

Experimental melting of hydrous low-K tholeiite: evidence on the origin of Archaean cratons

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Winthér, K.T. & Newton, R.C.: Experimental melting of hydrous low-K tholeiite: evidence on the origin of Archaean cratons. *Bull. geol. Soc. Denmark* vol. 39, pp. 213–228. Copenhagen, December 20th, 1991. <https://doi.org/10.37570/bgsd-1991-39-10>

Experimental melting studies were performed on a natural high-Al basalt and a synthetic average Archaean tholeiite (AAT) composition (0.3 wt.% K_2O) with variable amounts of H_2O . Microprobe analyses of quenched melts (glass) from runs at 5–30 kbar and 750°–1100°C showed that typical Archaean tonalitic and trondhjemitic “grey gneiss” compositions were produced from the average Archaean tholeiite over the entire experimental range, with 15% to less than 1% H_2O . The high-Al basalt produced liquids too high in Al_2O_3 (18–23%) for realistic grey gneiss compositions. The persistent generation in our experiments of low-K calc-alkaline magmas directly by vapor-undersaturated partial melting of low-K Archaean tholeiite strongly suggests this mechanism for the origin of early continents.

Temperatures of 850°–1000°C and pressures around 15 kbar are appropriate melting conditions. Tonalitic magmas are favored by higher temperatures, lower pressures, and higher H_2O contents in the source. Trondhjemitic magmas are favored by lower temperatures, higher pressures, and lower H_2O contents. Heavy REE depletion of magmas would be possible for partial melting above 15 kbar because of the stability at higher pressures of residual garnet. Unfractionated REE patterns of magmas could result from melting at lower pressures, where garnet does not coexist with liquid. The low-K trends of melts are maintained by very refractory amphibole (up to 0.7 wt. % K_2O) which coexists with liquid for bulk H_2O contents of 2 wt. % or more. Shallow subduction-zone melting of amphibolite with magma extraction, and partial melting of amphibolite under deep-crustal metamorphic conditions are models for early crustal evolution which appear to satisfy the experimental constraints.

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Introduction

Petrology of Archaean cratons

The dominant components of Archaean cratonal terrains are tonalitic to trondhjemitic “grey” gneisses of generally calc-alkaline chemistry but low in K_2O . Table 1 lists average compositions of grey gneisses from the W Greenland Archaean terrain (McGregor 1979). Some of the grey gneisses contain sufficient K_2O to qualify as granodiorites. Also abundant in the cratons are metasedimentary and metavolcanic rocks. These range from the widely-distributed low-grade “greenstone” belts, in part unconformable upon the grey gneisses in Zimbabwe (Bickle *et al.* 1975) and South India (Pichamuthu 1975) and intruded by tonalites and trondhjemites in western Australia (Glickson 1979; Jahn *et al.* 1981), to infolded higher-grade supracrustal relics. A third major component in many of the terrains is alkali feldspar granite with up to 6 wt. % of K_2O (Table

1). Cratonal K-rich granites are characteristically late Archaean, and cut earlier structures. Examples are the leucogranites of eastern Finland (Martin & Querré 1984), the Qôrqt granite of W Greenland (Brown *et al.* 1981), and the Closepet granite of Southern India (Radhakrishna 1956). The cause of the late-Archaean surge of K-rich magmatism, complementary to the earlier-Archaean low-K granitoids, is a major problem of continental evolution.

McGregor (1973) was instrumental in recognizing the intrusive igneous nature of the grey gneisses of W Greenland, and, by implication, those of other cratons. He demonstrated two major generations of grey gneiss in the Godthaabsfjord area by cross-cutting criteria. The younger of these suites, the Nûk gneisses, proved to have an emplacement age of about 3.0 Ga, on the basis of zircon U-Pb and whole rock Rb-Sr systems (Baadsgaard & McGregor 1981), and the older, the Amîtsôq gneisses, have ages ranging from 3.7 to 3.88 Ga (see McGregor *et al.* this volume, for

Table 1. Analyses of natural rocks, including basalt composition used in present experiments

wt, %	Basalt				Grey gneiss		Granite	Granulite gneiss	
	Hat Cr. Basalt	Avg. Arch Tholeiite	MORB Basalt	Nük Tonalite	Nük Trondhj.	Nük Granod.	Qörqut Granite	Bamble Zone C	Bamble Zone D
SiO ₂	48.2	49.2	49.8	65.7	71.0	71.7	72.9	67.1	68.9
TiO ₂	0.85	1.19	1.44	0.46	0.22	0.20	0.19	0.97	0.55
Al ₂ O ₃	19.3	15.6	16.4	16.9	15.8	15.4	14.6	13.6	14.3
"FeO"	8.94	13.6	9.93	3.2	1.5	1.4	1.5	6.48	6.79
MnO	0.11	0.15	0.17	0.05	0.02	0.02	0.02	0.04	0.09
MgO	8.72	6.89	7.87	1.7	0.7	0.5	0.5	1.00	1.65
CaO	10.5	10.8	11.5	4.1	3.0	2.2	1.4	3.12	3.54
Na ₂ O	3.11	2.35	2.77	5.0	5.3	5.0	3.6	3.03	4.39
K ₂ O	0.39	0.26	0.22	1.6	1.5	2.6	5.0	4.12	0.15
P ₂ O ₅	-	-	-	0.19	0.08	0.08	0.09	-	-
Total	100.12	99.99	100.00	98.90	99.12	99.10	99.80	99.77	100.36

Hat Creek Basalt: After Anderson & Gottfried (1971), avg. (2) of our analyses; *Average Archaean Tholeiite*: After Condie & Hunter (1976), avg. (4) of our analyses; *MORB Basalt*: Avg. of analyses of Cann (1971), Engel et al. (1965), Melson & Thompson (1971) and Pearce (1976); *Nük Tonalite*: Avg. (12) of McGregor (1979); *Nük Trondhjemite*: Avg. (8) of McGregor (1979); *Nük Granodiorite*: Avg. (13) of McGregor (1979); *Qörqut Granite*: Avg. (18) of McGregor (1979); *Bamble Zone C Pyroxene Gneiss*: Granulite C-408 of Field et al. (1980); *Bamble Zone D Pyroxene Gneiss*: Granulite 2-17 of Moine et al. (1972).

references). The discrete ages of the two generations of grey gneisses led to the concept of continental accretion episodes (Moorbath 1977). Very low initial strontium and lead isotope ratios indicate that crustal residence times of the source materials of the plutons were less than about 50 Ma; that is, the grey gneisses appear to be virtually mantle-derived. The great magnitudes of new crust generated in the two accretion events seemingly imply a specific tectonic mechanism of pulsed accretion. If, during each accretion event, a two-stage melting mechanism was operative, which may be necessary to derive felsic magmas from an ultramafic source (Wyllie et al. 1976), the intervals between melting events must have been comparatively short.

Most of the exposed Archaean cratons contain large tracts of granulite-facies rocks of lithologies similar to those of the grey gneiss-granite-greenstone terrains; they contain the diagnostic mineral orthopyroxene in addition to or instead of the hydrous mafic silicates amphibole and biotite. The metamorphic age of some of the granulites corresponds closely to the time of grey gneiss accretion in the Kapuskasing and Wawa terrains of Ontario (Percival 1983) and with episodes of accretion at 3.88-3.7 Ga and 3.0 Ga in W Greenland (McGregor 1979). It is tempting to conclude that magmatic heating explains the high-grade metamorphism. However, in the W Greenland Tasiusarsuaq terrain, the post-accretion Ilivert-

lik granite has the same age as a broad prograde amphibolite facies to granulite facies belt (2.8 Ga: Pidgeon & Kalsbeek 1978; Friend et al. 1988), and the terminal Archaean age of the Closepet granite of southern India coincides closely with granulite facies metamorphism (Buhl et al. 1983; Taylor et al. 1988). Both of these terrains contain transitional regions 10-20 km wide which display dark orthopyroxene-bearing veins and patches within a mixed-facies zone. Textural relations of the mixed-facies zones have suggested to Hansen et al. (1987) and Friend et al. (1988) that low-H₂O, presumably high-CO₂, fluids were an important agency in the metamorphism. Post-accretion K-rich granites and prograde granulite facies metamorphism may be related phenomena in these areas.

