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Record of magma chamber processes preserved in accessory mineral assemblages, Aztec Wash pluton, Nevada

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ABSTRACT

Field relations and geochemistry indicate that Aztec Wash pluton had a complex, open-system history. The tilted pluton represents a 2.5 km thick chamber that was recharged with both felsic and mafic magma. The lower portion is highly heterogeneous, with mafic sheets; cumulates; hybrid rocks; mafic, felsic, and composite dikes; and sheets and pods of granite (heterogeneous [H] zone). The upper part is granite that is generally homogeneous in texture and geochemistry (granite [G] zone). At the base of the G zone, a discontinuous zone (buffer [B] zone) records interaction between the G and H zones. Complexity of the H zone makes detailed reconstruction of magma chamber history difficult, and the relatively homogeneous G zone appears to offer few clues about the evolution of the pluton or the interaction between the felsic and underlying more mafic magmas. Accessory mineral textures, zoning, and assemblages in the G zone, however, are far from homogeneous and provide clear evidence for fluctuating conditions that elucidates magma chamber history.

Mafic rocks of the H zone contain the accessory mineral assemblage ilmenite + magnetite + quench apatite ± late sphene and zircon. G zone rocks have magnetite + apatite + sphene + zircon ± allanite, ilmenite, and chevkinite. The magnetite + allanite + early sphene, apatite, and zircon association that characterizes much of the G zone indicates a lower temperature and possibly higher f_{O_2} than the H zone assemblage. Mineral textures and zoning, however, document fluctuations in the stable G zone assemblage: (1) as many as five rounded surfaces truncate internal zones in zircon, each indicating a dissolution event; (2) in addition to euhedral concentric zoning, sphene contains regions of highly irregular zoning that are rich in inclusions, especially anhedral ilmenite; (3) ilmenite and allanite are mutually exclusive, but allanite is present in the matrix of rocks that contain sphene with ilmenite inclusions, and sphene grains in some samples have alternating regions with allanite and ilmenite inclusions.

We attribute fluctuations in the stable G zone accessory assemblage to fluctuations in temperature and possibly f_{O_2}, with appearance of the high-*T*, reduced assemblage indicating interaction with hot, mafic, H zone magma. These interactions certainly involve heat transfer and may involve limited chemical contamination. We infer that they must have taken place near the H zone-G zone boundary. The most frequent and intense fluctuations (marked by zircon with the highest number of truncation surfaces, and by sphene with irregular zoning and abundant ilmenite inclusions) affected rocks that are near the boundary, but ilmenite inclusions in sphene and truncation surfaces in zircon are present to the top of the pluton. We conclude that granitic magma was subjected to multiple cycles of thermally induced vertical transfer—convection—that, at least initially, affected the entire upper part of the chamber.

INTRODUCTION

Many recent studies have presented evidence for complex, multi-stage, open-system histories of granitoid intrusions (e.g., Wiebe 1993, 1994, Wiebe et al. 1997; Bateman 1995; Didier and Barbarin 1991; Metcalf et al. 1995; Michael 1991; and many more). There is nonetheless a widespread perception, supported by common field exposures, that granites are frustratingly homogeneous and that *either* the histories of the intrusions that they represent are simple and uninteresting, *or* the granites are ineffective recorders of magmatic history. Even in the composite plutons that provide clear evidence for repeated injections into active magma chambers, the granitic rocks are commonly quite uniform in geochemistry and texture (e.g., Michael 1991; Wiebe 1994). This observation suggests that absence of distinctive compositional variability or internal structures does not rule out active processes in granites, and therefore it supports a search for less-obvious but effective markers of such processes.

Accessory mineral assemblages are more variable in gra-

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nitic rocks than major minerals, and most felsic magmas are saturated in at least some accessories early in their histories. The accessory assemblage is sensitive to a range of important parameters, most notably temperature, f_{O_2}, and melt composition, and therefore the record of growth, compositional change (zoning), and dissolution of accessory minerals is a sensitive indicator of the history of the enclosing magma (cf. Paterson et al. 1989; Wones 1989; Vavra 1990; Hanchar and Miller 1993; Watson 1996). In this paper, we present an example of how accessory minerals in apparently homogeneous granite can provide clues to the history of both the granite and of the magma chamber of which it was a part.

