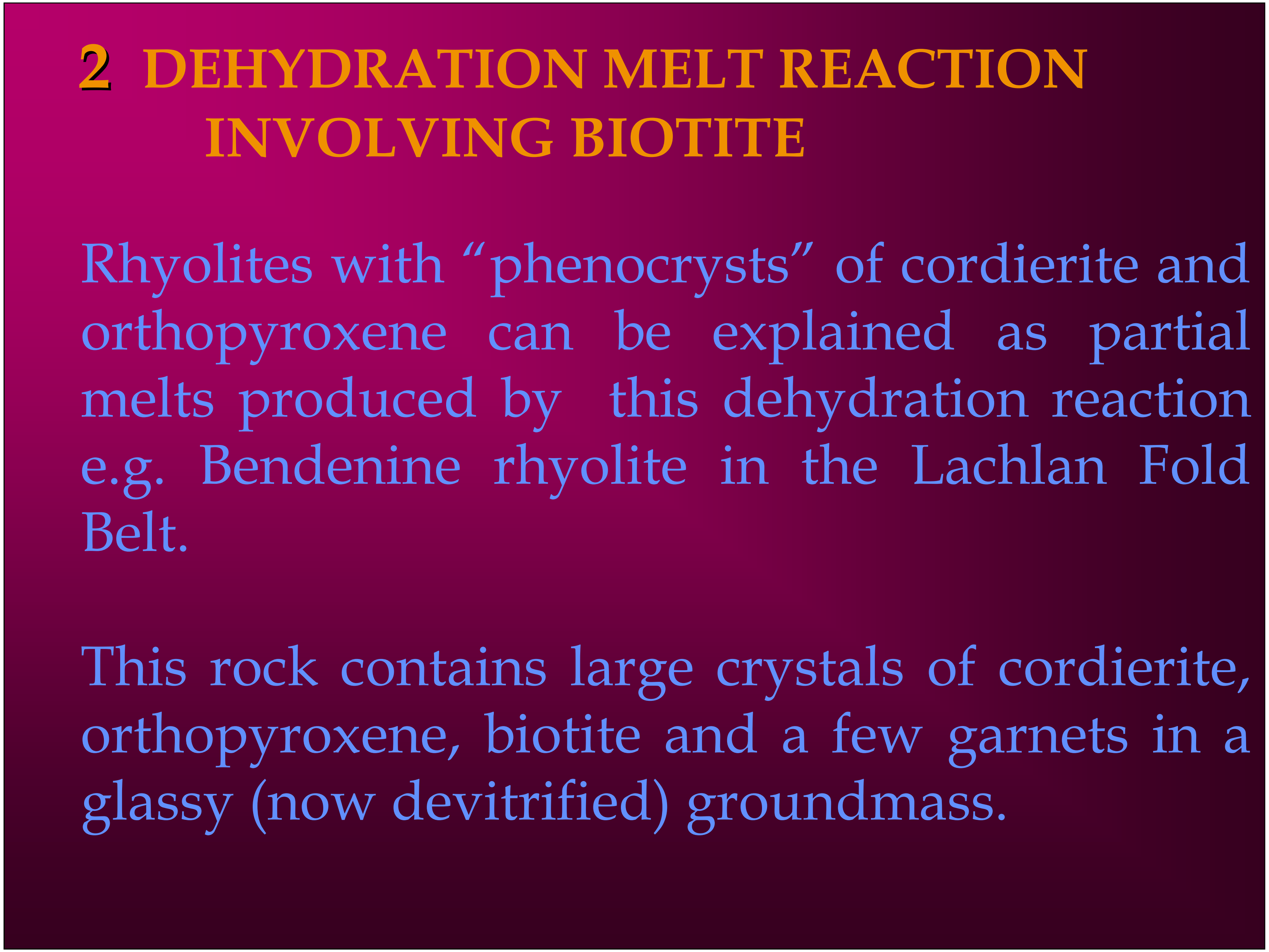
As written this is a simple univariant reaction. In nature dehydration melting involving biotite will be multivariant.