Marked depletion of large-ion lithophile elements (LILE), such as K, Rb, U and Th, characterizes the highest-grade granulites in the Bamble (South Norway) terrain (Field et al. 1980), the southern Karnataka (South India) terrain (Janardhan et al. 1982) and the Scourie (NW Scotland) terrain (Holland & Lambert 1975). The depletion of K₂O in the highest-grade pyroxene gneisses is typically several-fold relative to lower-grade gneisses of otherwise similar chemistry (Table 1). Extremely low K₂O has been interpreted as an effect of primary igneous accretion (Holland & Lambert 1975), and as a metamorphic effect, either attendant upon accretion of the

grey gneiss precursors (Tarney & Windley 1977), or during subsequent metamorphism.

Petrogenesis of grey gneisses

Most authors interpret the petrogenesis of the grey gneisses by assuming partial melting of mafic compositions, either with or without H₂O (McGregor 1979; Size 1979; Martin 1986). A rapid two-stage process is envisioned (melting of mantle peridotite to produce basalt followed by melting of basalt to produce tonalites and trondhjemites) during episodes of crustal accretion. Rare-earth elements (REE) provide a constraint on petrogenesis of grey gneisses. Fractionated REE with marked depletion of the heavy REE, commonly encountered in cratonal terrains, betokens a garnet-bearing residuum of partial melting, hence higher pressures of partial melting (O'Nions & Pankhurst 1978). Some 3.0 Ga trondhjemites from the Dharwar Craton of South India have unfractionated REE patterns, implying derivation of liquids at lower pressures with a garnet-free residuum (Rogers & Callahan 1989).

Essentially two kinds of tectonic mechanisms have been suggested for grey gneiss petrogenesis. One is static remelting of basalt in the roots of an accumulated thick pile analogous to the Hawaiian swell (Richter 1985). The other proposal envisions remelting of basalt in early subduction zones to form primitive island arcs and Andean margins (Krogstad *et al.* 1989). Large recumbent structures in some Archaean cratons have suggested the occurrence of important horizontal motions, implying some form of early plate tectonics (e.g. Bridgwater *et al.* 1974, in W Greenland).

Petrogenesis of mafic schists

Some authors regard the mafic volcanic rocks of the cratonal schist belts as likely examples of the source material from which the grey gneiss precursors were derived (Condie & Hunter 1976). The low-K basalt compositions (Table 1), analogous to modern mid-ocean ridge basalt (MORB), may account for the trondhjemitic character of the most felsic derivatives. Mechanical intercalation of some residual ocean floor basalt and asso-

ciated sediments into the newly-formed cratonal gneiss terrains could have been essentially synchronous with formation of gneissic foliation. Cratonal mafic volcanics which are younger and unconformable are possibly analogous to continental flood basalts. In the Dharwar craton greenstone belts, these may have been erupted into linear pull-apart basins within zones of long-lived cratonal transcurrent faults (Chadwick *et al.* 1989). Horizontal tectonics are prominent in both of these postulated settings.

Petrogenesis of K-rich granites

The most voluminous Archaean K-rich granites post-date and sometimes cut across both grey gneisses and greenstone belts. Most authors agree that the granites represent remelting of earlier crust, rather than juvenile derivation from the mantle (Wyllie *et al.* 1976). In this process, metasomatic redistribution of K₂O should be considered, in that K is a very mobile element capable of being transported by aqueous fluids. K-enriched portions of the crust and upper mantle are especially prone to subsequent melting because of high radioactivity and compositional factors. Many authors discuss K-enriched portions of the upper mantle as source regions for alkalic basalts (Griffin *et al.* 1984; Menzies *et al.* 1985), and most appeal to metasomatic K-transfer. It seems likely that this kind of process could affect the lower crust as well (Stolz & Davies 1989), perhaps contributing both to granulite facies K-depletion, as in Bamble Zone D (Table 1) and to K-enrichment of the source regions of the late Archaean granites.

Previous experimental work

Earlier experimental work has shown the possibility of generating low-K granitoids by partial melting of tholeiite, although the results have not been comprehensive or entirely definitive. Helz (1976) experimentally melted Hawaiian tholeiite model compositions under H₂O-saturated conditions at 5 kbar with QFM and HM buffers. Her lowest-K starting composition, the 1921 Kilauea tholeiite, had 0.77 wt. % K₂O. Near the 5 kbar solidus at 700°C, quenched glasses were granitic,

with $K_2O > Na_2O$ but Na_2O exceeded K_2O at higher temperatures and degrees of melting. Helz found considerable difficulty in electron microprobe analysis of alkalis in the hydrous glasses because of volatilization losses. Na_2O was semi-quantitatively estimated on the basis of feldspar analyses, point-counting of quenched charges, and mass-balance. Her adjusted glass compositions depart from typical tonalite-trondhjemite trends by very high Al_2O_3 (17–22 wt. %). Amphibole was stable to at least 1050°C on the QFM buffer. Garnet was not encountered.

Pulber & Rutherford (1983) experimentally melted low-K oceanic tholeiite at very low $f(O_2)$ (graphite-methane buffer) at 1–3 kbar. They found rhyolitic liquids for small amounts of partial melting (~ 10%) from a tholeiite of 0.4 wt. % K_2O , and trondhjemitic liquids only from comparable melting of a starting material extremely low in K_2O (0.06 wt. %). They showed that the instability of amphibole at pressures less than 2 kbar is a factor in producing granitic, rather than trondhjemitic, partial melts from basalts with moderately low K_2O .

Johnston (1986) investigated partial melting of an anhydrous high-Al basalt composition at 10–31 kbar and 1250–1500°C. Most of his partial melts were mafic, but a few were intermediate (technically tonalitic) with up to 60 wt. % SiO_2 . All melts were very high in Al_2O_3 and CaO, thus unlike natural tonalites. Johnston inferred by extrapolation of his measured liquid compositions that trondhjemitic liquids could be produced at pressures greater than 21 kbar and low degrees of partial melting (10–15%). Garnet coexists with liquid only above 24 kbar, even in this high-Al bulk composition.

Beard & Lofgren (1989a) reinvestigated partial melting of low-K tholeiite under H_2O -saturated conditions at 2 and 5 kbar. They produced tonalite-like melts which were, however, higher in Al_2O_3 and CaO than typical grey gneiss or modern tonalite compositions. They concluded that orogenic calc-alkaline tonalites are not produced by H_2O -saturated melting of tholeiite. Beard & Lofgren (1989b) experimentally melted tholeiite greenstones and amphibolites without excess H_2O vapor at 3 kbar. They found that tonalitic melt is produced by about 20% melting in reactions terminal to amphibole and quartz. Orthopyroxene, clinopyroxene, and plagioclase are the

residual silicates under these conditions. This work demonstrates that tonalitic liquids can be produced by vapor-undersaturated melting of tholeiitic compositions at low pressures. Wolf & Wyllie (1989) investigated vapor-absent melting of a natural amphibolite very low in K_2O (0.06 wt. %) and high in CaO (14.3 wt. %) at 10 kbar. Above 750°C, liquids formed which were generally tonalitic, but very high in CaO (14 wt. %) and Al_2O_3 (19–21 wt. %). Garnet and amphibole coexisted with liquid and disappeared simultaneously above about 1000°C.