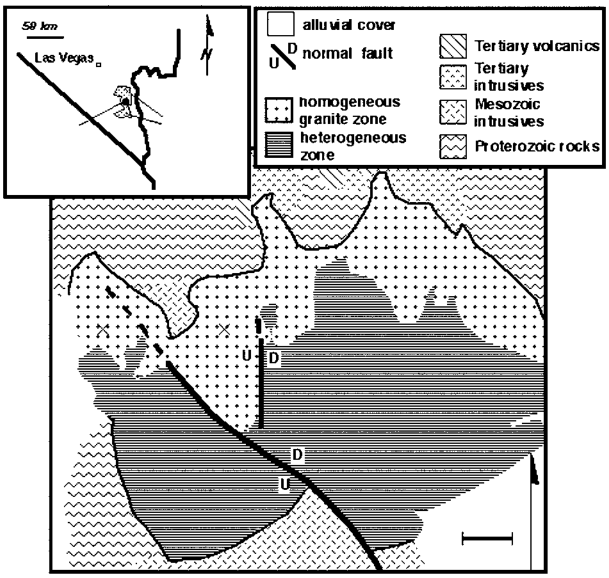


FIGURE 1. Sketch map of Aztec Wash pluton and surroundings, modified from Falkner et al. (1995) and Patrick and Miller (1997). Inset shows location in southern Nevada.

THE AZTEC WASH PLUTON

The 15.7 Ma Aztec Wash pluton is located in the central Eldorado Mountains near the southern tip of Nevada, in an area that underwent a brief episode of extreme extension in the mid-Miocene (e.g., Gans et al. 1989; Faulds et al. 1992). The pluton intrudes Proterozoic gneisses, Cretaceous granite, and slightly older Miocene intrusive and extrusive rocks (Fig. 1; Falkner et al. 1995). Northward tilting associated with extension resulted in exposure of a complete vertical cross section of the pluton; magmatic paleohorizontal markers, such as mafic sheets and cumulate layering, and hornblende barometry indicate an initial thickness of about 2.5 km, from ~5 to 7.5 km depth (Patrick and Miller 1997; cf. Wiebe 1993; Anderson and Smith 1995). This cross-sectional exposure provides an unusual view of open-system magma chamber processes.

The Aztec Wash pluton can be divided into two distinct, major zones (Figs. 1 and 2): a lower heterogeneous zone (H zone) and an upper "homogeneous" granite (G zone) (Falkner et al. 1995). The H zone, which comprises 60–80% of the exposure, includes sheets of fine-grained mafic rock; coarser mafic cumulates; intermediate rocks (apparent hybrids, enclave-rich granites, and cumulates from granite); mafic, felsic, and composite dikes; and sheets and pods of granite that are similar to G zone rock. There is abundant evidence within the H zone for recurring interaction between felsic and mafic magmas (Patrick and Miller 1997, Falkner et al. 1995). The mafic sheets, which display crenulate margins against intervening granite and are penetrated by granite protrusions, are interpreted as dense flows at the base of an existing felsic magma chamber (cf. Wiebe 1993). Mafic pillows in composite mafic-felsic dikes that cut most H zone units also have crenulate margins. Coarser, melanogabbros appear to represent multiple generations of crystal accumulation, possibly from unusually thick flows. Late dikes of granite are the youngest features in this part of the pluton (see below).

The G zone constitutes a felsic cap, 0.3 to 1 km thick, of relatively fine- to medium-grained biotite granite. Very sparse, small (typically ~1–5 cm, locally to > 1 m), ovoid, fine-grained

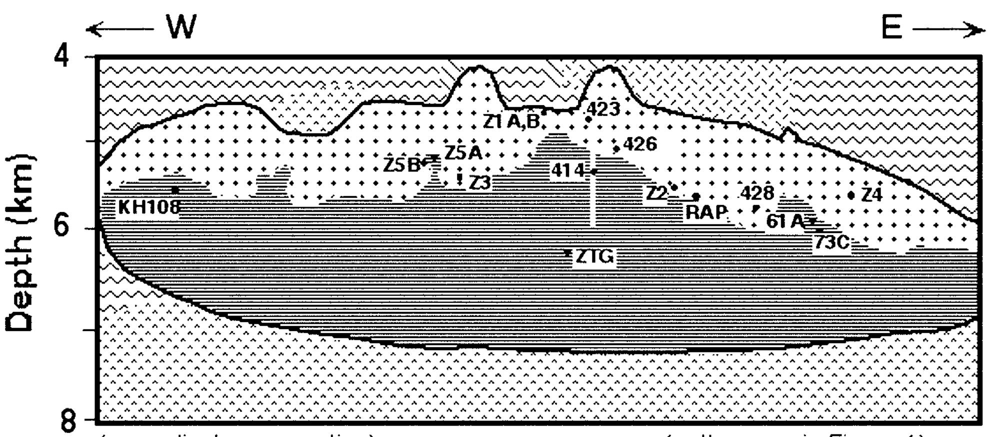


FIGURE 2. Schematic cross-section of Aztec Wash pluton, showing sample locations. Depths based on hornblende barometry. Modified from Patrick (1996) and Patrick and Miller (1997).

