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Origin of an A-type granite: Experimental constraints

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ABSTRACT

Numerous petrogenetic schemes have been proposed for the origin of the chemically distinctive A-type or anorogenic granites. The metaluminous Watergums Granite, from a bimodal association of A-type granite/rhyolite with basalt in southeastern Australia, has been experimentally studied so that constraints can be placed on its origin. The Watergums magma was emplaced at a very high level in the crust, in an almost entirely molten state. The crystal-liquid phase relations at 1 kbar are therefore compared with the petrographically determined crystallization sequence. The data indicate a minimum magma temperature of 830°C; it may have been >900°C. The inferred water content of the melt lies between 2.4 and 4.3 wt%. The high magma temperature implies that this granite had an origin distinct from the slightly older I-type granites in the region. Petrological, geochemical, and experimental data support an origin by direct, high-temperature partial melting of a melt-depleted I-type source rock in the lower crust. Mantle-derived magmas (basalts) provided the heat source for partial melting. The most likely melting reactions involve fluid-absent breakdown of somewhat halogen-enriched micas and amphiboles that were residual from a previous I-type–producing event. A-types, especially when fractionated, are low viscosity melts owing to their high temperature, moderate H_2O contents, and elevated F contents. This is consistent with the common occurrence of A-type rhyolite and obsidian flows. In contrast, both S- and I-type volcanics are generally ash-flow tuffs.

INTRODUCTION

Two fundamentally different kinds of granitic rocks were recognized in the mid-1970s. Chappell and White (1974) and White and Chappell (1977) designated those with characteristics indicating derivation from metasedimentary protoliths as S-types. Those with characteristics indicative of derivation from meta-igneous or igneous protoliths were called I-types.

Another distinctive group of granites has since been designated "A-type" by Loiselle and Wones (1979), who used the term to emphasize the anorogenic tectonic setting and the relatively alkaline composition as well as the supposedly anhydrous character of the magmas. These authors (pers. comm. 1980, 1984) also emphasized that the A-type classification (unlike the S- and I-type) does not imply a specific source or mode of origin. Just as there are S- and I-type volcanic rocks, A-type volcanic rocks are common and may be closely associated with the intrusive rocks. Typical rock associations that include A-types are (1) granites (including peralkaline granites), syenites, gabbros, and anorthosites (e.g., Pikes Peak, Colorado, Barker et al., 1975); (2) bimodal suites of granites (all metaluminous), rhyolites, gabbros, and basalts (e.g., southeastern Australia, Collins et al., 1982); and (3) topaz rhyolites (either metaluminous or peraluminous) that Burt et al. (1982) suggested may be related to A-types.

For a complete survey of rocks now classified as A-types, the reader is referred to Sørensen (1974), Barker et al. (1975), Burt et al. (1982), and Collins et al. (1982). However, the following are important characteristics of A-type suites: (1) They are usually true granites in the classification of Streckeisen (1973). (2) They occur in anorogenic settings and commonly in tensional regimes where they postdate the intrusion of other sorts of granites. (3) A-types commonly form small subvolcanic plutons or occur as lava flows; ash flows are less common. This contrasts with both I- and S-types, which mostly occur as large plutons forming huge batholiths. S- and I-type volcanic rocks are usually ash flows. (4) Typically, A-type granites and rhyolites are metaluminous and Ca-poor but have elements such as Sr, Ba, and Rb in abundances similar to those in unfractionated S- or I-type granites. However, these metaluminous A-types are commonly associated, in space and time, with perakaline A-type granites (e.g., Nigeria, Jacobson et al., 1958, and Bowden et al., 1974). Also, many peraluminous granites are anorogenic. Both peralkaline and peraluminous anorogenic granites show extremes in trace-element abundances (e.g., low Sr) in-

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Table 1. Bulk-rock chemical analyses of Watergums Granite GIG-1*

Major Oxides (wt.%)		Mode (vol. %)	
SiO_2	73.60		
TiO_2	.34	Quartz	31.3
Al_2O_3	12.44	K-feldspar	44.7
Fe_2O_3	1.42	Plagioclase	21.3
FeO	1.49	Biotite	1.5
MnO	.08	Amphibole	.7
MgO	.27	Magnetite	.2
CaO	1.24	Allanite	< .1
Na_2O	3.53	Apatite	< .1
K_2O	4.23	Fayalite	.1
P_2O_5	.07	Fluorite	< .1
F	.12		
S	< .02		