The previous experimental studies have demonstrated some of the conceptual advantages of deriving a felsic early crust by partial melting of tholeiite in H_2O -bearing systems. Melting occurs over a greatly expanded temperature range relative to dry systems, and produces felsic liquids immediately without the need for extensive subsequent fractionation. Melts with residual garnet can be produced at 10 kbar or less: garnet and amphibole accumulation could have occurred in the early lower crust by crystal settling. The bimodal trondhjemite-basalt suite of the Archaean cratons, which typically lacks andesitic rocks, can be explained plausibly by remelting of basaltic compositions to yield felsic grey gneiss compositions, as postulated by Barker & Arth (1976).

Scope of the present work

The earlier studies have found that typical grey gneiss compositions could be produced only under exceptional circumstances under the ranges of conditions that have been investigated. Most of the studies found that natural grey gneiss compositions can be matched by melting of tholeiite of extremely low K_2O content or by quite small amounts of melting. Subsequent crystal fractionation, particularly of plagioclase, would probably be necessary to reduce Al and Ca to typical grey gneiss levels, thus further restricting the amounts of liquids which could be yielded in early crust formation. The present work expands on earlier work by investigating partial melting of tholeiite under greatly expanded ranges of pressure, temperature and degree of H_2O -undersaturation, using low-K tholeiites of both low-Al and high-Al contents. In particular, physical and chemical regimes are sought in which abundant liquids of

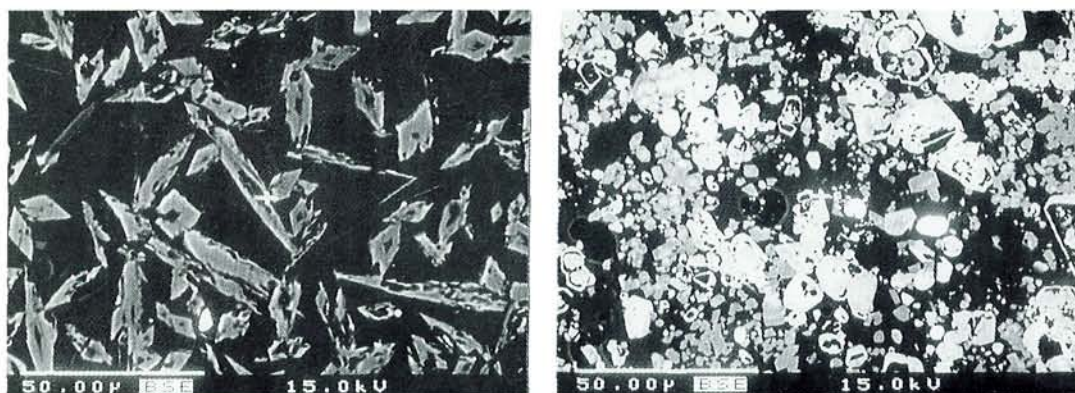


Fig. 1. Backscattered electron images of quenched charges from runs. The images were tuned to give maximum contrast between quenched liquid (dark) and crystals. 1A: Run on AAT + 15% H₂O at 1050°C and 21.0 kbar. Amphibolite, + liquid. 1B: Run on AAT + 5.12% H₂O at 902°C and 20.9 kbar. Garnet + liquid + clinopyroxene + ilmenite. Garnet shows resorption and regrowth in hollow shells enclosing relics of original garnet pregrown at 1002°C and 17.9 kbar.

strongly controlled (buffered) grey gneiss compositions might be yielded directly by melting of mafic rocks. The possibility of deriving K-rich granite by either H₂O-excess or dehydration melting of mafic rocks is explored. Temperature-pressure-hydration regimes are sought where orthopyroxene might be an abundant phenocryst

phase in felsic magmas; this would provide evidence on the hypothesis of syn-accretion granulites.

Table 2. Analyses of quenched melt (glass) from selected runs on AAT composition and comparisons with natural rocks

Run #	Expt'l (HC)		Experimental (AAT)							Tonalites		Trondhjemites			
	1	2	1	2	3	4	5	6	7	AAT	1σ	Amit.	AAT	1σ	Follst.
T°C	901	1001	1050	901	898	1002	850	1001	900	avg. (22)			avg. (27)		
P kb	14.9	17.9	21.0	14.9	13.1	13.2	18.0	17.9	29.7	5-30			5-30		
Class	Ton	Trdj	Ton	Ton	Ton	Ton	Trdj	Ton	Trdj						
H ₂ O %	4.0	4.0	14.8	14.3	5.1	5.1	5.1	2.7	2.7	0.8-15			0.8-5.1		
wt. %															
SiO ₂	71.3	65.7	66.4	68.4	66.4	62.6	74.1	70.3	74.9	68.15	3.20	67.8	71.84	1.61	71.4
TiO ₂	0.28	1.10	0.64	0.32	0.67	1.36	0.28	0.52	0.41	0.68	0.37	0.48	0.47	0.24	0.23
Al ₂ O ₃	18.9	19.9	19.2	18.6	16.2	17.2	14.4	16.1	13.9	16.3	1.12	16.3	15.4	0.75	16.6
"FeO"	1.86	32.46	2.58	1.57	4.96	7.02	1.73	3.36	1.28	4.04	1.62	3.66	2.17	0.74	1.41
MnO	0.13	0.06	0.25	0.09	0.08	0.08	0.12	0.00	0.00	0.07	0.06	0.06	0.07	0.05	0.02
MgO	0.75	0.68	0.15	0.23	2.26	1.56	0.51	0.28	0.21	1.05	0.50	1.53	0.52	0.23	0.52
CaO	3.77	2.87	10.0	5.75	5.66	5.00	1.75	4.57	1.47	4.67	1.39	3.97	2.36	0.62	3.07
Na ₂ O	2.16	5.05	0.44	4.74	3.13	4.62	6.34	4.52	4.95	4.32	1.25	4.68	5.99	0.84	5.41
K ₂ O	0.85	1.18	0.28	0.30	0.68	0.56	0.74	0.69	2.87	0.74	0.26	1.53	1.22	0.46	1.31
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.1	100.0	100.1	-	100.0	100.0	-	100.0
H ₂ O %	14.8	14.4	24.8	14.7	11.3	13.1	12.8	10.5	12.0						
xls	GtAm	GtAm	Am	GtAm	GtAm	Gt	GtCp	GtCp	GtCp						
(An%)	Mt			Mt	Pl(52)			Qz	KyQz						

Symbols: HC: Hat Creek basalt starting material; AAT: Average Archaean tholeiite starting material; Amit.: Avg. Amitsoq tonalite (McGregor 1979), recalculated to dry 100%; Follst.: Type locality Trondheim (Follstad) trondhjemite (Size 1979); Ton: Tonalitic normative composition (O'Connor 1965); Trdj: Trondhjemitic normative composition; Gt: Garnet; Am: Amphibole; Cp: Clinopyroxene; Pl: Plagioclase (Molar composition); Qz: Quartz; Mt: Magnetite; Il: Ilmenite; Ky: Kyanite; H₂O contents from microprobe analysis totals.

