Eruption of andesite triggered by dyke injection: contrasting cases at Karymsky Volcano, Kamchatka and Mt Katmai, Alaska

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Arc volcanoes often erupt andesite that appears to have been stored in reservoirs at shallow depth for protracted periods. As crystal-rich andesite is close in density to upper crust, such storage may be quite stable. Petrological evidence, and occasionally geological and geophysical evidence as well, suggests that the immediate trigger for eruption of the stored magma is injection of new magma into the reservoir, presumably through dykes rising from depth. When the dyke magma is more mafic than the stored andesite, effusive eruption typically results. When the dyke magma is voluminous and more silicic, the results are catastrophic, with production of discontinuously zoned tephra deposits and caldera collapse. Contrasting end-members are illustrated by the eruptions of Karymsky Volcano in 1996 and of Mt Katmai in 1912.

Keywords: andesite; dyke; Karymsky; Katmai; caldera; magma mixing

1. Introduction: the role of replenishment in triggering andesitic eruption

The recent, well-monitored eruptions of Unzen volcano, Japan (Nakada *et al.* 1999; Nakamura 1995; Venezky & Rutherford 1999); Mt Pinatubo, Philippines (Pallister *et al.* 1996); and Soufrière Hills, Montserrat (Murphy *et al.* 1998, 2000) have highlighted the importance of replenishment in initiating andesitic eruption. In each case, an andesitic or dacitic magma body had been present for some time, gradually crystallizing in the upper crust beneath the volcano. This chamber had been the source for many eruptive cycles, as attested by the similarity of successive outputs. The stored magma was probably quite stable, owing to its similar density—by virtue of intermediate bulk composition and high crystallinity—to enclosing basement. However, following quiet repose of between a few and several centuries, introduction of new mafic magma into the chamber caused the rise and eruption of a portion of stored magma from the reservoir, modestly contaminated by the newly introduced component. Clear petrological evidence of this encounter is provided by a disequilibrium phenocryst assemblage inherited from both stored and introduced magmas and by the presence of mafic enclaves. The enclaves are dark, millimetre-to-centimetre-sized diameter blobs of mafic magma quickly chilled in 'pillow'-like fashion within their cooler silicic hosts (Eichelberger 1978, 1980; Bacon 1986).

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1465

This petrological interpretation has recently been made more robust with the discovery that the zonal 'stratigraphy' of phenocrysts in the hybrid bear the isotopic, as well as the elemental, fingerprint of the interaction of two magmas (Tepley *et al.* 1999). That phenocrysts record isotopic evidence of surviving multiple recharge events that introduced mantle-derived components, with intervening periods of growth bearing a more crustal signature, lends strength to the view that the crystal-rich character of these magmas derives from protracted storage in cool crust. That the interval between mafic magma injection and eruptive quenching of the hybrid is short is required by preservation of the disequilibrium phase assemblage. It is similarly required by the steepness of concentration gradients arising from diffusion at crystal rims initiated upon mixing (Nakamura 1995). Finally, the process was actually 'seen' seismically at Mt Pinatubo (White 1996). There, hundreds of deep long-period (DLP) events were recorded and located in the lower-to-mid crust beneath the inferred location of a large dacite magma chamber. Days later, a hybrid andesitic dome bearing freshly chilled mafic enclaves emerged at the surface. Caldera collapse accompanying voluminous eruption of the dacitic end-member followed shortly thereafter. This, together with petrological evidence of shallow equilibration of the dacitic magma and the presence of an aseismic volume (Mori *et al.* 1996) just beneath the volcano, leave little room to doubt that mafic recharge of a crustal reservoir triggered eruption (Pallister *et al.* 1996).

Given that these reservoirs are enclosed in fairly rigid material, input volume may approximately equal output volume (except where reservoir roof collapse and catastrophic emptying of the stored contents occur). The entrained enclaves in hybrid eruption products would then represent only a modest proportion of the introduced mafic magma, most of which remains at the bottom of the chamber owing to its greater density. Such replenishment events can be viewed as subsurface eruptions, and, indeed, the mafic infusions are seen in exhumed granitoid plutons to have taken on a lava-like form as they spread across the floor of the chamber (Wiebe 1996). Such a process can also explain why andesitic volcanoes do not generally show a gradual increase in crystallinity of eruption products with time, as one would predict for an isolated shallow body. They are sustained by advective introduction of heat (see, for example, Lachenbruch *et al.* 1976). Thus, periodic infusions of mafic magma from depth are not only the triggers for eruption from these stalled pods of andesitic mush, but are their very reason for continued existence.