Selected Trace Elements (ppm)

Ba	710	Y	83
Rb	201	ΣREE	308
Sr	142	Cr	2
U	6	Ni	2
Zr	472	Zn	121
Nb	28	Ga	21.2

*all data from Collins et al. (1982)

dicative of fractionation. The topaz rhyolites show these features. (5) Fe/(Fe+Mg) is always high, and the rocks contain Fe-rich silicates such as annite and fayalite. (6) Compared with I-types with similar SiO_2 contents, the unfractionated, metaluminous A-types have high Zr, Nb, Y, REE, and Zn and high Ga/Al but low contents of first-row transition elements such as Ni and Cr. However, there is extreme variability of trace elements in rocks that show evidence of fractionation (White and Chappell, 1983).

Although A-type granitic rocks are volumetrically insignificant compared with the vast amounts of S- and I-type rocks exposed in various parts of the world, their genesis is of particular interest since Mo, Sn, W, Nb, Ta, REE, Be, and Li mineralization is commonly associated with A-types or fractionated and hydrothermally altered rocks that may have originated from more primitive A-type magmas. This paper addresses the question of how A-type magmas originate.

ORIGIN OF A-TYPE MAGMAS

Several mechanisms have been postulated to explain the generation of A-type magmas. The major ideas that have been discussed include the following: (1) Mantle-derived alkaline magmas fractionate to produce residual granitic liquids (Loiselle and Wones, 1979). (2) Mantle-derived alkaline magma reacts with crustal rocks to produce a syenitic derivative that fractionates to a granitic composition (Barth, 1945). Barker et al. (1975) suggested a variant of this scheme in which the syenitic magma further reacts with quartzose crustal rocks and eventually forms a granitic hybrid. (3) Liquid immiscibility occurs on a small scale in many basaltic liquids and has been suggested as a possible origin for peralkaline granitic magmas (e.g., Philpotts, 1976; Eby, 1979). (4) Liquid-state, thermogravitational diffusion has been suggested as the origin of chemical variations in some A-type rhyolite magmas (Shaw et al., 1976; Hildreth, 1979). (5) Fractionation of an I-type parent magma to produce an A-type residual liquid was discussed by Collins et al. (1982). (6) A-type magmas are due to melting of the lower crust under the fluxing influence of mantle-derived volatiles (Bailey, 1974). (7) Direct high-temperature partial melting of a depleted I-type source in the lower continental crust forms the A-type magmas (Collins et al., 1982; White and Chappell, 1983). This model assumes that A-type magmas are relatively anhydrous, high-temperature melts. However, little direct evidence has been produced to support this conclusion.

A wide variety of rocks is included under the A-type umbrella; because of this variety, we consider that no single one of the above schemes will be found responsible for the genesis of all A-types. It is possible, even probable, that more than one of these processes has played a part in the origin of any particular A-type suite.

THE WATERGUMS GRANITE

The Watergums Granite forms part of the Late Devonian Gabo Suite of A-type granites in southeastern Australia. The geology and petrology of these rocks have been described by Collins et al. (1982).

The Watergums Granite is a pluton of 28-km^2 outcrop, intruding deformed, low-grade Ordovician metasedimentary rocks. Rocks of this suite are associated with comagmatic rhyolites and transitional basaltic lavas of the Boyd Volcanic Complex. Some Gabo Suite plutons intrude the comagmatic rhyolites. The Watergums Granite contains no xenoliths or inclusions of any kind. The granites, rhyolites, and associated transitional-type basalts are thought to occupy a graben structure (McIlveen, 1975). Intrusion of the Gabo Suite occurred after emplacement of the Early Devonian, I-type Bega Batholith (Collins et al., 1982). The presence of miarolitic cavities, micrographic patches, the narrow (10–20 m wide) contact aureole and the fact that some Gabo Suite granites intrude comagmatic volcanics all show that the Watergums is a very high level, subvolcanic body. The lack of phenocrysts, xenocrysts, or rock inclusions and the fine, equigranular fabric of the rock also support magma emplacement in an almost wholly molten state.