enclaves are present locally within the G zone. The enclaves are compositionally similar to or slightly more mafic than the granite. Similar enclaves, as well as smaller, darker microenclaves, are more abundant near contacts with the H zone and above its upward projections. Adjacent to the roof and to large stoped roof blocks in the upper G zone, the granite is more felsic and finer-grained than elsewhere. Otherwise, the G zone is chemically and texturally homogeneous, essential minerals are weakly zoned or unzoned, and evidence for the dynamic history that is apparent in the underlying H zone is not obvious (Falkner 1993; Falkner et al. 1995). Zircon saturation thermometry indicates a temperature range of ~740–800 °C for crystallization of zircon (Falkner et al. 1995; cf. Watson and Harrison 1983). We interpret the upper limit to be near the temperature of the initially intruded magma, which carried a very small amount of inherited zircon. The lower T is for the aplitic rocks and probably represents the approximate temperature during segregation. Hornblende-plagioclase temperatures of ~650–685 °C (primarily rim data) probably reflect the approximate solidus of the magma (method of Blundy and Holland 1990; Patrick 1996).

The G-H zone boundary was broadly subhorizontal prior to tilting, but it had several hundred meters of relief and, in one area, a plume-like train of H zone mafic masses is preserved within the G zone (Patrick and Miller 1997). Granite that is characterized by more mafic composition than typical of the G zone, abundant rapakivi-textured feldspar phenocrysts set in a slightly finer grained matrix, and abundant enclaves is exposed semi-continuously along the G-H boundary. This unit is locally absent, but it is typically meters to tens of meters thick (pre-tilting) and locally up to ~200 m in thickness. Because it separates the mafic portion of the magma chamber (H zone) from the felsic, homogeneous upper portion (G zone) and appears to have played an important mechanical, thermal, and perhaps chemical role influencing interaction between the two (see below), we refer to this unit as the buffer zone (B zone).

The late granite dikes in the H zone are very similar to typical G zone granite. Some are similar to B zone rocks in having rapakivi texture and finer groundmass, but they lack abundant enclaves. These large (~2–10 m thick), N-striking, near-vertical dikes are most common near the center of the pluton. They are commonly traceable for hundreds of meters but do not cross the G zone-H zone contact, apparently merging with the B zone.

METHODS

In conjunction with detailed local mapping, we collected a suite of samples representing a range of environments within the magma chamber (see Robinson 1997 for more details). Our focus was on the G zone and B zone, but some samples were collected from the H zone for comparison. We also studied several others from the earlier collections of Falkner (1993) and Patrick (1996).

Zircons were separated from eight of the samples using conventional methods, mounted in epoxy, and polished. The zircon grain mounts were investigated by cathodoluminescence using a Nuclide ELM-2A Luminoscope at Vanderbilt University.

Polished thin sections of sixteen samples, including all that were used for zircon separation, were investigated using backscattered electron imaging (BSE) on an ETEC Omniscan scanning electron microscope at Vanderbilt University. An accelerating potential of 20 KV and sample current of 1.5 nA were used during BSE imaging. The accessory minerals were identified by their brightness and distinguished from one another by shape, relative brightness, and energy dispersive X-ray spectra.

ACCESSORY MINERAL ASSEMBLAGES AND TEXTURES

G zone and B zone rocks and intermediate to felsic rocks from the H zone contain zircon, apatite, magnetite, allanite, and sphene (Table 1). All B zone and most G zone samples have sparse ilmenite, and we have identified chevkinite in one sample. H zone mafic rocks contain ilmenite in addition to apatite, sparse zircon, and magnetite; allanite is absent, but sphene may occur as a late-stage mineral. We describe occurrences and textures of individual minerals below, emphasizing the B zone and G zone granitic rocks. The most important characteristics of mineral assemblages and textures are summarized in Table 1.

Apatite

Apatite is ubiquitous in Aztec Wash pluton. In the most-mafic rocks (cumulates) and in most G zone granites, it is present as stubby prisms. Some G zone granites, most mafic rocks, and all intermediate and B zone rocks contain acicular (quench) apatite.