Amid the discussion of petrological, isotopic and seismic evidence for the replenishment process, it has gone largely unnoticed that there is also simple field evidence for it: the simultaneous eruption of crustally stored andesite and a 'new' magmatic arrival from vents spaced kilometres apart. This would seem to represent the imperfect operation of replenishment, where an unusually large replenishing dyke both interacted with the 'target' reservoir and partly missed it, erupting directly on its own. In this paper, we describe two such cases, one studied by us and one investigated by others, that we believe display the rise of dykes and their incomplete trapping by a shallow andesitic reservoir: in one case a basaltic dyke beneath Karymsky Volcano, Kamchatka, Russia, and in the other a rhyolitic dyke beneath Katmai volcano, Alaska, USA (figures 1 and 2). The time- and distance-scales of interaction between dyke and reservoir are similar, but the consequences for the reservoir are opposite, owing to opposite density relationships between stored and intruding magma. The Katmai case further illustrates that chamber inputs are not always more mafic than
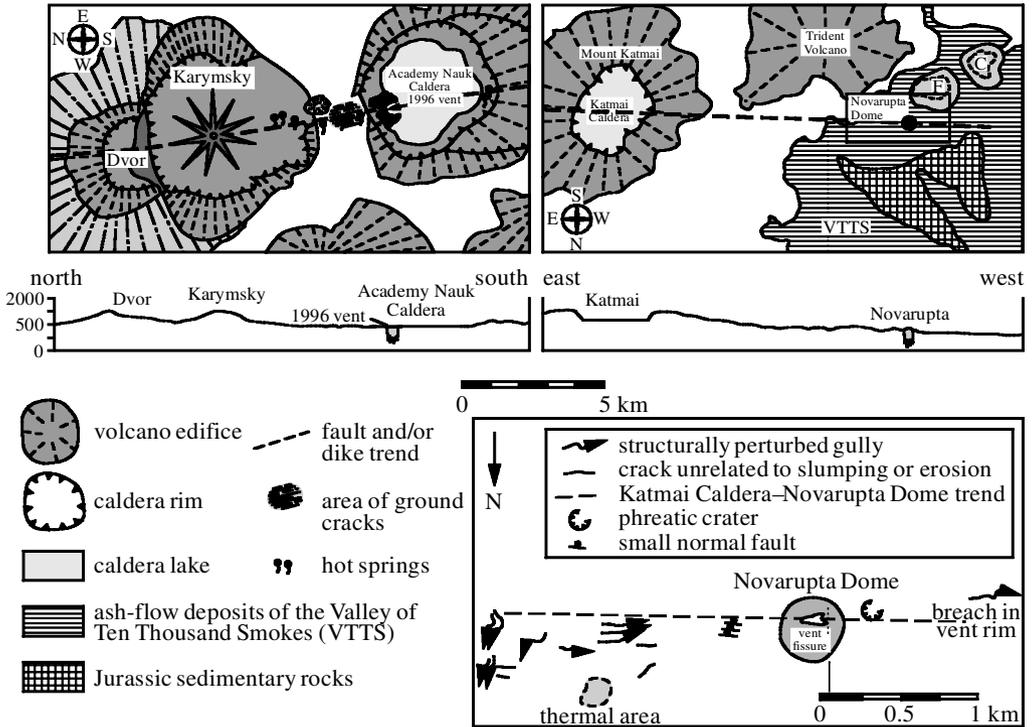
Figure 1. Principal surface features and topographical cross-sections of the Karymsky Volcano—Academy Nauk Caldera and Katmai Caldera—Novarupta Dome systems. For the Katmai region, F denotes the Falling Mountain dacite dome and C denotes the Mt Cerberus dacite dome. Expanded view shows structural features in tephra cover near Novarupta Dome that may reflect final adjustments in the subsurface feeder dyke for the eruption. These are selected features; another structural lineament intersects this trend at Novarupta Dome vent but is aligned with the subsequently active New Trident vent. However, it is the Katmai–Novarupta trend with which the elongation of the dome's fissure vent structure is aligned. We note that a rhyolite feeder dyke was confirmed by drilling to lie a few hundred metres beneath a similar alignment of features at Obsidian Dome, California, USA (Eichelberger *et al.* 1986). For details of surface deformation structures in the Karymsky region, see Leonov (1997).

the chamber contents as is commonly assumed. Indeed, silicic replenishment events may be an important cause of chemically zoned caldera eruptions in magmatic arcs.

2. The Karymsky case

Karymsky Volcano is one of the most active volcanoes of the Eastern Volcanic Zone of the Kamchatka Arc, which lies *ca.* 220 km landward of and parallel to the Kamchatka trench. Before 1996, it was considered the only active centre in a local linear chain of several volcanoes and calderas (figure 2). This chain formed during Holocene time along a north–south trending fault zone of the Zhupanovsky volcano-tectonic depression (Ivanov 1970). Karymsky is a strato-volcano located in the centre of a 5 km diameter caldera. The caldera formed *ca.* 6600 years ago as a result of an event that produced *ca.* 6 km^3 of dacite and rhyodacite ignimbrite (Ivanov *et al.* 1991). The
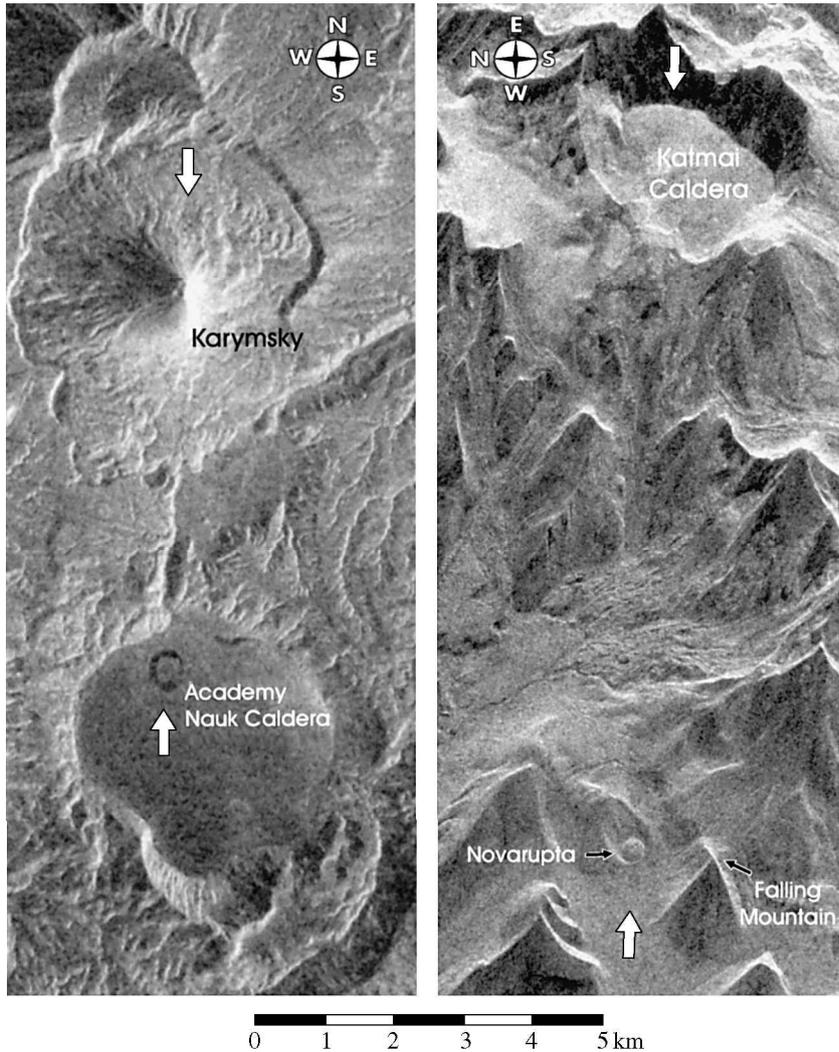
Figure 2. Synthetic aperture radar (SAR) satellite images of the regions depicted in figure 1. Heavy arrows point to postulated dyke traces, as discussed in the text. The Karymsky and Katmai images are reproduced courtesy of the Canadian and European Space Agencies, respectively.