According to many experiments, the complete dehydration of biotite at 500 MPa (5 Kb) in the presence of granite components, occurs near 800°C

2 DEHYDRATION MELT REACTION INVOLVING BIOTITE

Pseudosection of a mafic biotite cordierite granite calculated by Roger Powell (Univ Melb: unpublished) also shows biotite breakdown near 800^{0}C at 500MPa



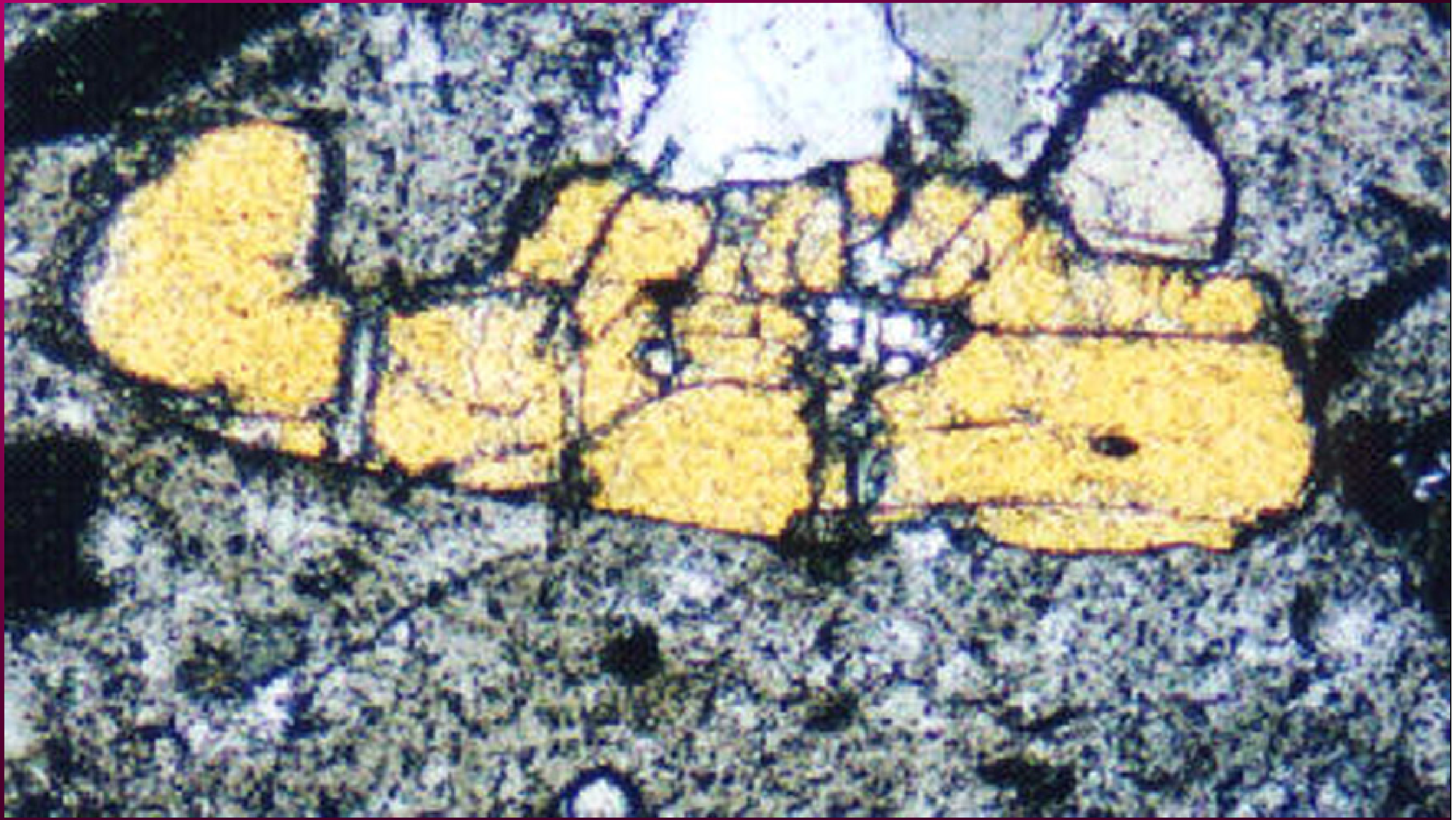


2 DEHYDRATION MELT REACTION INVOLVING BIOTITE

Rhyolites with “phenocrysts” of cordierite and orthopyroxene can be explained as partial melts produced by this dehydration reaction e.g. Bendenine rhyolite in the Lachlan Fold Belt.