Zircon

Zircon in the granites is fairly uniform in size (10's of μm to 200 μm) and shape (doubly terminated, stubby euhedra with aspect ratio ~1.5 to 3). Grains invariably exhibit oscillatory zoning. Major zones, bounded by rounded surfaces that truncate sets of euhedral, oscillatory zones, range in number from 1 to 5 within individual zircons (Fig. 3). The mean and maximum numbers of these truncation features generally decrease downward in the G zone and reach maxima in the B zone and in granite within the H zone. We interpret these rounded truncation surfaces to indicate resorption that reflects a temporary swing from oversaturation (growth) to undersaturation in the surrounding melt. In some cases, subsequent growth beyond a truncation surface resulted in different grain morphology, perhaps reflecting preferential growth on different faces under different, post-truncation conditions (cf. Vavra 1990, 1993).

Sphene

Sphene is ubiquitous and prominent in the G and B zones (and in felsic rocks in the H zone), where it is present primarily as large (to ~1 mm) euhedra. Sphene grains in these rocks can be subdivided into three categories based on their zoning and inclusion characteristics (Fig. 4): (1) those with concentric subhedral to euhedral zoning, mostly free of inclusions; (2) those that lack zones or have only anhedral, irregular zoning and contain inclusions of magnetite, ilmenite, zircon, apatite, or allanite; and (3) those with irregular zoning in the center, commonly with inclusions of ilmenite, and euhedral zoning in their outer portions. Grains that have inclusions of more than one mineral tend to incorporate different minerals in different parts of the crystal. For example, magnetite and allanite are included in different zones from ilmenite (Fig. 4).

In intermediate rocks of the H zone, and in those mafic rocks where it is present, sphene is smaller and interstitial to mafic minerals and plagioclase. Sphene in these rocks has irregular zoning and abundant ilmenite inclusions.

Ilmenite

Ilmenite is sparse or absent in the G zone and in the large granite dikes that cut the H zone; where present in these rocks, it occurs as irregular-shaped blebs in sphene (Fig. 4). It is ubiquitous but again restricted to inclusions in sphene at the base of the G zone and in the B zone. In the H zone and in enclaves in the G zone, ilmenite crystals are present outside of sphene and are more abundant than magnetite.

Magnetite

Magnetite is ubitiquous within the Aztec Wash pluton, but it is more abundant in the G and B zones and felsic dikes that cut the H zone than in the H zone itself (Fig. 4). Like ilmenite, it occurs as inclusions in sphene in the G zone, but unlike ilmenite it is subhedral to euhedral and is very common as discrete crystals outside sphene.

Allanite

Allanite is present throughout the G zone, the B zone, and in the granite dikes that cut the H zone, primarily as small inclusions within or discrete grains adjacent to sphene (Fig. 4). It is absent in the H zone.

Chevkinite

Chevkinite was observed in a single sample from the B zone. In this sample, a cluster of small subhedral crystals is rimmed and partially replaced by allanite, suggesting a reaction relationship (Fig. 5). Such a relationship is consistent with the similar compositions of the two minerals (Ca, Fe, REE silicates) and with the fact that allanite is hydrous and chevkinite anhydrous.