active cone of Karymsky was built during the last 5100 years, with an apparent hiatus in activity between 2800 and 500 BP. It is mostly comprised of andesite of quite constant composition (59–62 wt% SiO_2). However, at least twice in its history at 6100–5400 BP and at 2800 BP, Karymsky produced basaltic andesite (52–56 wt% SiO_2; see Ivanov (1996)). The mineral assemblage of the andesite is also fairly constant: phenocrysts of plagioclase, clinopyroxene, orthopyroxene, magnetite and sporadic olivine xenocrysts. The phenocrysts probably grow in—and the repeated similar eruptions evidently tap—a long-lived andesitic reservoir indicated by seismic data to lie at shallow depth beneath Karymsky (Zubin *et al.* 1971). Previously in the 20th
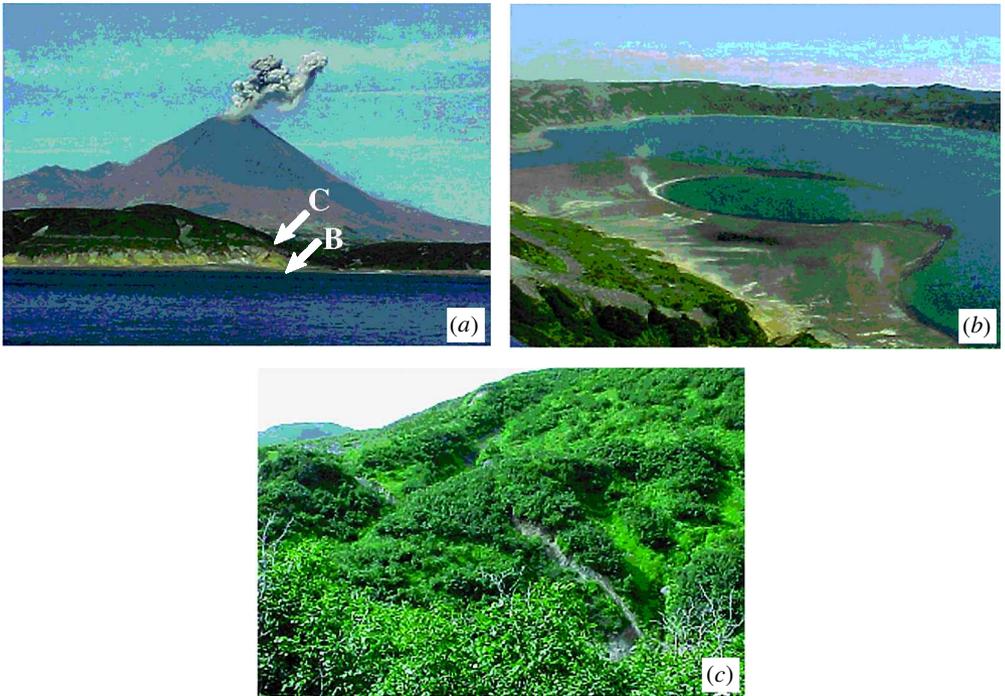
Figure 3. Views of the Karymsky Volcano: Academy Nauk Caldera system. (*a*) Karymsky Volcano in eruption (21 August 1999) from the south side of Academy Nauk Caldera and Karymsky Lake. Locations marked B and C denote the centres of the views in the accompanying photographs. (*b*) Basalt tuff ring formed 2 January 1996 at the start of the current episode. (*c*) One of many extensional cracks between the two vents formed at about the time of the start of the eruption. Field of view in (*c*) is *ca.* 1 km.

century, Karymsky erupted continuously during 1908–1915, 1921–1925, 1929–1935, 1943–1947, 1952–1967 and 1970–1982.

The latest cycle of eruptive activity of Karymsky began on 2 January 1996 after a five-month period of gradually increased seismic activity (figure 3; Muravyev *et al.* 1997; Leonov 1997). This activity culminated in a 6.9 M volcano-tectonic earthquake on 1 January located *ca.* 15 km to the south on the north–south fault. Unlike previous historic eruptive events, the cycle started with simultaneous eruptions from two vents located *ca.* 6 km apart: Karymsky summit vent, and a new eruptive centre formed within Academy Nauk Caldera, an *ca.* 40 000 year-old structure centred *ca.* 9 km south of Karymsky on the same fault. The hydroclastic eruption of the Academy Nauk Caldera centre produced *ca.* 0.04 km^3 of basaltic tephra and terminated before 3 January, while vulcanian and effusive andesite activity at Karymsky continued throughout 1999 (figure 4; table 1). Although there is some debate about how many hours separate the onsets of Karymsky and Academy Nauk eruptions (Fedotov 1997), the difference is less than 12 h. This means that from the perspective of how long an intrusion of modest thickness would remain molten, these *eruptions started simultaneously.*
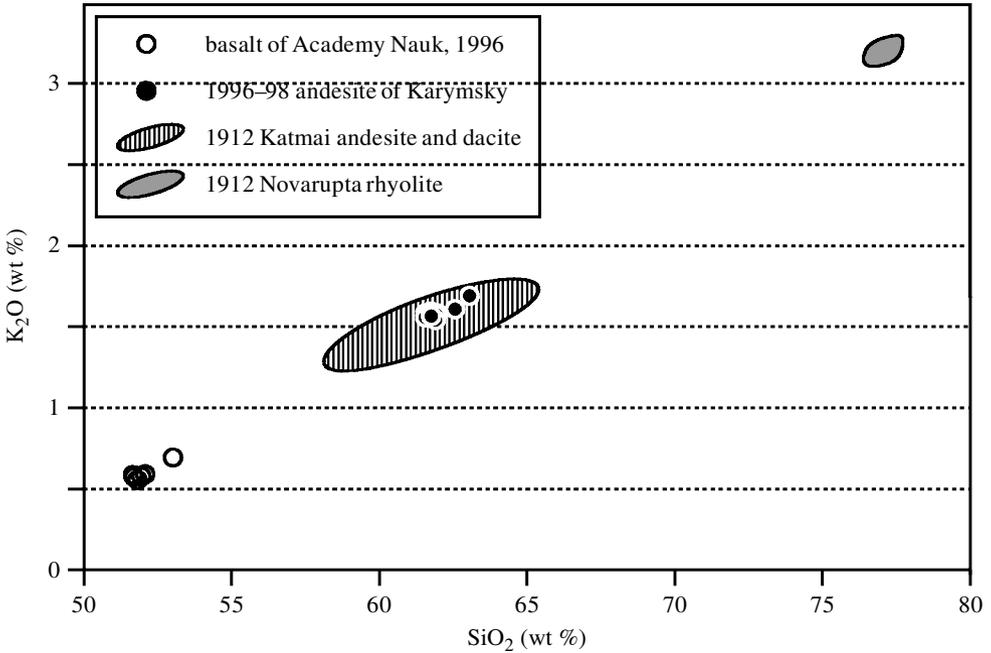
Figure 4. Bulk composition of simultaneously erupted magmas at Karymsky (this paper) in 1996 and at Katmai (Hildreth 1983) in 1912, in terms of weight per cent K_2O versus SiO_2. Note the similarity of the centrally derived (and centrally erupted in the case of Karymsky) andesitic magmas and their discontinuity with the homogeneous, distally erupted basalt and rhyolite.