This rock contains large crystals of cordierite, orthopyroxene, biotite and a few garnets in a glassy (now devitrified) groundmass.

2 DEHYDRATION MELT REACTION INVOLVING BIOTITE



Orthopyroxene “phenocryst” in Benendine rhyolite

2 DEHYDRATION MELT REACTION INVOLVING BIOTITE

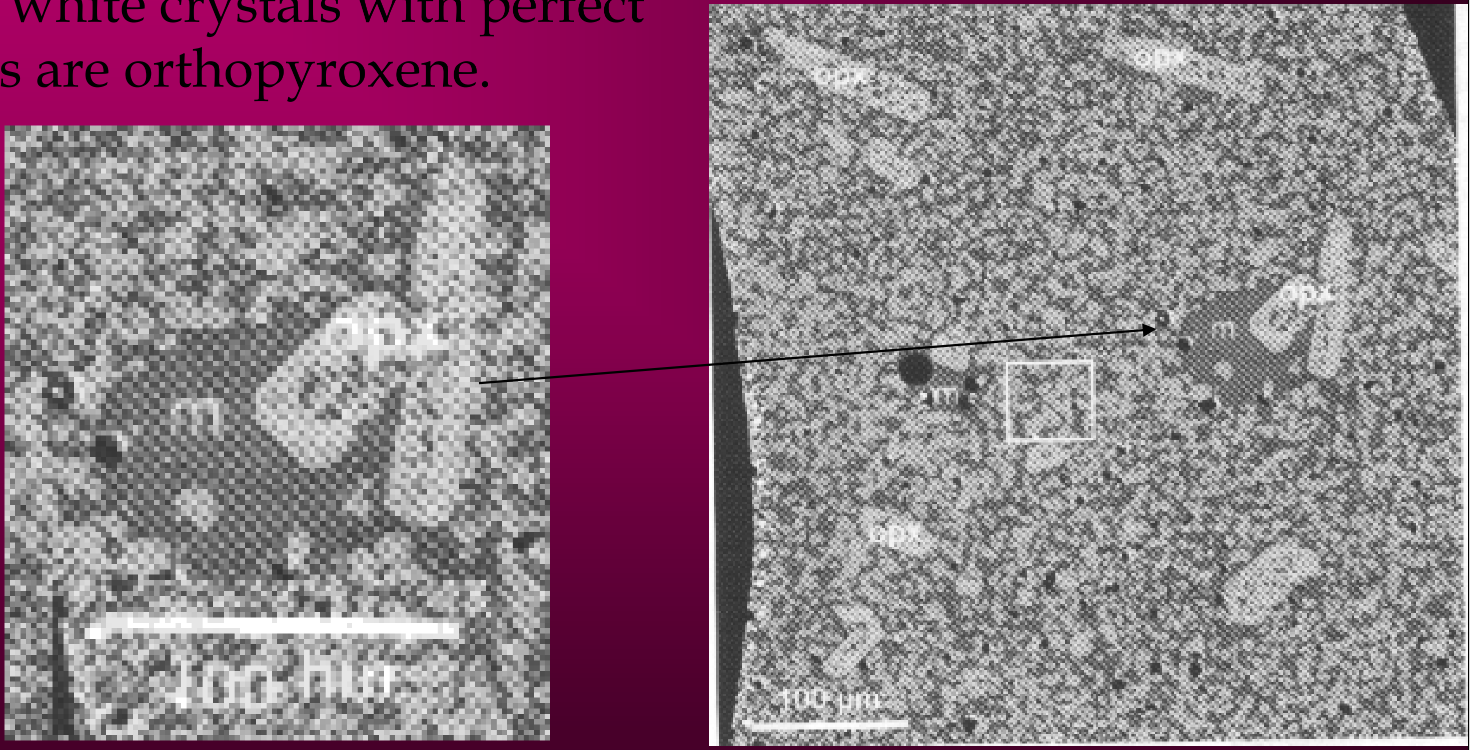
We say that the large crystals in Benendine rhyolite are restite crystals that are products of the melt reaction and not crystallised from the melt.