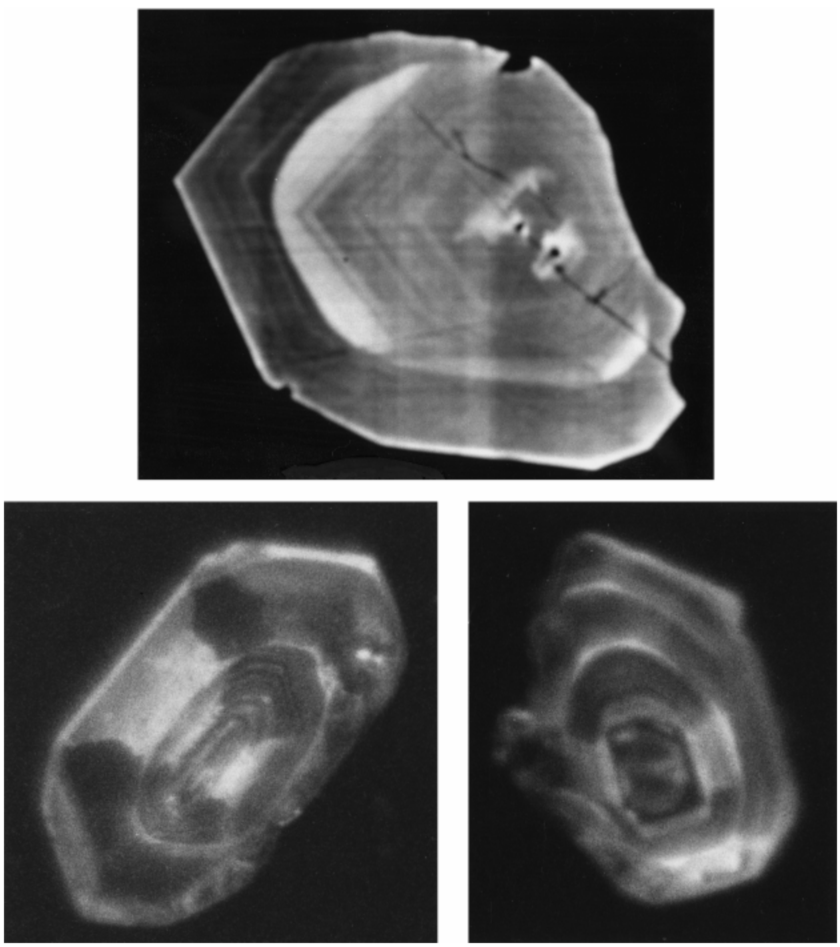
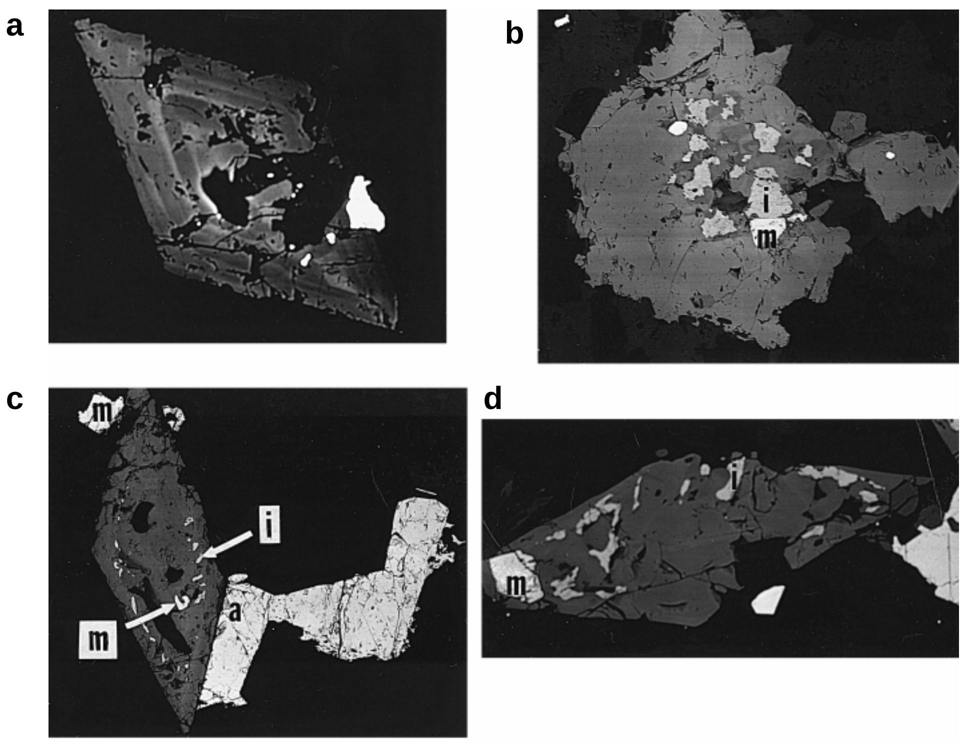


FIGURE 3. Examples of truncation surfaces in zircon grains from sample Z5A (granite in heterogeneous zone near contact with buffer zone). (**a**) Zircon showing a single well-developed rounded truncation (backscattered electron image; grain is about 45 μm long). (**b**) Zircon showing two rounded truncations, one very near rim (cathodoluminescence image; grain is ~90 μm long). (**c**) Zircon with three truncations, one very near rim (cathodoluminescence image; grain is ~80 μm long).