Geodetic measurements completed during the summer of 1996 showed that significant extension occurred perpendicular to the fault connecting the two eruptive vents (figure 1). The maximum amplitude of extension of 2.3 m lies *ca.* 1.5 km north of Academy Nauk eruptive centre (Maguskin *et al.* 1997). Here, impressive ruptures in the surface were formed in a broad zone spanning the fault (figure 3). Surprisingly, no damage was done to the Karymsky volcanological station located less than 4 km away, thus implying that extension occurred gradually rather than violently (A. Belousov, personal communication, 1999). Measurable extension occurred well north and south of the two vents, and thermal output of hot springs increased along the trend. This suggests that a *dyke penetrated the crust along the existing fault and intruded between and under the two eruptive centres: Karymsky and Academy Nauk* (figure 2). Given that the new vent erupted basalt, whereas the established vent simply resumed erupting andesite for which there is geophysical and petrological evidence of shallow storage, it is logical to postulate that the dyke magma was basalt. This magma erupted directly at the Academy Nauk vent. However, because basaltic magma is considerably denser than andesitic magma (see, for example, Bottinga *et al.* 1981), the basalt would have been trapped by, and would have ponded at, the base of Karymsky's shallow chamber, forcing chamber magma out of the top.

Continuing eruption of Karymsky offered a unique opportunity to examine the progress of any mixing between the two magmas with time, by sequentially sampling tephras produced during 1996–1999. Microprobe analyses showed that concentrations of major elements in volcanic glass of Karymsky tephra varied significantly in

Table 1. *Summary of events at Karymsky Volcano*

date	event
March 1995–1 January 1996	gradual increase of seismic activity at Karymsky volcanic centre (Muravyev *et al.* 1997; Fedotov 1997)
1 January 1996	set of significant volcano-tectonic events, from which the largest one was *ca.* 6.9 M with epicentre located 12 km south of Karymsky, at *ca.* 10 km depth
2 January, *ca.* 1:35 a.m.[a]	eruption of Karymsky Volcano started
2 January, *ca.* 2:00 p.m.	eruption of Academy Nauk centre began
3 January, *ca.* 11:00 a.m.	eruption of Academy Nauk centre terminated
2–11 January	explosive style of eruption: 15–35 min-long sequences of 3–5 explosions producing ash columns up to 1200 m in height followed by gas emissions
12–14 January	effusive activity began. First $650 \times 80 \times 10 \text{ m}^3$ lava flow formed in 3 days
15–21 January	explosive activity continued at the same level
22 January–21 February	sporadic explosive activity (2–3 explosions per day) with continuing effusion of lava flow
22–29 February	increase in numbers of explosions
30 February 1996–autumn 1999	constant effusive–explosive activity

[a] All times are shown in Kamchatka standard time (KST). KST = UTC + 12.

the initial phase of activity (Izbekov *et al.* 1998). With a single exception, the earliest analysed glasses have the lowest SiO_2 (as low as 67.9 wt%) content (figure 5). Approximately two months after the onset of activity, SiO_2 content rose and eventually stabilized at 72.0 wt% SiO_2. The changes are larger than analytical error. Complementary deviations of glass compositions were observed in concentrations of K_2O, CaO, MgO and Al_2O_3. Three general explanations can be suggested to account for the variations in major elements in the beginning of the eruption:

(1) pre-existing compositional heterogeneity of the Karymsky reservoir;

(2) higher magma flux at the beginning of eruption resulting in less syneruptive crystallization; and

(3) magma mixing.

If the Karymsky reservoir was already compositionally heterogeneous, then it has to be explained why the composition of volcanic glass stabilized and remained constant after the first two months of eruption. The behaviour looks more like a transient effect driven by some perturbation at time zero and decaying after that.

The second possibility is that these variations in melt composition could be related to higher magma flux at the beginning of the eruption. This early magma might have undergone less crystallization during more rapid ascent and, therefore, erupted
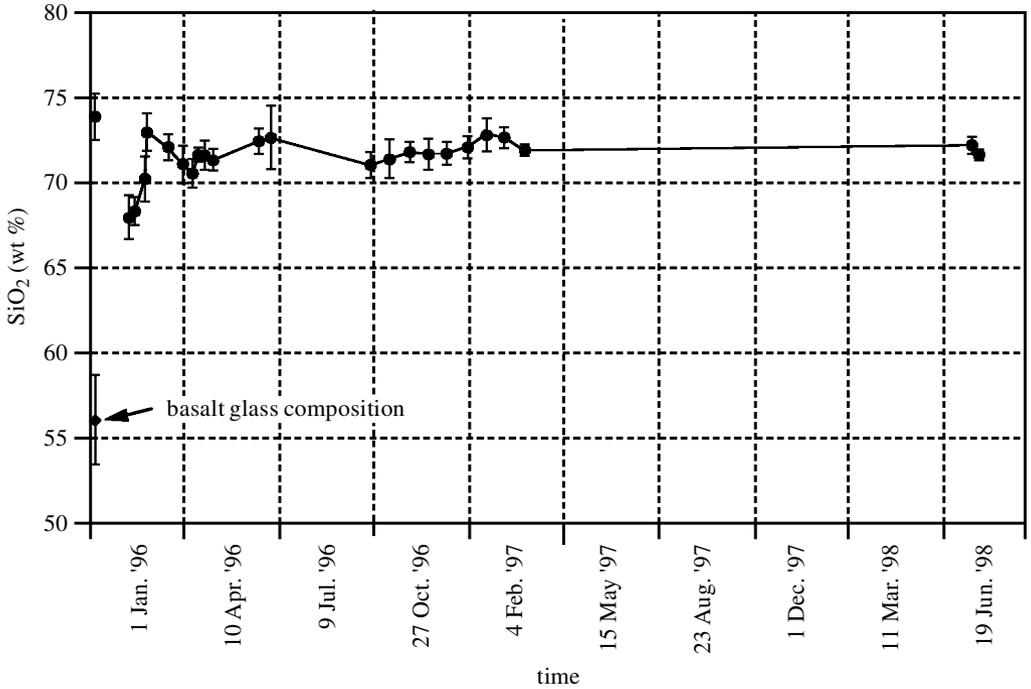
Figure 5. Silica content as a function of time for glass in tephra
erupted from Karymsky Volcano during the current episode.