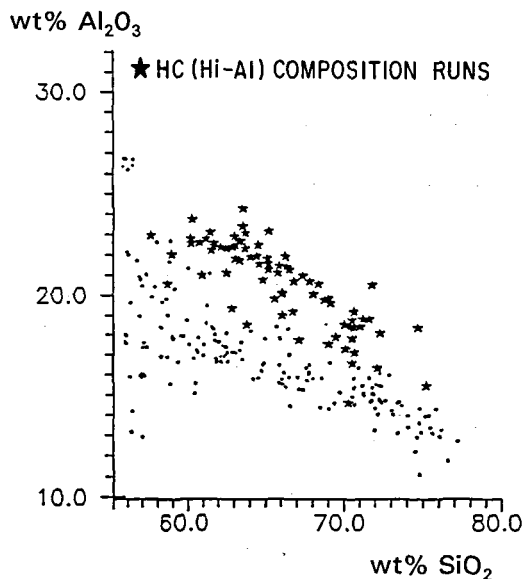


Fig. 2. Silicic variation diagram for Al_2O_3 . A star indicates an experimental partial melt from the HC (high-Al) basalt starting material; a dot indicates a natural rock or average of a group of rocks. All analyses recalculated to 100% on a volatile-free basis. The diagram indicates that most natural igneous rocks are not derived *directly* from partial melting of high-Al basalt. Sources for rock compositions: Barth & Ehlig (1988); Best (1982); Bingen et al. (1988); Borley (1974); Bowden & Turner (1974); Bridgwater & Harry (1968); Condie & Hunter (1976); Ewart (1979); Floor (1974); Gerasimovsky et al. (1974); Gill & Powell (1981); Glikson (1979); Iddings (1913); Pavlenko (1974); Philpotts (1974); Sørensen (1974); Wilkinson (1974); Verma & Nelson (1989); Weaver & Tarney (1980); Wimmenauer (1974); Winther (1986).

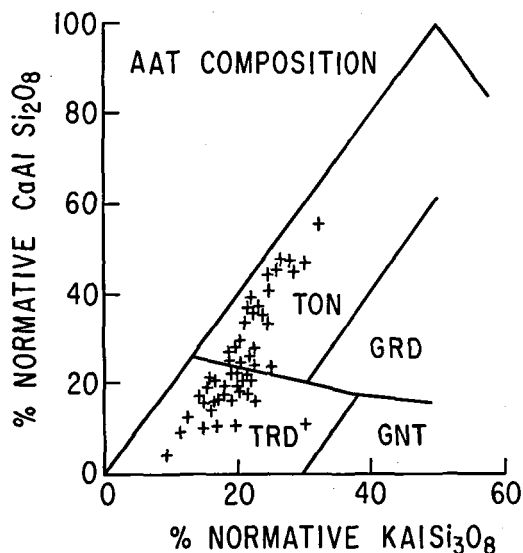


Fig. 3. O'Connor (1965) classification of compositions of quenched melt from runs on AAT composition. Coordinate (0,0) is 100% $\text{NaAlSi}_3\text{O}_8$ among feldspar components. TON = tonalite, TRD = trondhjemite, GRD = granodiorite, GNT = granite.

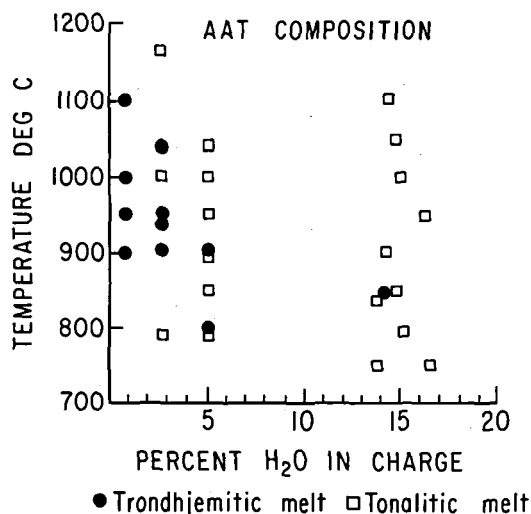


Fig. 4. Temperature and bulk H_2O controls of trondhjemitic versus tonalitic quenched melt from AAT runs. Low H_2O and low temperature favor trondhjemitic partial melts.

Nature of present experiments

Two low-K basaltic compositions were tested. One is a high-Al natural basalt from Hat Creek, California (18.2 wt. % Al_2O_3) and the other is the average Archaean tholeiite compiled by Condie & Hunter (1976) (Table 1) with 14.8 wt. % Al_2O_3 . This composition was prepared from finely ground and homogenized mixtures of reagent oxides and silicates. The H_2O was introduced in the form of $\text{Al}(\text{OH})_3$ and liquid water in amounts of about 1%, 2%, 5% and 15% by weight. The largest amount of H_2O was sufficient to saturate partial melts and create a free vapor phase during the experiments. Experiments were carried out in the 3/4" diameter piston-cylinder apparatus with NaCl pressure medium. Runs covered a pressure range of 5–30 kbar, a temperature range of 750–1100°C, and run times of one to ten days. Oxygen fugacity was controlled by QFM buffers external to the sealed gold capsules. It was demonstrated by a number of different tests that the oxygen buffer was effective and that Fe loss to the capsules was negligible. All synthetic phases were analyzed with the electron microprobe. The H_2O contents of the quenched melt phase (glass) were determined to be 9–16 wt. % by microprobe totals after correcting for Na loss in the analyses.

Phases produced in runs were usually conspic-

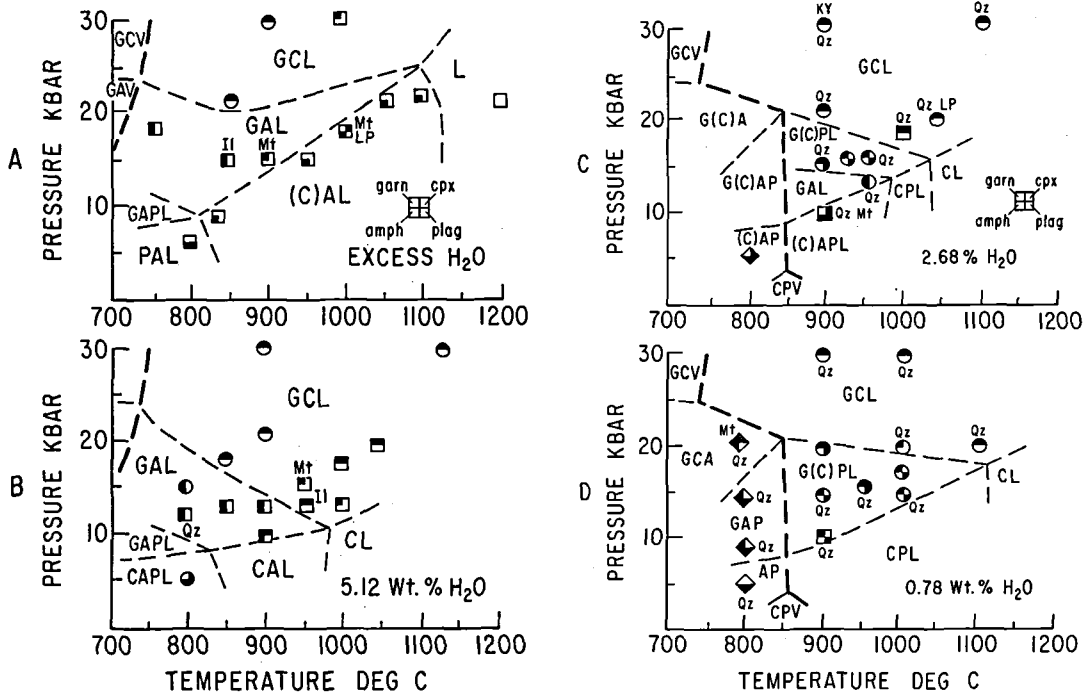


Fig. 5. Pressure-temperature fields of crystalline phases, coexisting with liquids and subsolidus, consistent with runs on AAT composition. *Circular symbol*: trondhjemitic melt; *Square symbol*: tonalitic melt; *Diamond symbol*: subsolidus; *L* = liquid; *G* = garnet; *C* = clinopyroxene; *A* = amphibole; *P* = plagioclase. *Minor phase detected*: *Mt* = magnetite; *IL* = ilmenite; *Qz* = quartz; *LP* = low-Ca pyroxene; *Ky* = kyanite. *Four-fold filled-sector designations*: Major crystalline phases present as indicated in the figure key. *Bold dashed line*: approximate location of solidus. Vapor-saturated solidus after Lambert & Wyllie (1972).