Some critics say that restite crystals should not have perfect shapes. However, experiments show that melt reaction products appear the same as phenocrysts.

3 DEHYDRATION MELT REACTION INVOLVING HORNBLENDE

from Johannes & Koepke (2001) Aust. Journ. Earth Sci. 48, p 587

Large white crystals with perfect shapes are orthopyroxene.



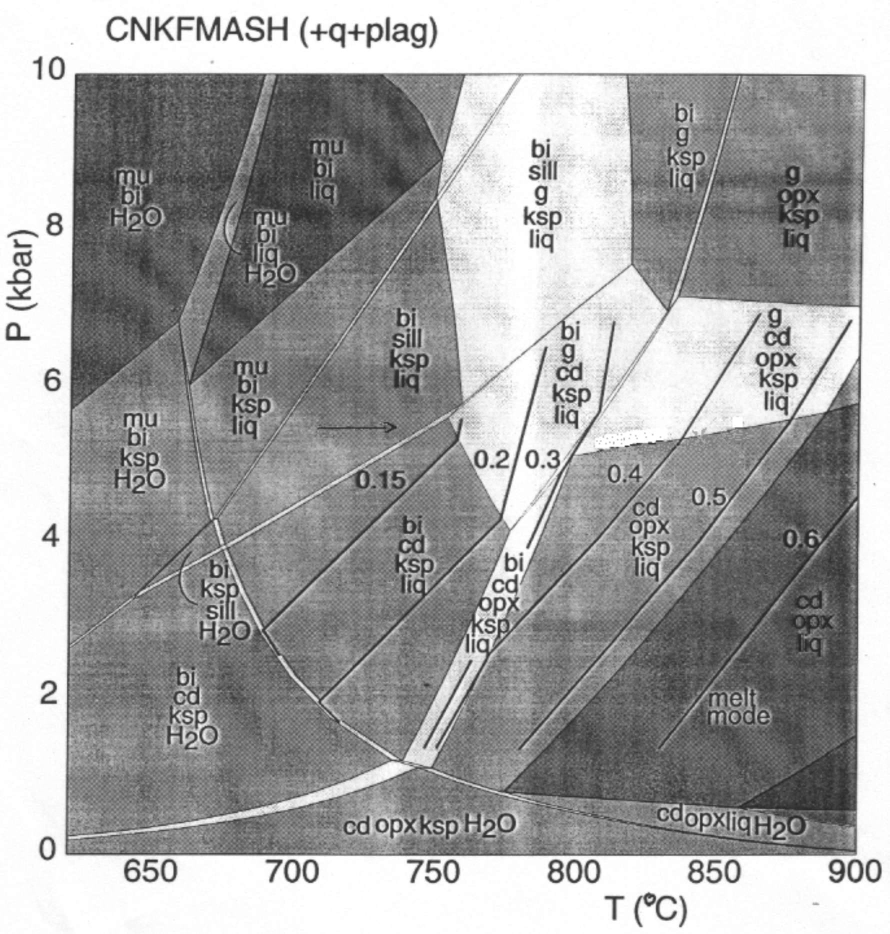
Enlargement shows perfect crystal of opx projecting into pool of glass (dark grey)

2 DEHYDRATION MELT REACTION INVOLVING BIOTITE

The large crystals in the Bennenine rhyolite preserve equilibrium established at 500- 600 MPa (5 – 6 Kb) and 800°C according to Wyborn et al. (1981). At this P and T the calculated pseudo section shows melt with opx, cordierite with or without garnet and alkali feldspar. There is about 35% melt consistent with the restite model.