The Watergums Granite is a fine-grained, brick-red rock. A modal analysis is given along with the bulk rock chemistry in Table 1. Orthoclase microperthite ($Or_{60}Ab_{40}$) is the most abundant phase, forming subhedral crystals and granular to microgranophyric intergrowths with small, anhedral quartz grains. Plagioclase occurs as euhedral to

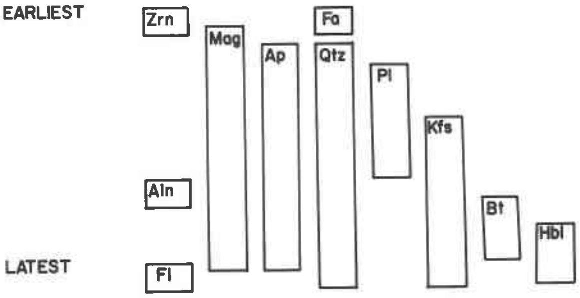

Fig. 1. Crystallization sequence for Watergums Granite GIG-1 as deduced from rock textures. The standard mineral abbreviations used are taken from Kretz (1983). Appendix 1 gives the meanings of all the less common abbreviations used in this paper.

subhedral, normally zoned crystals (An_{30-5}) with fine oscillatory zoning. Most other minerals are molded on these early-formed plagioclases. Quartz forms some large, embayed crystals with β-habit, usually wrapped in K-feldspar. Rarely, the large plagioclases partially wrap around the large quartz crystals. Fayalite forms small rounded grains with reaction rims of biotite. Various secondary minerals replace the olivine in most samples. Hastingsitic hornblende is mostly anhedral and interstitial. In some cases there are ragged, blue riebeckite-arfvedsonite patches on the hornblende shreds; these (and possibly all of the amphiboles) have a very late or subsolidus origin. Biotite (annite) is also interstitial and anhedral to subhedral. Zircon and magnetite are early-crystallized accessories found included in most other minerals. The zircons are euhedral and zoned but have no relict cores. Apatite needles formed later than the other common accessories. Allanite forms scarce, brown, euhedral to subhedral, zoned crystals intergrown with the late-crystallizing quartz and K-feldspar. Clear, colorless, late magmatic fluorite is also intergrown with these late-crystallizing phases. Figure 1 shows the deduced crystallization sequence.

The Watergums Granite has the following characteristics typical of A-type rocks: (1) It was emplaced at a high level after the major plutonic events in the region. (2) It occurs in an anorogenic setting, associated with brittle deformation. (3) It is part of a bimodal suite containing both intrusive and extrusive units. (4) It is felsic, metaluminous, and, according to the geology and petrology of the Gabo Suite, appears to be the most primitive (unfractionated) member. All these features make this rock ideal for an experimental study to clarify the petrogenesis of this suite of A-type rocks. It is hoped that the results will shed light on the origin of similar rocks in similar settings.

EXPERIMENTS

In keeping with the inference that nearly all crystallization occurred at low pressure, the crystallization phase relations of Watergums Granite (GIG-1) have been determined at 1-kbar total pressure, as a function of water content of the melt. Since the rock contains early-formed fayalitic olivine, magnetite, and quartz, it can reasonably be assumed that crystallization took place at an oxygen fugacity at, or slightly above, that of the quartz-fayalite-magnetite buffer assemblage (QFM). Accordingly, all experiments were performed with f_{O_2} controlled at ~0.3 log units above Hewitt's (1978) calibration of the QFM equilibrium.

Table 2. Compositions[1] of the original rock, starting material, and some run products

	GIG-1	starting glass	GI-3-2[3] glass	GI-3-2[3] Pl[5]	GI-2-2[4] glass	GI-2-2[4] Pl[5]
SiO_2	74.74	75.35	76.42	62.93	75.97	58.65
TiO_2	.35	.30	.15	.23	.27	.21
Al_2O_3	12.63	12.47	12.13	22.00	12.96	25.21
FeO[2]	2.85	2.72	1.57	1.44	1.67	1.16
MnO	.02	.11	.16	.06	.10	.03
MgO	.27	.29	.27	.17	.12	.02
CaO	1.26	1.16	.92	5.48	1.11	7.68
Na_2O	3.58	3.54	3.82	6.62	3.76	6.44
K_2O	4.30	4.02	4.58	1.06	4.08	.61

[1] normalized to 100% anhydrous

[2] total Fe as FeO

[3] 846°C, 2.42 wt% H_2O in melt

[4] 895°C, 2.36 wt% H_2O in melt

[5] small amounts of Fe, Ti, Mg and Mn in the plagioclase analyses represent interferences from dust-like magnetite inclusions in the feldspar crystals.