with less evolved glass: a glass closer to the melt of pre-eruption chamber condi-
tions. In this case, bulk composition would be constant but glass composition would
vary with crystal content. Because our high time resolution sample suite is neces-
sarily restricted to ash, which cannot yield reliable bulk compositions—lava samples
have uncertain eruption times and undergo variable groundmass crystallization after
extrusion dependent upon position within the flow—it is not possible to directly
measure bulk composition as a function of time and in relation to glass composition.
However, syneruptive crystallization-caused melt variations should be accompanied
by variations of microlite content in the groundmass. According to the Melts model
(Ghiorso & Sack 1995), the observed increase of 4 wt% SiO_2 in crystallizing melt
would require an increase in volume fraction of solid phases of 12–17 vol.%. To test
the postulate that variations of melt composition are related to different degrees of
crystallization, while the overall magma composition is constant, we studied vari-
ations of microlite content in tephra using back-scattered electron (BSE) imagery
(P. E. Izbekov, unpublished data). Results indicated that variations of microlite con-
tent are much smaller than what would be required to account for the variation in
melt composition, making the initial assumption implausible.

Thus, with elimination of the most obvious alternatives and support from the
eruption chronology and from the fact that early deviation of concentrations of all
major elements in melt are toward 1996 basalt, it appears that the third possible
explanation is the most probable one. The significant deviations of the composition
of glass in andesite tephra early in the eruption were probably caused by influx of
basalt into the shallow magmatic system of Karymsky. Whether the effect is due

to direct mixing of components or simply heating of the andesite by basalt causing phenocryst resorption and making the melt less evolved remains to be established. Either, however, requires direct contact between the two magmas in the Karymsky chamber.

We conclude that a basalt dyke intruded along the pre-existing fault, intercepted a shallow andesite magma system beneath Karymsky Caldera, and triggered the eruption of Karymsky Volcano. Perhaps because the axis of the dyke was close to Academy Nauk Caldera, the dyke continued its ascent in this region also. Here, it found no active magma body blocking its path, only the crystallized granitic remnants (some entrained and erupted as xenoliths) of the rhyolite magma that produced this older structure. Consequently, the basalt breached the bottom of Karymsky Lake, on the northern side of the caldera. Meanwhile, in the hydrodynamic regime of the Karymsky andesite system, a portion of the introduced volume of basalt was either quickly blended into the chamber magma, some of which reached the surface soon after that, and/or some of the basalt remained on the floor and altered the adjacent reservoir magma by heating it. No mafic enclaves were produced in this interaction, perhaps supporting the view that heating rather than direct mixing was the main consequence. In two months, the new 'hybrid' andesite or 'heated' andesite produced by contact with new basalt was exhausted (and/or diluted below detectability), and then unaffected chamber magma of Karymsky erupted. This is analogous to the more explosive and voluminous sequence of hybrid then uncontaminated reservoir magma that followed basalt injection at Mt Pinatubo (Pallister *et al.* 1996).

3. The Katmai case

Although different in many ways, the great eruption that formed the Valley of Ten Thousand Smokes (figures 1 and 2) in what became Katmai National Park, Alaska, was similar to Karymsky in one important and remarkable aspect: the simultaneous occurrence of volcanic activity at the central vent of an andesitic system and at a 'flank' (actually, well beyond the flank of the edifice in both cases) vent several kilometres distant. This has been viewed as an 'odd' eruption of a 'normal' zoned magmatic arc system, because the centres of collapse and eruption are separate rather than coincident and because the progression of magmatic compositions with time is not regular. But, like Karymsky, it may be a 'normal' case of dyke injection mobilizing a shallow pod of andesitic magma.

The volcanism of the Katmai region (Hildreth 1983) comprises a segment of the eastern Aleutian volcanic arc (Kienle *et al.* 1983). Mt Katmai itself is in the centre of this segment, which is a straight line (one volcano excepted) of unusually closely spaced stratocones within the arc. These cones are beautiful but not imposing: they owe much of their elevation to a gentle upwarp of Mesozoic sedimentary basement upon whose crest they are aligned. With volumes of tens of cubic kilometres or less, they each represent little more effusive accumulations in their presumably lengthy Quaternary eruption histories than vented explosively in two days in 1912. This one eruption also produced a far greater range in chemical composition than had been seen before in the Quaternary volcanic record of the region.

Pioneering geological work in the area was conducted by the National Geographic Society-funded Griggs expeditions, a response to the botanical devastation of Kodiak

by the 1912 ash fall (Griggs 1922). These workers found a newly formed caldera and an even more remarkable ignimbrite-filled valley, which they named the Valley of Ten Thousand Smokes. They also noted a small, profusely steaming lava dome, within an asymmetrical crater and broader region of fracturing, which they named Novarupta. They were naturally drawn to the caldera as a significant source of the eruptive activity. It was only through later diligent study of the pyroclastic deposits that evidence was presented that much (Curtis 1968) and, eventually, virtually all (Hildreth 1983; Fierstein & Hildreth 1992) of the magma emerged in the vent basin now occupied by Novarupta Dome. Hildreth and co-workers went on to characterize the major associated andesitic centres (Hildreth & Fierstein 2000). The one historic 'normal' andesitic eruption of the region, that of Southwest Trident Volcano, which actually postdates the 1912 event and occurred only 4 km from Novarupta, has been studied in detail by Coombs *et al.* (2000). In this discussion, we draw on the results of these workers to suggest what the 'normal' state of affairs is for magma chambers in the region and what happened to perturb this situation in 1912.