2 MELT BACK REACTION CTD

The large crystals in the Bennenine rhyolite preserve equilibrium established at 500-600 MPa (5 – 6 Kb) and 800°C according to Wyborn et al. (1981).



2 MELT BACK REACTION

The volcanic rock matches the chemical composition of mafic biotite-rich cordierite granites of the Bullenbalong Suite of the Kosciuszko Batholith, Lachlan Fold Belt. The magma produced at the P and T determined for the volcanic rock has low a_{H2O} and hence could come to the surface to produce volcanic rocks. Opx produces biotite at a peritectic during cooling of the granite magma. This is a back reaction.

In simplified form, the peritectic reaction of orthopyroxene with melt phase to produce biotite is:-

$6(Mg,Fe)SiO_3$ + $2KAlSi_3O_8$ + $4H_2O$ =
orthopyroxene quartz

___melt components___

$K_2(Fe,Mg)6Si_6Al_2O_{20}(OH)_4$ + $6SiO_2$
biotite (phlogopite-annite)

In summary, these data show that orthopyroxene was present in cordierite-biotite granite at an early stage, and that the orthopyroxene reacted with the melt phase as crystallisation proceeded with falling temperature.

PLAGIOCLASE IN MELT FORMING REACTIONS - solubility of H_2O in plagioclase melts

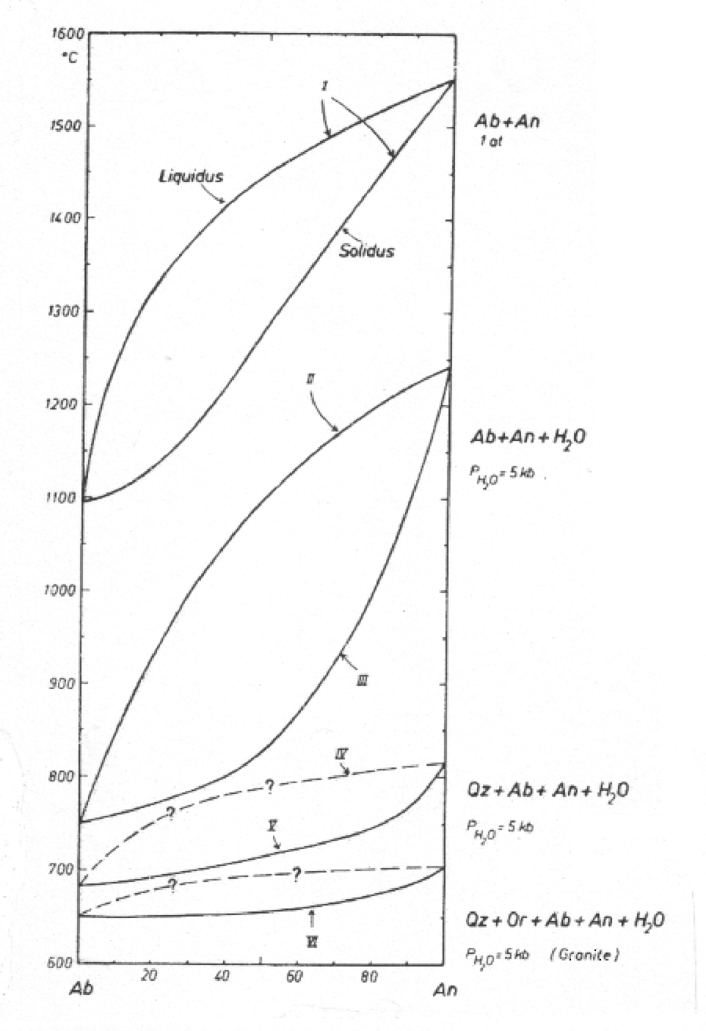


Figure from Johannes (1984)
Contrib. Min. Pet. 86, 264-273

Top curves represent the dry plagioclase system (from Bowen).