Methods

The starting material for the experiments was prepared by two-stage 1-atm fusion. An initial fusion of small batches of finely powdered rock on an iridium strip heater (Nicholls, 1974) produced a glass that was crushed and then remelted at 1400°C for 15 min. This technique results in minimal Na loss. The product consists of ~98% light-brown to colorless, relatively bubble-free glass with ~2% relict quartz crystals and a trace of zircon. The composition of this starting glass was determined by electron-probe analysis (see Table 2).

Experiments were all carried out in a small-volume, internally heated vessel with an argon pressure medium. Temperatures were measured with two chromel-alumel thermocouples and are believed accurate to within 2°C of the values reported. Temperature uncertainties given in Table 3 are the thermal gradients over the lengths of the sample capsules. Pressures were monitored throughout most runs with a factory-calibrated Heise gauge and are believed to be accurate to within 10 bars. Pressure errors given in Table 3 represent the range of variation in pressure recorded during each run. Run durations varied, as a function of temperature, from ~360 h at 725°C to ~48 h at 1000°C. All quenches were isobaric.

Samples consisted of ~0.03 g of powdered starting glass plus excess H_2O for water-saturated runs. For experiments with $X^{Fl}_{H_2O} < 1$, CO_2-H_2O fluid phases were generated by loading both silver oxalate and water into the capsules.

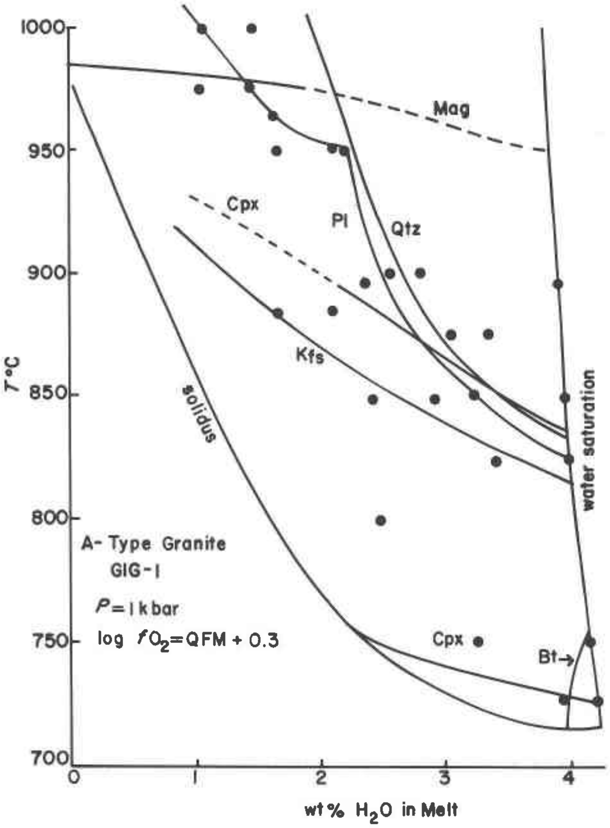

Fig. 2. Isobaric (1 kbar) T vs. melt water content diagram showing the experimentally determined crystallization phase relations of the Watergums A-type granite. The phase-saturation boundaries are labeled with the appropriate mineral abbreviations.

Thus, all runs were performed with an "excess" fluid phase present. The composition of the $Ag_2C_2O_4$ was determined, in triplicate, by thermal decomposition. Results indicate that the compound contains 70.473 wt% Ag, 28.661 wt% CO_2 and 0.866 wt% adsorbed H_2O. In all cases the mass ratio of sample to fluid phase was kept ~1.0. To minimize Fe-loss problems, the capsules were made from either $Pd_{30}Ag_{70}$ or $Pd_{25}Ag_{75}$ alloys. Bulk microprobe analysis of the products of high-temperature, near-liquidus runs indicated that Fe-loss is <20% relative.

Oxygen fugacity was controlled indirectly by using a $Pd_{70}Ag_{30}$ H_2-diffusion membrane. The P_{H_2} applied was appropriate to produce $f_{O_2} = 0.3$ log units above Hewitt's (1978) calibration of the QFM buffer equilibrium. Corrections were applied for reduced a_{H_2O} in runs with CO_2-H_2O fluids present.