(a) Steady state

The predominant products of volcanism in the Katmai region are small-volume, partly explosive, partly effusive eruptions of andesite to dacite. The eruptives are characteristically highly porphyritic (30–50 vol.% crystals) with, in order of abundance, plagioclase, pyroxene and oxides $\pm$ hornblende. Quartz is never seen as a phenocrystic phase (except, as will be noted, in the 1912 rhyolite). Because virtually all the magmas would crystallize significant amounts of quartz before reaching the solidus, this means that material from cool marginal zones of magma bodies are never entrained and incorporated into erupting magma. Nevertheless, there are crystal-rich mafic enclaves present in abundance in most lavas. As in other cases, they appear to represent new mafic magma injected into and crystallized within cooler and more silicic stored magma as represented by their host.

Based upon its petrological similarity to many of the cone-building lavas and in particular to the andesite and dacite of the 1912 eruption, Southwest Trident Volcano may represent the 'normal' state of affairs for magma systems of the region (Coombs *et al.* 2000). Half a cubic kilometre of magma was erupted during 1953–1968 as multiple flows and lesser scoria and ash. The eruption products span *ca.* 10 wt% SiO_2, from andesite to dacite, and bear evidence of shallow storage and mixing. Such modest batches of poorly stirred slush are a common product of central vent andesitic centres (e.g. Tatara–San Pedro (Feeley & Dungan 1996); Redoubt (Wolf & Eichelberger 1997); Ruapehu (Gamble *et al.* 1999)). At Southwest Trident, the mafic end-member is represented not only by the enclaves but also by mafic scoria. SAR interferometry of the volcano indicates present-day inflation due to a pressure source at *ca.* 2 km depth (Lu *et al.* 1997). Experimental replication of phase assemblages (melt and crystal rim compositions) suggests equilibration at pressures corresponding to a depth of *ca.* 3 km (Coombs *et al.* 2000). Intense microseismicity is clustered at a few kilometres depth beneath the volcano (Jolly & McNutt 1999).

These data suggest that a relatively small-volume, perhaps at most a few cubic kilometres, storage chamber exists just below the volcano (Coombs *et al.* 2000). The recent eruption was triggered by infusion of new, more mafic, andesitic magma into the chamber. The volume of the infusion was probably balanced by the volume of eruptive output. The reservoir is small enough that vigorous injections are

able to pass through it with minimal interactions, to erupt as mafic scoria. During less vigorous injections, interaction occurs, some of the injected magma is entrained as thermally equilibrated enclaves, and hybrid lavas are produced. Because of the pristine character of glass in the enclaves in contrast to that of the host, it is further suggested that all enclaves are 'freshly made' and related to the current mafic replenishment cycle (Coombs *et al.* 1999).

(b) *The 1912 eruption*

Following a period of regionally felt seismicity (Abe 1992), and during a span of only two and a half days, some $13 \, \text{km}^3$ of magma erupted as $30 \, \text{km}^3$ of pumice and ash from a vent near, but not on, the crest of the Aleutian Range (figure 2; see also Hildreth (1983)). Hildreth (1983) identified three magmas involved in the 1912 eruption: a continuum from porphyritic andesite to porphyritic dacite, and a distinct, nearly aphyric (but quartz-bearing) high-silica rhyolite (figure 4). In the initial episode, rhyolitic Plinian and pyroclastic flow eruptions were followed by a period of mingling, when all three magmas participated to complete emplacement of the chemically zoned ignimbrite sheet of the Valley of Ten Thousand Smokes (Fierstein & Hildreth 1992). During the first night when andesite and dacite magmas joined the eruption, Mt Katmai began its collapse (Hildreth 1991). On the second and third days, dacite occasionally mingled with andesite erupted in mostly Plinian fashion. Emergence of a small dome of andesite-contaminated high-silica rhyolite concluded the activity, perhaps immediately after the cessation of explosive activity but in any case before the site's discovery four years later.

By the end of the eruption, the magmatic proportions were 7–$8 \, \text{km}^3$ rhyolite, $4.5 \, \text{km}^3$ dacite, and $1 \, \text{km}^3$ andesite (Hildreth & Fierstein 2000). Significantly, bandings between rhyolite and andesite and between andesite and dacite are common, whereas banding between dacite and rhyolite is rare. This would seem to suggest that the andesite was somehow interposed between the dacite and rhyolite during the syneruptive contact that produced the mixing, rather than being at the bottom of a downward rhyolite–dacite–andesite layering that simple density stratification of a single magma body would require.

There are things about this eruption that were unprecedented for the region, and some that were normal. Unprecedented aspects are the volume, explosiveness and chemical range of the eruption. In terms of volume, the eruption is comparable with an entire volcanic edifice. As for explosiveness, virtually all the erupted magma fragmented explosively; the volume of the associated effusion was trivial, less than one-thousandth of the erupted products. Chemically, the magma assemblage included high-silica rhyolite, which had never appeared before in the Quaternary volcanic record. In addition, enclaves are completely lacking in the andesitic and dacitic eruptives, despite their nearly ubiquitous presence in 'normal' lavas, such as those of Southwest Trident and the Mt Katmai cone.

On the other hand, there is nothing remarkable about the composition and petrography of the andesite and dacite participants in the eruption (except complete absence of enclaves): they closely match common lavas of the surrounding volcanoes (Hildreth 1983). Indeed, except for the rhyolite, which is remarkably homogeneous in composition despite its considerable volume, the range of compositions is very similar to that observed to have been erupted during the nearly 15 years of activity

at Southwest Trident (Coombs *et al*. 2000). One can imagine that the 1912 eruption involved the complete emptying of a shallow crustal storage system similar to that which fed the Southwest Trident activity. Hildreth & Fierstein (2000) have shown that although Katmai, Trident and Mageik volcanoes all produce lavas of this major-element composition, there are enough subtle and consistent variations in trace-element chemistry to suggest that each centre has its own storage system. Further, these data implicate the Katmai system as the likely source of the 1912 andesite and dacite, a finding consistent with the obvious surface evidence that magma was withdrawn from beneath Mt Katmai and erupted at Novarupta.