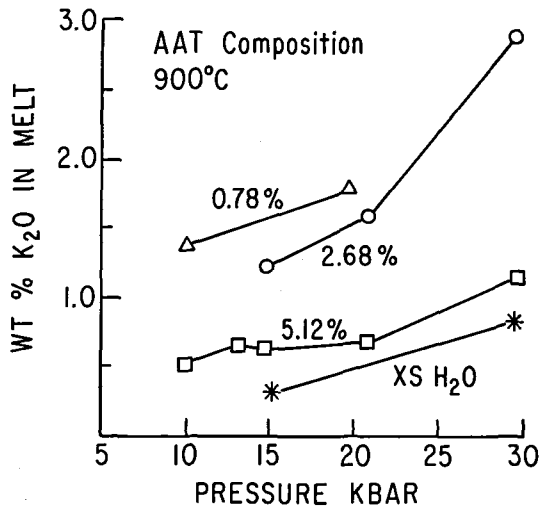


Fig. 6. Effect of run pressure on K_2O contents of quenched melts from AAT runs at $900^\circ C$. Low H_2O contents and high pressures favor K_2O -richer partial melts.

uous in polished mounts of the quenched charges (Fig. 1). They included glass, garnet, amphibole, clinopyroxene, plagioclase, quartz, and rare magnetite, ilmenite, and orthopyroxene. Relative amounts of phases, including glass, were determined by automated electron-beam point-counting. Reliability of point-counting was established by comparing the nominal bulk composition with the sum of the products of the modes and their compositions (mass-balance). Further details of experimental procedure are presented elsewhere.

Major results of experiments

Effects of starting material and H_2O content

The high-Al basalt starting material did not produce realistic tonalitic or trondhjemitic partial melts. Analyses of quenched melts in two typical runs are listed in Table 2. It is seen that the Al_2O_3 contents are very high. The variation diagram of Fig. 2 shows the unrealistically high Al_2O_3 con-

Table 3. Analyses of minerals crystallized in selected runs on AAT composition

Run #	Garnets						Amphiboles			Clinopyroxenes			
	2	3	4	5	6	7	1	2	3	4	5	6	7
T°C	901	898	1002	850	1001	900	1050	901	898	1002	850	1001	900
P kb	14.9	13.1	13.2	18.0	17.9	29.7	21.0	14.9	13.1	13.2	18.0	17.9	29.7
H ₂ O %	14.3	5.1	5.1	5.1	2.7	2.7	14.8	14.3	5.1	5.1	5.1	2.7	2.7
wt %													
SiO ₂	38.8	38.9	39.1	38.2	36.9	37.7	40.3	42.9	42.2	48.8	53.7	47.7	53.5
TiO ₂	0.91	0.87	0.51	1.51	1.79	1.15	1.38	0.64	1.95	0.64	0.25	0.86	0.53
Al ₂ O ₃	20.2	21.4	22.0	20.8	21.1	20.3	12.8	12.8	14.7	6.28	3.94	7.77	13.5
"FeO"	22.1	21.7	20.2	19.4	20.3	21.8	16.6	13.4	17.6	12.4	14.8	15.3	6.53
MnO	0.20	0.15	0.09	0.22	0.10	0.20	0.18	0.00	0.21	0.00	0.20	0.15	0.15
MgO	7.70	8.45	9.30	5.00	8.57	3.96	11.5	13.9	8.90	9.64	24.3	5.41	6.79
CaO	10.5	8.15	8.19	13.8	8.84	12.3	8.00	10.7	9.33	20.2	3.10	20.4	13.3
Na ₂ O							2.25	2.33	2.34	1.48	1.04	1.88	5.90
K ₂ O							0.24	0.23	0.66	0.11	0.11	0.07	0.10
Total	100.4	99.6	99.4	98.9	98.3	98.7	93.3	96.9	97.9	99.6	101.4	99.5	100.3
Si	2.98	2.98	2.98	2.97	2.88	2.98	6.28	6.35	6.30	1.86	1.92	1.85	1.92
Ti	0.05	0.05	0.03	0.09	0.11	0.07	0.16	0.07	0.22	0.02	0.01	0.03	0.01
Al	1.83	1.93	1.97	1.91	1.94	1.89	2.35	2.24	2.58	0.28	0.17	0.35	0.57
Fe	1.42	1.39	1.29	1.26	1.33	1.44	2.17	1.66	2.20	0.39	0.44	0.49	0.20
Mn	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.00	0.03	0.00	0.01	0.00	0.01
Mg	0.88	0.96	1.05	0.58	1.00	0.47	2.68	3.07	1.98	0.55	1.29	0.31	0.36
Ca	0.86	0.67	0.67	1.15	0.74	1.15	1.34	1.71	1.49	0.82	0.12	0.84	0.51
Na							0.68	0.67	0.68	0.11	0.07	0.14	0.41
K							0.05	0.04	0.13	0.01	0.01	0.00	0.00
Σ	8.03	8.00	8.00	7.98	8.01	8.01	15.73	15.81	15.64	4.04	4.04	4.01	3.98

Run numbers refer to same runs as in Table 2. *Clinopyroxenes*: #5 is low-Ca clinopyroxene; #7 is omphacitic clinopyroxene; others are augites.

tents of quenched melts in the high-Al basalt runs compared to many published grey gneiss and other igneous rock compositions. Our tentative conclusion is that high-Al basalt compositions are not suitable for direct generation of Archaean continental crust.

In contrast to the high-Al basalt, the average Archaean tholeiite starting material yielded quenched glasses whose compositions are very similar to typical grey gneiss compositions. The present glass analyses were classified as tonalite or trondhjemite by the normative classification of O'Connor (1965) (Fig. 3). The K₂O is low in all of the quenched melts: only one charge yielded a glass close to the field of granodiorite. Table 2 gives the averages of the oxide analyses of quenched melts from 27 runs in the ranges 5–30 kbar and 800–1100°C and with 1–5 wt. % H₂O which are classified as trondhjemites. The close correspondence with the type trondhjemite from Trondheim, Norway (Size 1979) is evident. The only oxide more than one standard deviation from the present average is Al₂O₃. Table 2 shows

the average glass analyses from 22 runs which can be classified as tonalites. The close correspondence with the compilation of McGregor (1979) is evident, except for higher K₂O in the natural composite.

Quenched glasses from runs with excess H₂O (15 wt. %) were almost always tonalitic, with compositions similar to those from H₂O-undersaturated runs in a few experiments below 850°C and above 15 kbar. At other run conditions, melt compositions were technically tonalitic, but most of them were higher in Al₂O₃ (average 19.6 wt. %) and CaO (average 8.8 wt. %) than typical tonalitic grey gneisses. This result parallels that of Beard & Lofgren (1989a) from H₂O-saturated melting experiments on Iceland tholeiite, and suggests that vapor-saturated partial melting of basaltic compositions was not a common mechanism of early crust generation. In general, higher H₂O contents of our starting material favored tonalitic partial melts, as shown in Fig. 4. At a constant H₂O content, higher temperatures and lower pressures favor tonalitic melts, as shown in

Fig. 5. These effects are attributable to the amounts of hornblende and garnet absorbed into melts: higher H_2O contents increase the amounts of melt produced, other factors being equal.