TABLE 1. Summary of accessory mineral distribution and features

Sample	Location* (from top to bottom – see Figure 2)	Zircon truncations†			Sphene‡		Allanite§		
		no. of grains	mean	max	inclusions	zoning	in sphene?	discrete?	abund#
Z1B	Gz, near roof	28	0.9	2	mt, al	E	Y	Y	4
Z1A	Gz, near roof	25	1.1	2	il, mt, al	I/E	Y	N	2
Z3	mid-Gz	39	2.2	3	il, mt, al	E	Y	N	1
423	mid-Gz	–	–	–	il, mt, al	I/E	Y	N	2
Z4	mid-Gz	34	1.8	3	il, mt, al	I/E	Y	N	3
428	enclave, Gz	–	–	–	il, mt	I/E	N	N	0
Z2	Bz	22	1.5	3	il, mt, al	I/E	Y	Y	3
426	Bz	–	–	–	il, mt, al	I/E	Y	Y	4
RAP	Bz	–	–	–	il, mt	I/E	N	N	0
Z5B	Bz, adjacent to Hz protrusion	26	2.4	4	il, mt	I/E	Y	Y	1
Z5A	felsic pod, Hz protrusion	30	2.0	4	il, mt, al	I/E	Y	Y	1
414	felsic dike, Hz	–	–	–	il, mt, al	I/E	Y	N	2
ZTG	cumulate granite, Hz	37	2.2	3	il, mt	I	N	N	0
AW61A	Hz, hybrid monzodiorite	–	–	–	il, mt	I	N	N	0
AW73C	Hz, hybrid qtz monzonite	–	–	–	il, mt	I/E	N	N	0
KH108	Hz cumulate gabbro	–	–	–	(no sphene)	–	N	N	0

* Location: Gz = homogeneous granite zone; Bz = buffer zone; Hz = heterogeneous zone.
† Zircon truncations: number of grains counted; mean and maximum number of truncation surfaces (counts were made for 8 of 16 samples).
‡ Sphene: minerals included (il = ilmenite, mt = magnetite, al = allanite); euhedral (E) or irregular (I) zoning, or irregular core with euhedral rim (I/E).
§ Allanite, ilmenite: included in sphene?; discrete grains outside of sphene?
\# Abundance: relative abundance (0 = absent, 4 = most abundant).



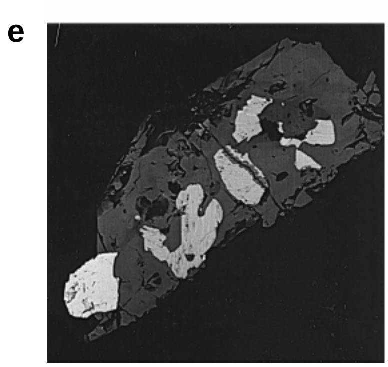


FIGURE 4. Backscattered electron images showing zoning and inclusions in sphene (magnetite = m; ilmenite = i; allanite = a). (**a**) Euhedral zoning (sample Z5A, granite in heterogeneous zone near contact with buffer zone) (field of view 300 μm). (**b**) Irregularly zoned core with anhedral ilmenite inclusions, subhedral magnetite inclusion just outside core (sample 423, granite zone) (field of view 575 μm). (**c**) Anhedral magnetite inclusion in core, anhedral ilmenite in narrow intermediate zone, magnetite and allanite at edge (sample 426, buffer zone, field of view 850 μm). (**d** and **e**) Anhedral ilmenite in interior, subhedral magnetite toward rim (d: sample RAP, buffer zone, field of view 350 μm; e: sample 414, felsic dike in heterogeneous zone, field of view 220 μm).

Ilmenite§			Magnetite
in sphene?	discrete?	abund#	(abundance#)
N	N	0	4
Y	N	1	4
Y	N	1	4
Y	N	2	4
Y	N	2	4
Y	Y	2	3
Y	N	2	4
Y	N	1	4
Y	N	4	2
Y	Y	3	3
Y	Y	3	3
Y	N	1	4
Y	Y	4	3
N	Y	3	2
Y	Y	4	2
N	Y	4	2

EVALUATION OF RESULTS

There are clear correlations among accessory mineral occurrences, textures, and location within the pluton that indicate cyclical variations in conditions and constrain the processes within the magma chamber. Noteworthy relationships include (cf. Table 1, Fig. 2):

(1) There appear to be two distinct accessory mineral assemblages, one typical of deeper levels and/or more mafic rocks (apatite + ilmenite + magnetite + zircon) and another typical of shallower and/or more felsic rocks (apatite + magnetite + sphene + zircon + allanite); the diagnostic minerals are ilmenite (deep) and sphene + allanite (shallow).

(2) Many rocks contain minerals from both of these assemblages, but textural relationships consistently indicate that the two assemblages formed separately. Rocks with strongest development of both assemblages occur near the bottom of the G zone and in the B zone.

(3) Dissolution surfaces are present in zircon in all granitoids but become more abundant toward the bottom of the G zone and in the H zone; likewise, sphene exhibits irregular, anhedral zoning and contains more common ilmenite inclusions at deeper levels.

Variability in accessory mineral assemblage must be a consequence of variation in either melt composition, ambient conditions, or both. We discuss below constraints and implications indicated by characteristics of the assemblages and textures.