Water contents in the melt were calculated from the known masses of H_2O and CO_2 loaded and from Burnham's (1981) solution model based on albite-H_2O relations. Optical estimates were made of the amounts of glass (melt) in the run products. Fluid compositions were corrected iteratively for H_2O solubility in the coexisting melts, and it was assumed that H_2O and CO_2 mix ideally over the P-T range of interest. These calculations were made with the aid of a BASIC computer program originally written by D. Eggler (Pennsylvania State University). Calculated H_2O contents are considered accurate to within 0.3 wt% absolute.

After the runs, the products were examined in optical grain mounts. Glass (quenched melt) forms colorless to very pale brown patches enclosing or interstitial to the crystals. Zircons, for the most part relict, form tiny, highly birefringent crystals. Magnetite forms small (2–10 μm) opaque octahedra. Quartz is present as large (~20 μm), equant, rather rounded grains, and K-feldspar forms feathery intergrowths with other phases. Near the solidus, plagioclase is also feathery but at higher temperature occurs as euhedral tabular crystals up to 30 μm long and showing multiple twinning. Clinopyroxene crysals vary from tiny stubby prisms in runs at low temperature to pale yellow-green needles up to 30 μm long. This phase was easily identified by its high relief and ~45° extinction angle. When present, biotite forms very small (5–10 μm across), somewhat rounded platelets. Sections parallel to the **c** axis show straight extinction and pleochroism from very pale yellow brown to light brown. In run products with large proportions of small crystals, X-ray powder diffractometry was also used to identify the phases present. This technique is particularly useful for confirming the presence or absence of K-feldspar. Table 3 shows run results, and the deduced phase relations are presented in Figure 2.

Results

The phase diagram in Figure 2 is an isobaric T-X section where X is the H_2O content of the melt in weight percent. The solidus shown is an approximation based on the calculated locus of the Qtz-Or-Ab-H_2O solidus at reduced a_{H_2O}. The calculated water saturation surface is also shown, on the right-hand side of the diagram. Experimental points are marked as black dots. The position of each phase saturation boundary has been drawn in accordance with the abundance of the relevant phase at each experimental point.

There are several striking features of the relations in Figure 2. The liquidus phases at H_2O contents above ~2.3 wt% are magnetite and zircon. Zircon is so refractory that its saturation boundary could not be located experimentally. All run products contained zircons (Table 3). However, at low H_2O contents (<2.2 wt%), the liquidus phase is quartz, and both the plagioclase and quartz saturation boundaries sweep toward very high temperatures. The origin of the cusp on the plagioclase boundary is unknown, but its existence was verified by replicate experiments and we do not believe it is an artifact. Near 2.4 wt% H_2O in the melt, the Qtz and Pl boundaries converge and continue very close together with increasing H_2O content of the melt. The Kfs-saturation boundary has a much shallower negative slope and would meet the solidus at a lower temperature than the other tectosilicate curves. Clinopyroxene is stable over a broad T-X interval and has both upper and lower thermal stability limits. The shape of the Cpx field is shown consistent with the shapes of Opx and Cpx fields determined for other granitic compositions (e.g., Naney and Swanson, 1980; Clemens and Wall, 1981). Biotite is only present at the highest melt water contents (>4 wt%) and at $T \leq 750°C$; thus, it occupies a miniscule field in the lower right of the diagram. The Qtz, Pl, Kfs, and Cpx boundaries converge as the melt water content increases so that all these phases are virtually on the H_2O-saturated silicate liquidus. Amphibole readily nucleates and grows from metaluminous andesitic to rhyolitic melts. Thus, if an amphibole stability field exists, it probably lies at very low temperature (<750°C) and at H_2O contents of <4 wt% (perhaps at subsolidus conditions).

INTERPRETATIONS

The phase relations in Figure 2 can be used to constrain the temperature and H_2O content of the original A-type magma. Since textures in the Watergums granite imply that the magma from which it crystallized was nearly 100% molten when emplaced at low pressure, the H_2O-saturated silicate liquidus provides an estimate of *minimum* magma temperature. Thus, magma temperature must have exceeded 830°C. If all the magnetite in the rock is of magmatic origin then the temperature may have been well over 900°C.