The highest K_2O contents of any melts produced in the present study were generally less than for McGregor's (1979) average Amitsôq granodiorite. Higher K_2O was favored by low H_2O in the charge, which inhibited the formation of amphibole. Melts of elevated K_2O contents were encountered in the H_2O -undersaturated melting of AAT at 20–30 kbar, above the stability limit of amphibole (Table 2). Fig. 6 shows that the effect of pressure on K_2O content of the liquid is systematic. The high-pressure liquids are also low in Al_2O_3 and have moderate Na_2O contents because of a garnet- and omphacite-rich residue. It appears that small amounts (10–20%) of melting of a low-K-tholeiite composition with low H_2O content at pressures in the 30-kbar range can produce compositions similar to cratonal granodioritic gneisses.

Phenocryst phases in the AAT runs

Amphibole was found abundantly in most runs below 20 kbar and temperatures up to 1100°C, which is the maximum temperature allowed by the NaCl pressure medium. The amphibole is a rather standard product (typical analyses in Table 3). It is generally pargasitic, with about 0.3 wt. % K_2O . This value is nearly the same as for the liquid in runs with only amphibole and liquid. The melt-amphibole partition coefficient near unity, and the great thermal stability of the amphibole help to maintain the low-K grey gneiss trend of partial melts.

Garnet was ubiquitous above 10 kbar, except in the H_2O -excess runs. It proved possible to reverse the appearance of garnet: runs which were pre-reacted to garnet-bearing assemblages at high pressures and then reequilibrated at pressures below 10 kbar lost most or all of their garnet. Reequilibration of garnet in pre-reacted starting materials usually produced a variety of resorption and regrowth textures, including atoll texture (Fig. 1b). The garnet stability boundaries are not well-constrained by the runs in Fig. 5. Our preliminary placement of the garnet-in line on the AAT composition with ~2 wt. % H_2O is shown in Fig. 7.

Garnet analyses are quite variable (Table 3). The typical garnet is high in grossular with about 15 mole % pyrope. The high grossular content of residual garnet is a major factor in producing trondhjemitic, rather than tonalitic, liquids. The absolute stability of garnet compositions at various conditions of pressure, temperature and H_2O content is a complex problem which we cannot address in this preliminary study.

Plagioclase (oligoclase to labradorite) was a phenocryst at temperatures up to ~1050°C for runs with H_2O below 3 wt. %, but was much more restricted in runs with higher H_2O , as shown in Fig. 5. Crystalline anorthite was one of the starting material phases, and it proved difficult to reequilibrate this phase in the low- H_2O runs. Complex zoning of phenocryst plagioclase prevented accurate characterization.

Clinopyroxene formed in many of the H_2O -undersaturated runs. It occurred in three varieties: augite, low-Ca clinopyroxene and omphacitic pyroxene. Typical analyses of these types are given in Table 3. Low-Ca clinopyroxene was recognized by CaO contents in the range 1–4 wt. %. Omphacitic pyroxene contained 4–8 wt. % Na_2O and was found only above 20 kbar.

Orthopyroxene with CaO content below one wt. % was found only in a few runs near 1000°C. The stability of this phase relative to low-Ca clinopyroxene is not certain.

Quartz was commonly encountered. *Forsteritic olivine* was encountered in only three runs above 5 kbar. Its stability is not certain (one occurrence was with quartz). *Magnetite* and *ilmenite* were occasional run products. *Kyanite* was found in a run charge at 30 kbar. It is not clear if it was a phenocryst or a quench product from the liquid.

Fig. 5 gives a generalized account of the fields of stability of crystalline phases coexisting with liquid based on the AAT experiments. Although the suggested field boundaries are consistent with the experimental run products, they are not tightly constrained, and not confirmed by reversed experiments.

Amounts, H_2O contents, and compositional controls of liquids

The amounts of quenched liquid in the charges varied from 20 to 60 percent in the ranges of

temperature, pressure and H₂O content investigated. At near solidus temperatures, the amounts were too small for reliable point-counting. The lowest melt percentages coincided with the most K₂O-rich melts; these were from runs with 2.7% H₂O or less. Melts in amounts greater than 55% were tonalitic. In spite of the great variations in physical parameters, H₂O contents of starting materials, and amounts of melt produced, the chemical variation of melts is quite small. H₂O in liquids is 10–15 wt. % in all runs without excess vapor, with only small dependence on melt composition, pressure, temperature, amount of H₂O in the charge, or degree of melting. The remarkable buffering of the liquid is a “plateau effect” similar to that governing the composition of basaltic liquid generated over a wide range of partial melting of peridotite at low pressure (Wyllie 1960; Scarfe *et al.* 1972). An obvious implication of this compositional monotony is that grey gneiss-like granitoids may result from simple extraction and freezing of partial melts of hydrous low-K-tholeiite over a wide range of conditions without need for significant fractionation.

The runs at 27–30 kbar produced melts with the smallest Al₂O₃ (Table 2) because of the large amounts of garnet crystallized. These melts, averaging about 14 wt. % Al₂O₃, resemble in composition the low-Al suite of grey gneisses in the western Dharwar craton (Rogers *et al.* 1986). The low-Al Dharwar gneisses also typically have higher K₂O contents than other Indian Archaean trondhjemitic gneisses.

Our runs did not produce any high-K liquids comparable to the late-Archaean K-rich granites or to granitoid gneisses like some of the undepleted Zone C rocks of the Bamble area (Table 1). Moreover, it is doubtful that such granitic liquids could be produced even by third-stage melting of low-K granitoids. Johnston & Wyllie (1988) found only small K₂O enhancement in vapor-excess and vapor-undersaturated partial melting at 10 kbar of an Archaean trondhjemitic composition with 2.3 wt. % K₂O: the most potassic liquid they produced had only 2.9 wt. % K₂O. It is equally unlikely that fractional crystallization of a viscous felsic magma could give rise to large volumes of granite with 4–6 wt. % K₂O. Some independent (possibly metasomatic) K₂O enrichment process seems necessary.

None of our experimental liquids approached

the low K₂O values observed in some of the depleted Zone D pyroxene gneisses of Bamble (Table 1). Purely igneous processes seem quite unlikely to have resulted in such K-depletion on a large scale, and metasomatic processes seem necessary here also. This conclusion is consonant with that of Lamb *et al.* (1986), who showed the impossibility of modelling Rb depletion in the Bamble Zone D gneisses by conventional fractional crystallization.

Interpretations and conclusions

Gneiss precursors as second-stage magmas

The most significant finding of the present work is the ubiquitous tonalitic to trondhjemitic compositions of our quenched partial melts of low-K tholeiite under H₂O-undersaturated conditions. The immediate generation of these liquids over a broad range of physical conditions and water contents strongly suggests remelting of hydrated basalt as a likely mechanism of generation of the first large felsic continental masses. Other authors have advanced this conclusion on the basis of trace element geochemistry (Barker & Arth 1976; Tarney *et al.* 1979; Martin 1986; Arkani-Hamed & Jolly 1989). The grey gneiss-like compositions of partial melts of low-K tholeiite can be produced at conditions as modest as 800°C and 6 kbar; i.e., conditions appropriate for a shallow subduction zone or the base of a thick mafic early crust, according to the present study.