Occurrence of ilmenite, sphene, and magnetite

Stability of ilmenite requires relatively high temperature and/or low f_{O_2}—at lower T or higher f_{O_2} it is replaced by sphene + magnetite (Wones 1989). This suggests that the "deep" ilmenite-bearing assemblage of the H zone represents a higher T and/or lower f_{O_2} environment than does the "shallow" ilmenite-free assemblage, which is not surprising. More informative are the composite assemblages in the G and B zones, which indicate fluctuating T and/or f_{O_2}. Ilmenite in the G and B zones invariably is preserved only as anhedral inclusions within highly irregularly shaped zones in sphene. This indicates that ilmenite was stable only during a limited portion of the solidification history of the granitic magma, *after* sphene began to crystallize, and suggests a reaction relation between ilmenite and sphene (and probably magnetite). The simplest interpretation is that conditions changed but that contamination played no role in ilmenite paragenesis. An alternative explanation would involve mechanical introduction of ilmenite during contamination of the granite by more mafic H zone magma. The uniformly felsic composition of the G zone and, for the most part, of the B zone, and the absence of other chemical or mineralogical markers of contamination in ilmenite-bearing samples indicate that contamination was probably minimal.

The presence of ilmenite in granites and in enclaves all of the way to the roof of the pluton indicates that either the appropriate conditions for ilmenite crystallization affected the entire magma chamber at one time (or more than once), or that ilmenite grains that had crystallized deeper in the chamber were transported to the top.

The sample from the felsic dike that cuts the H zone contains very sparse ilmenite that is restricted to the cores of sphene grains. This suggests that its history is similar to that of the G zone granites and less complex than that of the B zone.

Occurrence of allanite, and allanite/chevkinite relation

The presence of allanite suggests a relatively high f_{O_2} and a temperature of approximately <800 °C (Chesner and Ettlinger 1989), which is entirely consistent with its incompatibility with ilmenite and its restriction to granites that for the most part crystallized below 800 °C. The chevkinite rimmed by allanite in a single B zone sample probably reflects high-T crystallization, with subsequent reaction to produce allanite upon cooling.

Zoning in zircon

We interpret zoning truncations in zircons to indicate resorption, which must be a consequence of exposure to zircon-undersaturated melt. Compositional changes in zircon marked by changes in brightness in the images in Figure 3 are attributable either to changes in melt/zircon elemental partitioning at different T or to local compositional changes in melt related to dissolution of the zircon. Repeated growth-truncation-growth sequences indicate fluctuating conditions. Melt composition influences saturation level, so it is possible that periodic changes resulting from contamination could induce these sequences. Increased temperature, however, is much more effective at inducing dissolution of zircon (Watson and Harrison 1983), and so we favor fluctuation in T as the mechanism responsible for alternating growth and dissolution. Because zircon dissolution is sluggish, significant resorption must mark either a prolonged (probably $>10^3$ yr) or a large-magnitude (~100 °C) temperature excursion (cf. Watson 1996). In a shallow, active magma chamber like Aztec Wash, we suspect that the latter is more realistic.

Three mechanisms could account for the increase in number of resorption surfaces in zircon grains toward lower levels of the G zone and the B zone: (1) fewer temperature fluctuations toward the top of the chamber; (2) fewer fluctuations that were intense enough to induce dissolution near the top; or (3) restriction of temperature fluctuations and resulting zircon re-

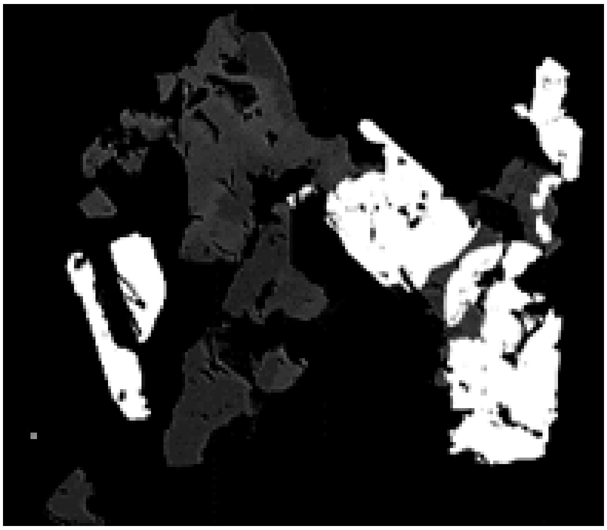


FIGURE 5. Allanite (gray) rimming chevkinite (white), sample Z2 (buffer zone) (BSE, field of view 220 μm).

sorption to the lower part of the G zone, with truncated zircon in the upper G zone indicating upward transport. All of these possibilities suggest vertical material transport within the G zone: either zircon grains were circulated up and down between areas of over- and undersaturation, or hot granitic magma periodically was transported upward, heating surrounding magma and inducing dissolution of zircon.