Additional contraints on temperature come from use of Zr and P solubilities in granitic melts as chemical thermometers (Harrison and Watson, 1983, 1984; Watson and Harrison, 1983). Textural evidence suggests that all zircons and apatites in GIG-1 have a magmatic origin. Watson and Harrison's data may be coupled with the known Zr and P_2O_5 contents of GIG-1 to calculate the saturation temperatures for apatite and zircon. The results are 910°C and 940°C, respectively. Again, these figures provide *minimum* estimates for magma temperature. The presence of biotite but not of clinopyroxene in the Watergums Granite shows that *final* magma temperature was below 730°C. The inferred high temperature means that clinopyroxene must have been a near-liquidus phase. However, Cpx is not found in the rock. Figure 2 shows that there is a lower thermal stability limit for Cpx. As crystallization proceeded, a_{H_2O} and a_{Kfs} rose so that reactions of the type

$$\text{Mag} + \text{Cpx} + \text{melt} \pm (\text{Pl, Kfs, } H_2O) = \text{Hbl} + \text{Bt} + \text{Qtz} \pm O_2 \quad (1)$$

took place. Thus, during late crystallization, early-formed Cpx reacted with the magma to form hydrous ferromagnesian silicates.

The crystallization sequence depicted in Figure 1 shows that magnetite crystallized before quartz. Examination of Figure 2 shows that, for this sequence to have occurred, the melt must have contained >2.2 wt% H_2O.

Table 2 shows electron probe analyses of coexisting plagioclase and melt in two experimental run products. At lower temperature the feldspar becomes both more sodic and more potassic. The 895°C experiment GI-2-2 (Table 3) was just below the plagioclase saturation boundary at ~2.4 wt% H_2O in the melt (Fig. 2). Here, the plagioclase has a composition of An_{38} whereas the Watergums granite actually contains plagioclase crystals with cores of An_{30}. This suggests that the crystallization path for the magma crossed the plagioclase phase boundary at a melt water content of >2.4 wt% and at $T < 900°C$.

It is also possible to constrain the melt water content using the zircon and apatite saturation temperatures calculated above. Figure 1 shows that zircon began crystallizing before any other silicates and that apatite crystallization predated that of plagioclase. These relationships constrain the melt water content to >2.4 wt%. Miarolitic cavities in the rocks are evidence that the magma eventually became fluid saturated. However, according to the phase relations depicted in Figure 2, this must have occurred late in the crystallization history at or below 750°C and within the biotite-stability field. We therefore conclude that the original magma had between 2.4 and 4.3 wt% H_2O. In view of the late attainment of water saturation, the water content was most likely close to the minimum value of 2.4 wt%.

DISCUSSION

The conditions under which the A-type Watergums magma was generated are unknown. However, it was emplaced at a rather shallow crustal level, probably in an almost entirely molten state. The magma was very hot for a granite or rhyolite (T of >830°C and possibly >940°C). Such temperatures are considerably in excess of those (750–850°C) inferred for S- and I-type magmas in this region and with similar SiO_2 contents (Clemens and Wall, 1981; Wyborn et al., 1981; Clemens, 1984). This result implies that this A-type magma had an origin distinct from those of the I-types of the region. Thus, we may eliminate the possibility that the Watergums Granite is a fractionation product of an I-type magma. Collins et al. (1982) and White and Chappell (1983) have cited geochemical evidence that supports this conclusion.

Mantle-derived mafic magmas apparently coexisted with the A-type magmas in the Gabo Suite. These are now represented by lava flows of olivine basalt (transitional in chemistry between tholeiitic and alkaline). However, there remains a wide SiO_2 gap in this bimodal suite. There are no exposed intermediate members of any proposed differentiation series that might lead from transitional basalt to rhyolite.

The proposals of Barth (1945) and Barker et al. (1975) involve contamination of mantle-derived magma to form syenitic liquids that either further react with crustal rocks or fractionate directly to A-type granitic magmas. For the Gabo Suite, the objection to this idea is the absence of associated syenites and the presence of basalts that represent substantially unhybridized mantle-derived magmas.