Unquestionably, then, there was a transfer of magma from beneath Mt Katmai to the Novarupta vent, with the result that collapse occurred at Katmai and eruption at Novarupta (Hildreth 1991). Wallmann *et al*. (1990) argued that the likely direction for dyke propagation would be from nearest-neighbour Trident, not from Katmai. On the contrary, however, there is an alignment of features associated with the Novarupta vent trending toward Katmai Caldera (figure 1). These include kinked gullies established on the 1912 surface, small faults, phreatic craters, and the orientation of Novarupta's elongate fissure feeder. Glaciers cover the remainder of the route from the caldera. There is, however, an alignment of topographical lows along the pathway evident in SAR imagery (figure 2). Perhaps this represents a zone weakened by previous fracturing and preferentially eroded by glaciation.

The volume of collapse at Katmai, equivalent to less than half the eruption, coincides with the volume of dacite and andesite (Hildreth 1983; Hildreth & Fierstein 2000), consistent with a shallow source for those magmas beneath Katmai. The abundant phenocrysts in these magmas, including complexly zoned plagioclase-containing melt inclusions with relatively low water content (Westrich *et al*. 1991), are also suggestive of protracted shallow storage, which had contributed to crystallization and volatile loss. Analogy to the similar Southwest Trident lavas, where both phase relations and SAR interferometry indicate a shallow reservoir (Coombs *et al*. 2000; Lu *et al*. 1997) further strengthens this view, as does the distribution of microseismicity beneath Katmai region stratocones: discrete clusters of events at a few kilometres' depth beneath each volcano (Jolly & McNutt 1999). However, because mafic enclaves are absent from the 1912 andesite and dacite—features associated with mafic replenishment-triggered eruptions in this region, if Southwest Trident is a reliable guide—it may be that the 1912 eruption had a cause other than mafic recharge.

If the crystal-rich character and long history of eruption of magmas like the 1912 andesite and dacite suggest protracted shallow storage, then the opposite characteristics of the rhyolite—low crystallinity and lack of representation in the eruption record—may indicate the rhyolite's recent arrival from a deep source. To this evidence can be added the lack of compensating caldera collapse. If the rhyolite came from a separate, deeper source, its withdrawal might have been compensated for by ductile flow at depth over a broad region, rather than the brittle failure in the upper crust that compensated only for withdrawal of the andesite and dacite. Also suggestive of derivation from greater depth, the rhyolite exhibits significantly higher water contents in melt inclusions than the shallow-sourced andesite and dacite. Although Lowenstern (1993) and Westrich *et al*. (1991) reported water contents of 4 wt% in quartz phenocrysts in rhyolite pumice based upon FTIR and ion microprobe analyses, not exceptional but still higher than the andesite and dacite, Cowee *et al*.
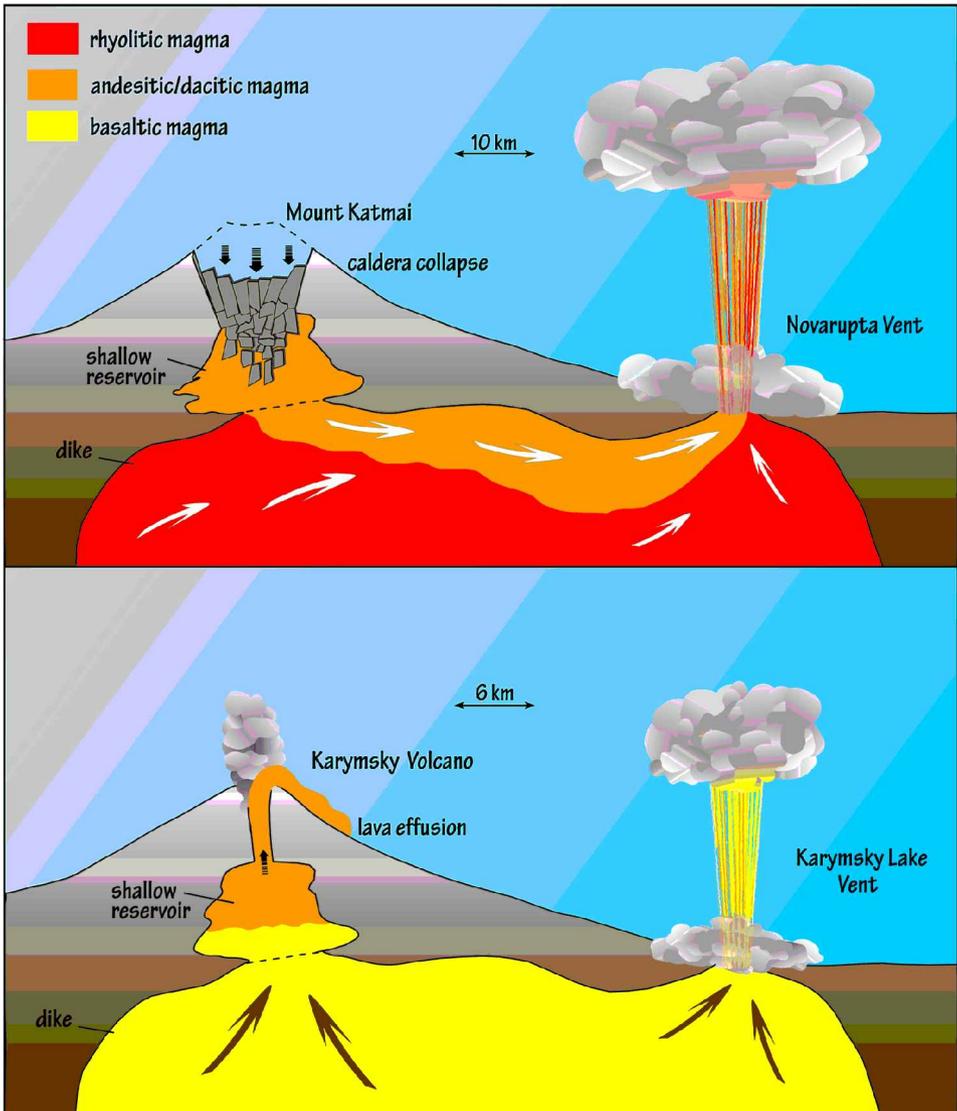
Figure 6. Cartoon depicting the triggering of eruption from a stagnant shallow andesitic reservoir by dyke injection. In the Katmai case (top), the dyke drains the reservoir because the dyke magma is less dense than the reservoir magma. In the Karymsky case, the dyke causes reservoir magma to be expelled upward because the dyke magma is denser than the reservoir magma. Note that the dyke, shown in plan view, may be only a few metres thick, whereas the reservoir is likely to be a kilometre or more in extent in the direction of view. As the Katmai–Novarupta dyke crosses the former base of Falling Mountain (figure 2), its emplacement may have played a role in that dome's collapse on the first day of eruption.