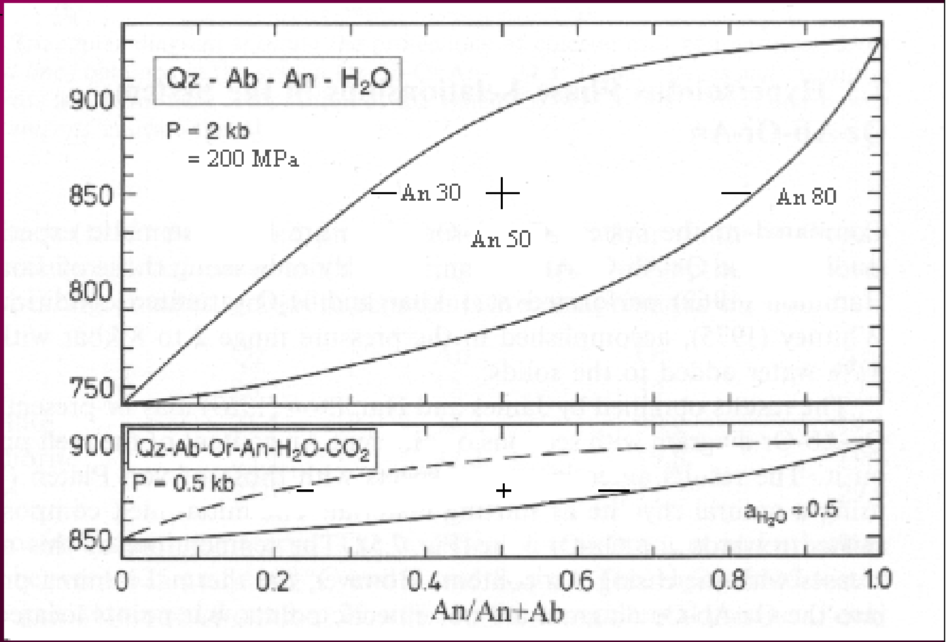
At 500MPa, H_2O saturated, the melting point of albite is lowered 350^0C slightly more than anorthite. Melting point of anorthite is lowered much more than albite with the addition of quartz as well.

Anorthite MP lowered even more with addition of K-feldspar + quartz i.e.in a granite melt. This is critical in melt-forming reactions.

FLATTENED PLAGIOCLASE LOOP – CONSEQUENCES

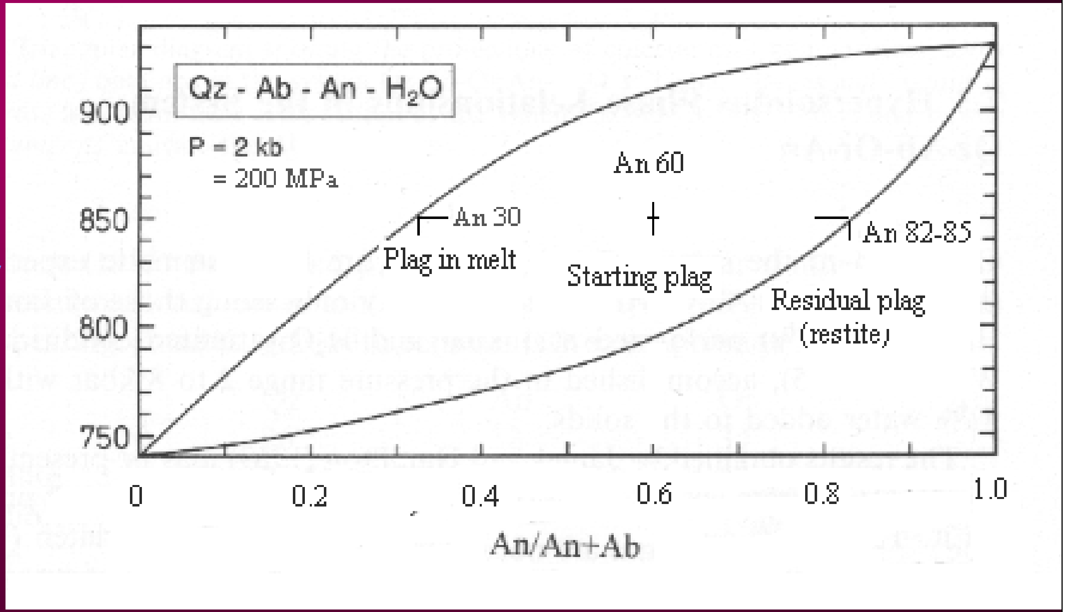
Diagram from Johannes (1989, Contrib.Min.Pet. 84, 264-273) shows flattening of loop by addition of quartz at low pressures.