The discrete radiometric ages of generations of grey gneiss seem to demand an episodic mechanism in which large quantities of a low-K mafic source are rapidly mobilized. Static models of early continent formation (Richter 1985) in which thick basaltic continents are remelted at their roots do not seem adequate to have produced great volumes of low-K gneisses over relatively brief periods, unless the protocontinental roots became hydrated by some mechanism not operative today. Modern thick basaltic accumulations, as in Hawaii or Iceland, do not give rise to major quantities of felsic by-products. The small amounts of Icelandic rhyolite and plagiogranite may represent residual liquids of extreme fractional crystallization of tholeiite (Spulber & Rutherford 1983) or small partial melt fractions

of tholeiite at low pressures under H_2O -excess conditions (Helz 1976), perhaps formed in deep meteoric circulation cells. The onset of subduction recycling in the Archaean, as envisioned by Martin (1986), could provide a mechanism for the sudden generation of large volumes of granitoids. Plausible conditions of remelting of tholeiitic amphibolite are near $900^\circ C$ and 15 kbar, where somewhat cooler subduction paths could have allowed residual garnet and fractionated REE patterns of granitoids, and somewhat hotter subduction paths could have eliminated garnet from the residue assemblage. These controls on granitoid composition are quite similar to those advocated by Martin (1986).

Two possibilities for generating somewhat K-richer granitoids from melting of low-K tholeiite are suggested by the present work. The first is deeper melting of a subducted slab. At pressures above the stability of amphibole, more K_2O would go into the liquid, which would, in general, explain the trend shown in Fig. 6. Such magmas might tend to be generated late in an accretion episode, under conditions of a foundering slab of reduced subduction velocity. The second possibility is upward transport of K_2O in the abundant vapor phase which is necessarily liberated when the granitoid magmas freeze. Higher-level plutonic bodies would thus be subject to metasomatic K-enrichment.

Origin of granulite facies terrains

The H_2O fluids liberated by freezing of grey gneiss precursors would not be in equilibrium with orthopyroxene at deep-crustal pressures: granulite facies assemblages, if they formed in the accretion process, would have to be differentiated during an early H_2O -undersaturated magmatic stage. The rarity of orthopyroxene encountered as a phenocryst phase in our experiments makes it seem doubtful that the pyroxene gneisses of Archaean cratons commonly formed by "freezing into the granulite facies," as envisioned by Holland & Lambert (1975) and Drury (1980), if H_2O was the major volatile species involved. Igneous fractionation as a mechanism to produce Rb-depleted granulites also has the disadvantage that it requires large amounts of

fractionation of feldspars, which are hard to separate from viscous felsic magmas.

It is possible that abundant pyroxenes could crystallize from H_2O -saturated felsic liquids at very low pressures, below the stability field of amphibole (pyroxene-hornfels facies). Pyroxene granites resulting from this process are found in the upper cupola portions of the Cloudy Pass batholith of Washington state (Grant 1969) and the Cheviot (N England) granite (Haslam 1986). These pyroxene-bearing granitoids, if subsequently buried deeply, as, for instance, during collision processes, could be metamorphosed in a dry condition, essentially retaining igneous pyroxenes. If the magmas contained large amounts of CO_2 , the fluids released upon freezing could have been in equilibrium with orthopyroxene and could conceivably have carried off LILE, particularly Rb, leaving depleted granulites, as envisioned by Lamb *et al.* (1986). Our experimental results for hydrous systems do not address this possibility. Additional pyroxenes could have been produced by breakdown of amphibole during metamorphism; this process has been demonstrated on a limited scale by field observations of arrested charnockite formation in southern India (Hansen *et al.* 1987) and in the Bjørnesund area of W Greenland (Friend *et al.* 1988).

Mafic residues and mantle enrichment

The abundant garnet, clinopyroxene and amphibole residual in partial melting of hydrous basalt could have accumulated by gravitative settling in the lower portions of the primordial crust. Garnet granulites in minette pipes cutting the western Sierra Nevada of California (Dodge *et al.* 1988) and amphibole-garnet granulite masses in the deeply-dissected southern Sierra arc (Ross 1985) suggest that similar processes may have occurred during more recent continental growth periods.

A significant part of the mafic residues may be carried by low-angle subduction to the bottom of the crust or to the subcontinental upper mantle, where they may be seismologically indistinguishable from peridotite mantle. It seems almost inevitable that the mantle under the cratons must, to some extent, be chemically and mineralogically different from suboceanic mantle by virtue

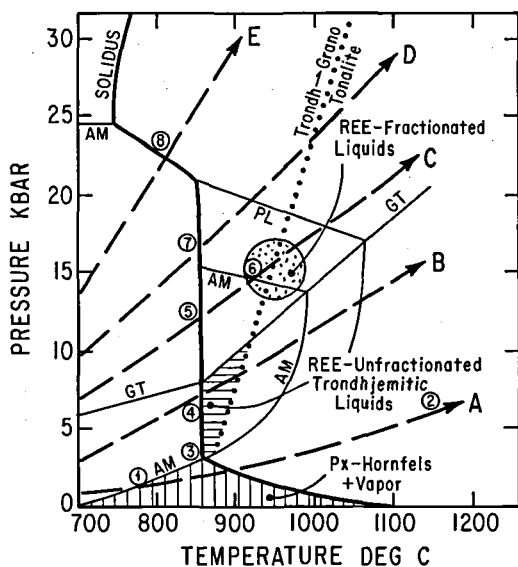


Fig. 7. Semi-schematic P-T stability diagram of low-K, moderate-Al basalt with, ~2 wt. % H₂O, based on present AAT runs. Solidus is bold line. Paths A-E indicate increasingly cooler geothermal regimes. Very hot path A does not penetrate the field of amphibole (AM) + liquid; hence generation of felsic magmas by a subduction process is not feasible. Path B does not intersect garnet (GT) field of stability, hence felsic magmas produced are REE-unfractionated. Path C produces REE-fractionated magmas of trondhjemitic to tonalitic character near the amphibole-out line; this P-T path is therefore considered feasible for the origin of many Archaean gneiss compositions. Paths D and E produce K-enriched partial melts by dehydration melting of amphibolite; path D may leave a plagioclase (PL)-bearing residue. For significance of numbered points, see text.

of containing garnet-amphibole-clinopyroxene residues from crust formation. A mantle lodging place for these ultramafic residues would be enriched in Al, Ca, alkalis, H₂O and trace elements. Enrichment of the upper mantle by subduction processes is frequently discussed (Saunders & Tarney 1984; Davidson 1987; Pe-Piper & Piper 1989). This enriched state may be a transient one because of the enhanced heat production, volatiles and alkalis, which could eventually lead to the production of alkaline mafic or ultramafic magmas. The time-scale of this post-orogenic magmatism would be variable, depending on the degree of mantle enrichment.

Origin of K-rich granites

Metastability of lower to middle crust or upper mantle enriched in heat-producers and hyperfusibles is a logical working hypothesis for the origin

of the late Archaean K-rich granites. Subsequent to massive accretion of granitoids, the lower crust and upper mantle would begin to self-heat at a rate roughly three times as fast as at present. Several modes of granite production suggest themselves. Basaltic melts generated in melting of enriched mantle might intrude the crust, causing remelting. Freezing of volatile-rich magmas in the lower crust would liberate H₂O-CO₂ volatiles, which could carry K₂O and heat upward, thus inducing melting in the middle crust. Some of the K could be liberated from biotite and amphibole in granulite facies metamorphism of the lower crust. The complementary roles of K-depletion and K-enrichment may explain the association of postaccretion granites and granulites in the late Archaean. The action of volatiles in such processes may be an essential, though at present poorly understood, factor.