Implications of the accessory assemblage

The characteristics of the accessory mineral assemblages described above require fluctuating conditions and/or a compositionally open system within the upper part of the Aztec Wash magma chamber. Furthermore, correlations in the fluctuation record (cf. Table 1) suggest that all of the variations in growth and resorption histories of all of the accessory minerals are attributable either to the same parameter or to parameters that are linked closely. There is a close correlation between the abundance of ilmenite, presence of ilmenite outside of sphene grains, number of zoning truncations in zircon, and irregularity of zoning in sphene, and each of these is correlated negatively with the presence of allanite. Although compositional modification can influence accessory mineral growth and dissolution, limited compositional variability in G zone granites suggests that this was not the dominant factor. Relations among sphene, allanite, and ilmenite, and distribution of inclusions in sphene, can all be attributed to fluctuations in either T or f_{O_2}, whereas zircon dissolution is almost certainly a consequence of fluctuation of T. Thus, the simplest interpretation is that all variations indicate responses to variations in temperature. According to this interpretation, the "deep" assemblage is a hot assemblage (approximately >800 °C), the "shallow" assemblage is a cooler assemblage, and most samples of granitic rock from all parts of the pluton have composite assemblages that record fluctuations between the two conditions. High temperatures and fluctuations are especially pronounced in the B zone and at the base of the G zone; the felsic dike sample appears to have had a less complex history, more like typical G zone samples.

DISCUSSION

An accessory mineral-based model for the upper Aztec Wash magma chamber

We attribute the fluctuations in the stable accessory mineral assemblage in the granitic rocks of Aztec Wash pluton to fluctuations in conditions—probably primarily temperature—experienced by the magma. The close spatial correlation between the "deep," presumably high T assemblage and proximity to the H zone strongly suggests that heat was transferred from solidifying mafic magma emplaced in the H zone. Although the most frequent and intense fluctuations (marked by most abundant truncation surfaces in zircon, most ilmenite, most extensive irregular zoning in sphene) took place in and near the B zone (just above the top of the H zone), evidence of fluctuation in the form of relatively ilmenite-rich fine grained enclaves, zircon truncation surfaces, and ilmenite inclusions in sphene persists to the roof of the G zone. We conclude that granitic magma was subjected to multiple cycles of vertical transfer that, at least initially, affected the entire G zone magma column. This convective transport may have been initiated by input of heat from fresh pulses of mafic magma into the upper H zone. Heated, low density granitic magma from the B zone or base of the G zone would thus be impelled to ascend as plumes into the upper G zone.

The felsic dike sample from the H zone predominantly contains the "shallow," lower-T assemblage. These dikes, which are essentially identical to G zone granite, do not cross the B zone, rather appearing to blend with it. We interpret them to be feeders for the G zone.

The B zone apparently continued to be active during and after the dikes were active as conduits. It was a zone of extensive thermal, and probably very limited chemical, exchange between the overlying G zone granitic magma and the underlying H zone magmas. The B zone is highly variable in thickness and is apparently discontinuous. Non-uniform thickness probably reflects either local removal by late-stage movement of the G zone magma or variable activity in the underlying H zone.

Early freezing of the magma against its shallow, cold roof may have arrested convection in the upper part of the magma chamber and limited opportunities for fluctuations in temperature prior to final solidification. The roof zone rocks are distinctly finer-grained than those deeper in the pluton, and there are distinct chill zones around large stoped roof blocks whose descent was apparently arrested by solidification of the surrounding granite (cf. Wiebe 1991).

Utility of accessory minerals in assessing magma chamber histories

Accessory minerals provide a potentially effective tool for assessing magmatic histories. They are very sensitive to their surroundings with respect to stability and commonly composition, tend to preserve their compositions in growth zones because of low diffusivity, and are commonly preserved metastably as inclusions in larger mineral grains or because they dissolve slowly. Therefore, accessory minerals may record complex magmatic processes that do not leave a clear imprint in rock and major mineral geochemistry, petrography, or field relations. In the generally homogeneous granites of the Aztec Wash pluton, a clear record is preserved of evolution of the upper part of a composite magma chamber, including repeated thermal interaction with underlying mafic magma. Accessory mineral assemblages, including their zoning patterns, textures, and inclusion relations, can be a widely useful tool for deciphering the histories of felsic igneous rocks.

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