Bottom . Johannes & Holtz (1991, Trans. Roy.Soc.Edin.. Earth Sci. 83, p 417-422) is for very low pressure, but it shows that when activity of H_2O is reduced well below 1, the loop is still flattened.



PLAGIOCLASE IN MELT FORMING REACTIONS CTD

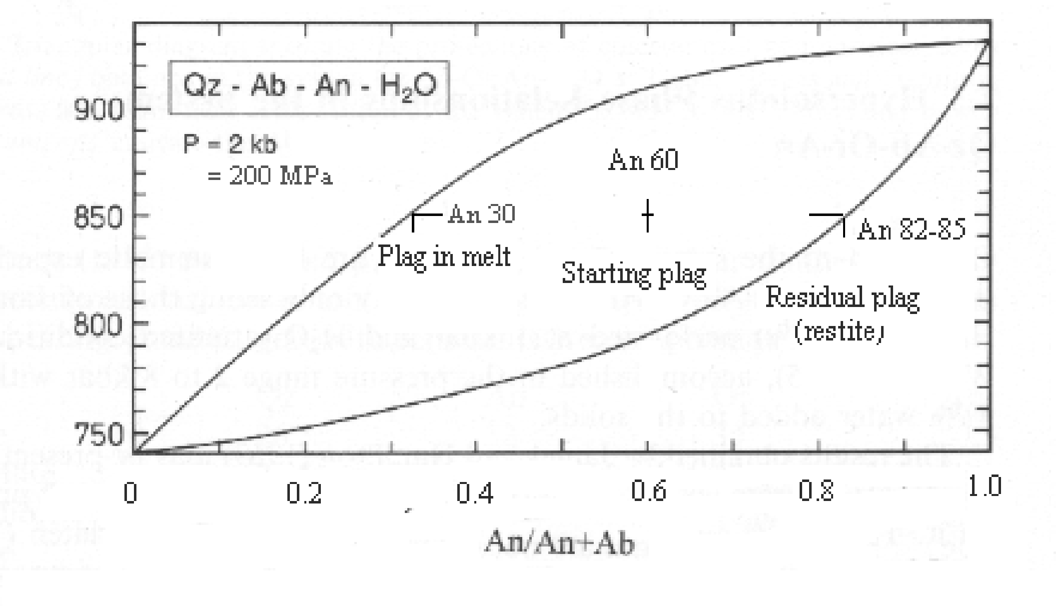
Johannes (1989) showed that partial melting of plagioclase (An_{60}) in the system Qz-Ab-An-H_2O at 200MPa (2 Kb) and 850°C produces new plagioclase crystals An_{82-85} as well as a more sodic plagioclase component in the melt..



Johannes, W., 1989, Melting of plagioclase - quartz assemblages at 2Kb water pressure. *Contributions Mineralogy Petrology*, **103**, 270 - 276.