A tectonic factor which may deserve consideration in the genesis of late-Archaean K-rich granites is late-orogenic transcurrent faulting. Such large-scale faulting is often associated with more modern voluminous post-orogenic granites, such as those of the Najd Fault Zone, western Arabian Shield (Stern 1985). Change from direct plate convergence to oblique and eventually transcurrent motions is well-documented in post-Archaean plate tectonics (Bobyarchick 1988), and is implicated with increasing frequency in discussions of Archaean tectonics, as in the southern Superior Province (Devaney & Williams 1989). Late-orogenic transcurrent faulting might be a fundamental factor in liberation of volatiles and alkalis from a lithosphere previously enriched by subduction.

Summary

The experimental work described here is compatible with a uniformitarian view of crustal accretion and post-accretion magmatism and metamorphism. Ancient continental crust could have been generated episodically by partial melting of subducted hydrous ocean-floor basalt. Tonalitic and trondhjemitic plutons may have accumulated in primitive island arcs and Andean margins in a manner analogous to modern calc-alkaline magmatism, the major difference being the low-K character of the ancient subduction-zone mag-

mas. This difference could be explained by the lack of a K-rich sedimentary component in the subducted plate, the absence of contamination by a previously differentiated crust, or by generally shallower angles of early subduction zones, which, according to the present experimental work, would produce magmas somewhat lower in K at lower pressures. The calc-alkaline character, and, to some extent, the low-K aspect of the Archaean tonalites and trondhjemites are explained by the high thermal stability of calcic amphibole in the residues of partial melting at pressures in the range 5–20 kbar.

The present experimental results are equally compatible with the production of granitoid magmas by partial melting of amphibolite at conditions of high-grade deep crustal metamorphism (~900°C, 10–15 kbar). It is conceivable that a tectonically thickened pile of hydrated basalt would shortly undergo melting at its roots under the high geothermal regimes existing in the Archaean. Additional heat and volatiles could have been supplied by underplated basalts, perhaps from an underlying subduction zone. This hypothesis suggests that early continental accretion processes may have been considerably different from those prevailing in post-Archaean times.

Fig. 7 is a semi-schematic rendition of the character of partial melting expected in a basaltic system of constant 2 wt. % H₂O under a variety of geothermal regimes, perhaps corresponding to subduction paths. A very hot path A lies below the pressure threshold of amphibole plus liquid. If all H₂O in hydrated basalt escapes by subsolidus dehydration (point 1), felsic liquids could not be generated. Mafic liquids would eventually form around point 2. In a somewhat cooler path B, which falls above the pressure threshold for amphibole-liquid stability (point 3), felsic liquids could be generated with residual amphibole, starting at about 850°C (point 4). Garnet is not stable, and unfractionated REE patterns would characterize the derivative plutonic rocks. At higher pressures, along path C, garnet coexists with felsic liquid, and thus exerts its influence on REE contents. Melting produces trondhjemitic liquids at point 5. If these do not segregate immediately from their source, they become tonalitic near the amphibole-out curve at point 6. For steep dP/dT paths like path D, increase of garnet and decrease of amphibole give rise to decreased

Al₂O₃ and CaO and increased K₂O in partial melts. Liquids are first generated by dehydration melting at point 7. Thus, granodioritic liquids could have been created in the waning stages of an early accretion episode, within a foundering plate, or, more abundantly, in later geologic time under lower geothermal regimes.

A very cool path E would first encounter a small amount of dehydration melting at low temperature (point 8). Subsidiary dehydration of some amphibole could have released free H₂O upwards prior to melting. If the overlying mantle wedge is substantially hotter than the descending slab, melting of peridotite fluxed by free H₂O or granodioritic liquid could occur above the subduction zone to produce a new generation of tholeiites. This mechanism could conceivably be involved in the origin of unconformable cratonal basalts like the Dharwar greenstones (Drury 1983) or modern back-arc magmatism. This line of reasoning suggests that massive felsic plutons like those of Andean margins may originate directly from subduction zones, and that basalt- and andesite-dominated volcanics such as in the oceanic island arcs, may originate from infiltration of subduction-zone volatiles or magmas into the overlying hot mantle, as envisioned by Nicholls & Ringwood (1973) and Arkani-Hamed & Jolly (1989).

The present study indicates that K-rich granites cannot be derived in significant quantities by melting of mafic rocks, and other work (Johnston & Wyllie 1988) casts doubt on the possibility of deriving such rocks from remelting of low-K granitoids. Some process of metasomatic K-enrichment of the crust followed by melting seems necessary; this process might have been complementary to K- and H₂O-depletion in lower-crustal metamorphism, as the final stages of consolidation of the Archaean cratons.

Acknowledgements. The experimental research of this paper was supported by a U.S. National Science Foundation grant, #EAR-8707156 (RCN). K.T. Winther gratefully acknowledges a Danish Natural Science Research Council grant, #11-6433.

Ian M. Steele provided much technical assistance with microprobe analyses. Valuable advice and encouragement was given by A.T. Anderson, J.J.W. Rogers, S.M. Wickham and P.J. Wyllie. Helpful reviews of a first version of this paper were provided by N.T. Arndt and V.R. McGregor. The authors profited from discussions with many scientists at the Steno Medal Award Meeting, Copenhagen, November 25, 1989.

Dansk sammendrag

Der blev udført smelteeksperimenter på naturlig høj-Al basalt og en syntetisk gennemsnits-Arkæisk tholeiit (AAT) (0.3 vægt % K_2O) med varierende mængder H_2O . Mikrosondeanalyser af lynafkølede smelteprodukter (glas) dannet fra den Arkæiske gennemsnits-tholeiit med H_2O -indhold varierende fra 15% til <1%, under forsøgsbetingelser mellem 5–30 kbar og 750–1100°C, viste, at der i hele dette forsøgsinterval blev produceret smelter med sammensætninger, der svarer til typisk Arkæisk tonalitisk og trondhjemitisk „grå gnejs“. Høj-Al basalten gav smelter med Al_2O_3 -indhold, der er urealistisk høje for små gnejsjer. Den vedvarende dannelse af lav-K kalk-alkaline magmaer direkte ved H_2O -undermættet partiel opsmeltning af lav-K Arkæisk tholeiit tyder stærkt på, at denne mekanisme var aktiv ved dannelsen af tidlige kontinenter.

Temperaturer på 850–1000°C og tryk omkring 15 kbar er passende smeltebetingelser. Magmaer af tonalitisk sammensætning fås ved forholdsvis høje temperaturer, lave tryk og høje H_2O -indhold i udgangsmaterialet. Trondhjemitiske magmaer fås ved lavere temperaturer, højere tryk og lavere indhold af H_2O . Smelter med lave indhold af tunge sjældne jordarters grundstoffer kan dannes ved tryk over 15 kbar, på grund af granats stabilitet i residualbjergarten under høje tryk. Magmaer med ikke-fraktionerede mønstre af sjældne jordarter kunne dannes ved opsmeltning under lavere tryk, hvor granat ikke er stabil sammen med en smelte. Lave K_2O -værdier i smelterne opretholdes på grund af den høje stabilitet i residualbjergarten af amfibol (op til 0.7% K_2O), der kan kooksistere med smelter under totale vandindhold på 2 vægt % eller derover. Både opsmeltning af amfibolit og ekstraktion af magma i den øvre del af subduktionszoner, og partiel opsmeltning af amfibolit under metamorfe betingelser dybere i jordskorpen er modeller for den tidlige udvikling af jordskorpen, der ser ud til at opfylde de nærværende eksperimentelle betingelser.

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