Table 3. Experimental results

Run Number	P bars	T°C	$X^{Fl}_{H_2O}$	Melt Water Content wt.%	Run Duration hrs.	Phases Present
GI-11-1	1000	727±4	.905	3.95	355	Gl,Qtz,Pl,Kfs,Mag,Zrn
-2			1.0	4.25	355	Gl,Qtz,Pl,Kfs,Cpx,Bt,Mag,Zrn
GI-4-1	1010±19	750±10	1.0	4.15	328	Gl,Qtz,Pl,Kfs,Cpx,Mag,Zrn
-2			.709	3.26	328	Gl,Qtz,Pl,Kfs,Cpx,Mag,Zrn
GI-1-1	1004±4	800±5	1.0	4.05	334	Gl,Qtz,Pl,Kfs,Cpx,Mag,Zrn
-2			.498	2.50	334	Gl,Qtz,Pl,Kfs,Cpx,Mag,Zrn
GI-16-1	1002±14	825±1	.798	3.32	90	Gl,Q,Pl,Kfs,Cpx,Mag,Zrn
-2			1.0	3.93	90	Gl,Q,Pl,Cpx,Mag,Zrn
GI-14-1	1000	850±1	.651	2.94	211	Gl,Qtz,Pl,Cpx,Mag,Zrn
-2			.742	3.22	211	Gl,Qtz,Pl,Cpx,Mag,Zrn
GI-3-1	1015±18	846±5	1.0	3.96	217	Gl,Mag,Zrn
-2			.489	2.42	217	Gl,Qtz,Pl,Cpx,Mag,Zrn
GI-8-1	1000	875±4	.697	3.05	192	Gl,Mag,Zrn
-2			.796	3.36	192	Gl,Mag,Zrn
GI-15-1	1000	885±1	.279	1.68	149	Gl,Qtz,Pl,Cpx,Mag,Zrn
-2			.402	2.10	149	Gl,Qtz,Cpx,Mag,Zrn
GI-2-1	1013±3	895±5	1.0	3.91	147	Gl,Mag,Zrn
-2			.482	2.36	147	Gl,Qtz,Pl,Cpx,Mag,Zrn
GI-13-1	1000	900±1	.547	2.57	119	Gl,Qtz,Mag,Zrn
-2			.625	2.81	119	Gl,Mag,Zrn
GI-5-1	1011±14	951±14	.273	1.63	96	Gl,Qtz,Mag,Zrn
-2			.414	2.11	96	Gl,Qtz,Pl,Mag,Zrn
GI-6-1	1007±14	950±3	.354	1.91	116	Gl,Qtz,Pl,Mag,Zr
-2			.442	2.20	116	Gl,Qtz,Pl,Mag,Zrn
GI-10-1	1019±2	975±5	.131	1.04	72	Gl,Qtz,Pl,Mag,Zrn
-2			.227	1.44	72	Gl,Qtz,Pl,Mag,Zrn
GI-9-1	1000	1000±6	.143	1.09	48	Gl,Qtz,Zrn
-2			.240	1.48	48	Gl,Qtz,Zrn

Liquid immiscibility (e.g., Philpotts, 1976; Eby, 1979) has not been shown to have operated on a large enough scale to have produced large, separate A-type plutons such as in the Gabo Suite. There is no field or petrographic evidence suggesting that liquid immiscibility had any role in the genesis of these rocks. Likewise, thermogravitational diffusion (e.g., Hildreth, 1979) need not be invoked for the origin of the Gabo Suite since it consists mostly of sizeable granite plutons with little or no internal variation (Collins et al., 1982) and there are no rocks compositionally intermediate between the granites and any proposed parent material. In any case, recent experimental studies have shown that Soret diffusion acts in the opposite sense of that required to explain chemical variations in magmas and igneous rock suites (e.g., Lesher et al., 1982; Schott, 1983; Baker and McBirney, 1985).

The most credible mechanism for the origin of the Gabo Suite A-types involves high temperature partial melting of melt-depleted I-type source rocks in the lower continental crust (Collins et al., 1982). Under such conditions, melting would most likely involve fluid-absent breakdown of residual, halogen-enriched micas and amphiboles. It is also possible that melting could occur in a fluid-present regime where volatile species, other than H_2O, might be supplied by a subcrustal source (e.g., Bailey, 1974; Clemens and Wall, 1981). In both cases, a_{H_2O} would be $\ll 1$, and the melts would be relatively water poor. Fusion would necessarily occur at high temperature owing to the relatively refractory nature of such parent materials. The low H_2O contents of such sources would also mean that only small quantities of magmas with this amount of H_2O could be extracted. Hence, the relatively small volumes of A-type plutons compared to those of I-type granites. The high (Na + K)/Ca of the magmas probably results from the breakdown of residual micas coupled with the highly refractory nature of any residual calcic plagioclase. Despite the high temperatures of the probable melting reactions, the A-type magma still represents the "low"-temperature melting fraction of the source rock. An extracrustal heat source (such as a mantle-derived magma) would be required for such melting reactions to occur (e.g., Clemens, 1984). The transitional basalts associated with the Gabo Suite may represent magmas that supplied some of this heat. Derivation of primary A-type magmas by partial melting of a residual source also explains why these magmas are commonly developed late or last in the magmatic sequence for any particular region.