PLAGIOCLASE IN MELT FORMING REACTIONS CTD

New plagioclase formed by melt-forming reactions are likely to be in equilibrium because of increased reaction rates with rising temperatures. In this system the new equilibrium plagioclase has a composition near An_{80}.



Johannes, W., 1989, Melting of plagioclase - quartz assemblages at 2Kb water pressure. *Contributions Mineralogy Petrology*, **103**, 270 - 276.

PLAGIOCLASE IN BACK REACTIONS DURING CRYSTALLISATION

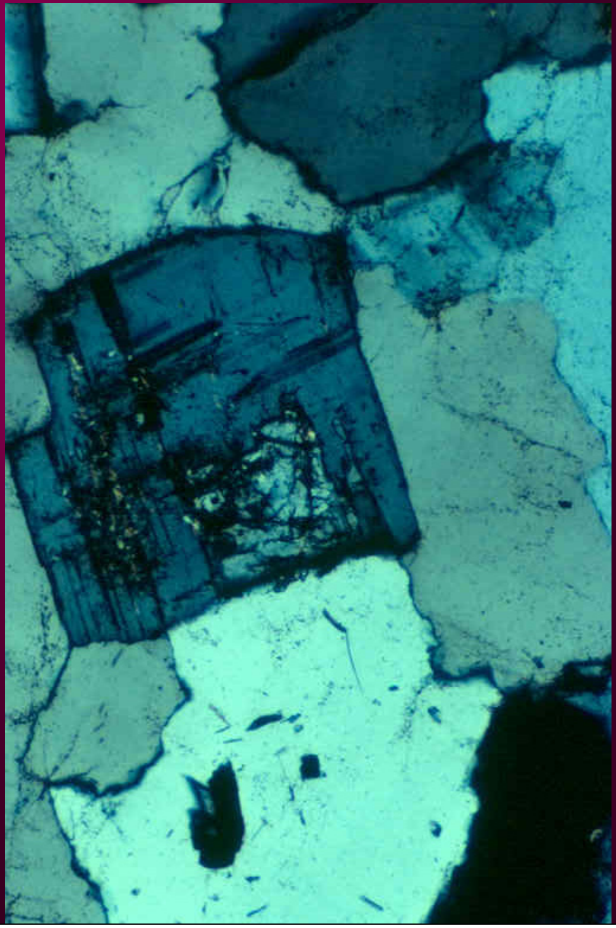
With falling temperature localdisequilibrium is likely.

Low temperature I-type tonalites and some granites have partly resorbed calcic cores in plagioclases.

Cores have fairly uniform composions near An_{80}. These are considered to be restite. Calcic cores are not relict metamorphic plagioclases– they are products of melt-forming reaction.

PLAGIOCLASE IN BACK REACTIONS DURING CRYSTALLISATION

Calcic core in plagioclase (1 mm across). Jindabyne suite tonalite. Cores are considered to be restite. There is no need to invoke basalt mixing to explain them.



SUMMARY AND CONCLUSIONS

Low temperature melt-forming reactions involving dominant muscovite produce a strongly peraluminous melt. Crystallisation is essentially a back reaction to muscovite granite.

Reactions involving biotite in a biotite + quartz + feldspars protolith gives melt at around 850^0 C consistent with theoretical and experimental data. Orthopyroxene, a product of the melt-forming reaction, is only sparingly soluble in the melt.. Most opx occurs as a restite phase,.which may be carried upwards as part of the magma. On cooling to a granite opx back reacts with the melt to form biotite. The granite is an S-type.

Melt-forming reactions involving dominant hornblende and plagioclase are less well understood but produce residual clinopyroxene and lesser orthopyroxene which are sparsely soluble in the melt phase. Both are restite phases.The granite is an I-type.

Experiments show that residual crystals may be perfectly shaped and if appearing as restite crystals in the magma, they could be confused with phenocrysts in vocanics.

Calcic cores in plagioclases have compositions expected to be produced during melt-forming reactions. Cores in plagioclase are best explained as relics of melt-reaction plagioclase (i.e. restite).