A-type magmas are relatively F enriched. The F content of the magma source region can be constrained by using our estimates of H_2O content for the magma. The relatively low H_2O content and the high temperature argue for a high-temperature, fluid-absent melting reaction similar to those proposed by Clemens and Wall (1981):

$$6\ \mathrm{Bt} + 6\ \mathrm{Qtz} + 3\ \mathrm{Ab} = 4\ \mathrm{Opx} + 2\ \mathrm{Or} + 10\ \mathrm{melt}. \quad (2)$$

The stoichiometric coefficients shown are in *mass* units and were estimated using a Ca- and Ti-free model Watergums melt composition with an assumed H_2O content of 2.6 wt%. For this reaction to occur, the source rocks would have to contain biotite, quartz, and plagioclase. The mass ratio of melted biotite to silicate liquid would be 1:1.6, and because of probable relative abundances of source-region phases, the amount of biotite would probably be the limiting factor in melt production. If we assume that all of the biotite initially present is consumed in the above melting reaction, then we can estimate the F content of the source region. We assume that the measured F content of GIG-1 (0.1 wt%) was the original melt F content. The source-region F content (C_o) is then given by

$$C_o = 0.1f, \quad (3)$$

where f is the fraction of partial melting. If f ranges from 10% to 15%, then C_o ranges from 0.01% to 0.15 wt% F. That amount of melt production would require an amount of biotite in the source region equal to $0.61f$, or 6 to 9 wt%. The biotite would contain about 0.17 wt% F. Thus, the F content of the source region as a whole, and of the initial biotite, need not be exceptionally high. If biotite remained as a restite (residual) phase then the source region would necessarily contain more F for a given value of f, and the residual biotite may be quite F-rich.

The high temperatures and low to moderate melt water contents imply that the A-type magmas were relatively fluid, highly mobile melts, able to reach very shallow depths in the crust, especially in tensional regimes where major crustal fracturing may occur. A-type volcanics commonly occur as lava flows, whereas S- and I-type volcanics are mostly ignimbritic. However, the H_2O content of the Watergums magma was apparently not very different from that of other sorts of granitic magmas in southeastern Australia (e.g., Clemens, 1984). This presents a problem since the explosive potential of a magma is usually related to its H_2O content (e.g., Burnham, 1972; Wilson et al., 1980). Partial resolution of this problem may lie in consideration of the high temperatures of A-types. Viscosity also affects the explosivity of a magma, and A-type magmas may have had relatively low viscosities by virtue of their high-temperature character.

Another feature of A-types that may help explain this behavior is their elevated F contents; especially in fractionated types. Dingwell et al. (1985) showed that F lowers the viscosity of alkali aluminosilicate melts as much as an equivalent quantity of dissolved H_2O does. Unlike H_2O, however, F partitions strongly into the melt phase relative to a coexisting aqueous fluid (Hards, 1976). Consequently, F would be retained in the magma and viscosity would remain low even if H_2O were lost during "second boiling."

The typical A-type rock studied here contains only 1.24% CaO (Table 1). The plagioclase-saturation boundary is, however, at rather high temperatures, and there is a wide crystallization interval between this phase boundary and the solidus (>100°C; see Fig. 2). Thus, a small degree of fractionation of early-formed plagioclase would greatly deplete the melt in CaO. This effect, coupled with the high Na_2O/K_2O and early crystallization of K-feldspar, means that two feldspars (Pl + Or) would soon be replaced by a single feldspar during fractionation. The products of such processes are the hypersolvus granites of Tuttle and Bowen (1958). The high CaO and the *late* crystallization of K-feldspar in I-types and the low Na_2O/K_2O in S-types mean that these magmas are unlikely to produce hypersolvus granites.

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Appendix 1. Abbreviations used

P	pressure in bars
T	temperature in °C
f_{O_2}	oxygen fugacity
a_{H_2O}	activity of water
$X^{\mathrm{Fl}}_{H_2O}$	mole fraction of water in the fluid phase
Qtz	quartz
Ab	albite
Or	$KAlSi_3O_8$
An	anorthite
Pl	plagioclase
Kfs	potassic alkali feldspar
Bt	biotite
Hbl	hornblende
Fa	fayalite
Opx	orthopyroxene
Cpx	clinopyroxene
Mag	magnetite
Zrn	zircon
Aln	allanite
Gl	glass