(1999) found water contents in melt inclusions in quartz phenocrysts in rhyolite of Novarupta Dome as high as 7 wt%.

How could the rise of new rhyolitic magma from depth cause both eruption at Novarupta and collapse at Mt Katmai 10 km away? Hildreth (1983) noted the possi-

bility that a rhyolite 'reservoir' close to Novarupta was breached by Katmai andesite–dacite magma. However, Hildreth & Fierstein (2000) argue that the rhyolite was a separately convecting cap on the andesite/dacite. They postulated that the rhyolite was crystal poor not because of recent formation but because of continuous heating from below within a zoned chamber. Here, in contrast, we note the spatial and temporal similarity of the distribution of events at Karymsky and Katmai: simultaneous eruption of crystal-rich andesite derived from a long-established central magma system and of a 'fresh' magma from a kilometres-distant flank vent. Inspection of crustal exposures of the plutonic regime indicates that the most common means of flow of magma in the crust is as dykes, and that such features commonly have lateral extents of multiple kilometres. We therefore suggest that a rhyolite dyke breached the surface at Novarupta and simultaneously intersected the shallow andesite–dacite reservoir beneath Mt Katmai. In the Karymsky case, the dyking event caused the expulsion of andesite from the central vent by virtue of the lesser density of the stored than the intruding magma. In contrast, the lower density of the Novarupta rhyolite than of the stored Katmai magma allowed the draining of the intermediate-composition magma into the dyke; that is, a reversal of flow. The Katmai magma could, however, erupt in artesian fashion through the open flank vent at Novarupta, because that vent was at a lower elevation than the subsiding column (andesite–dacite magma plus collapsing edifice) within Mt Katmai. This driving force ceased to operate when the floor of the caldera approached the elevation of the exit point, Novarupta vent, and the eruption was essentially over except for a small bit of underlying rhyolite dyke magma that buoyantly oozed to the surface to form Novarupta Dome.

Wiebe (1987) has documented plutonic evidence for draining, on a similarly massive scale, of a mafic chamber by silicic dyke intrusion in Precambrian exposures in Labrador. Indeed, an earlier version of this event may be recorded in the Katmai area itself. Several kilometres west of Novarupta in the southwest corner of the Valley of Ten Thousand Smokes, a rhyolite dyke–sill complex in the Jurassic sedimentary basement merges up-slope with a stock of granodiorite (Lowenstern *et al.* 1991); a relationship that may reflect partial draining of the stock into the intercepting rhyolite body.

4. The 1912 and 1996 eruptions in context

Figure 6 shows the interpreted subsurface geometric similarity between the Karymsky and Katmai cases. We postulate that at Katmai the sudden transfer of andesitic magma from storage to surface caused by intrusion of the rhyolite dyke, as opposed to the slow expulsion that would have occurred had the intruding magma been basaltic, led to the uncharacteristically explosive dumping of the andesite–dacite magma. Lateral flow of the andesite–dacite magma through gas-impermeable basement inhibited vapour-loss to the dyke walls and to the surface during transport (Eichelberger *et al.* 1986), also contributing to the explosiveness of the magma's emergence. At Karymsky, the more usual slow upward expulsion of andesite through a gas-permeable cone led to a dominantly effusive eruption. In both cases, propagation of laterally extensive dykes produced the notably strong seismicity (*ca.* 7 M).

Were these eruptions rare aberrations in the history of these volcanoes, or unusually well-displayed examples of normal replenishment processes? Examination of the geological record at Karymsky suggests the repeated rise of both basaltic and rhy-

olitic dykes along the same north–south fault structure (figure 2). The Karymsky centre developed on this trend, subsequent to a major rhyolite event. To the south, no andesite centre developed, and a caldera-forming rhyolite event has been followed by repeated basalt eruptions, some bringing up zero-age granitic xenoliths. These are the intrusive equivalents of earlier rhyolite tuffs and they themselves bear the mark of basalt injections previous to the one that brought them to the surface (P. E. Izbekov, unpublished data). Indeed, two eruptions *ca.* 4 000 years ago, when Karymsky Volcano was already active and growing, were very similar to the 1996 event (A. Belousov & M. Belousova, personal communication, 1999). It is possible that many other eruptions of Karymsky have been basalt-dyke triggered as well, but that the basaltic magma did not also separately vent from the flank.

At Katmai, the simultaneous eruption of andesite from the central vent and of either basalt or rhyolite from a flank vent may be unprecedented. Nevertheless, there is strong petrological evidence of repeated mafic recharge of the Katmai system in the form of abundant mafic enclaves in older Katmai lavas. Silicic recharge events may have occurred before as well, perhaps countering the cumulative chemical effects of mafic injections, but too small to cause the sort of separate venting that occurred in 1912.

If the Karymsky andesites are fed from a shallow reservoir (Zubin *et al.* 1971), then this reservoir is on the path of repeated basalt and rhyolite dyke intrusion, and the Karymsky andesite developed within the last 6600 years, since the last rhyolite caldera event (figures 1 and 2). It would be tempting to suggest that residual rhyolite was left in the system 6600 years ago, and that the andesites were mixtures formed by mixing of that magma with subsequent basalt infusions. This simple answer is precluded by the chemical data. Karymsky andesite cannot be solely a mixture of Karymsky-region rhyolite and basalt, nor can Katmai andesite be solely a mixture of high-silica rhyolite and basalt (Hildreth 1983). At the least, the operation of additional processes of wall-rock assimilation and/or internal fractional crystallization are required, enriching the stored andesite in sodium and iron (and aluminium in the case of Katmai) and depleting it in calcium and magnesium, relative to a simple mixture.

5. Application to chemically zoned caldera eruptions

The Karymsky interpretation is hardly revolutionary. Rather, it adds recent field observations to a scenario for andesitic eruptions already under active discussion. Figure 7 presents a comparison of the Karymsky case with several other 'arc-dome' and 'arc-cone' cases where evidence for mafic replenishment has been presented. These are plotted in terms of the silica content of the stored magma versus the lower silica content of the intruding magma. There is a broad scatter of points, but a commonality of petrological characteristics in the eruption products. The dome and cone field may well extend closer to the $y = x$ line of chemical identity between stored and intruding magma. However, the closer that two magma batches are in temperature and composition to each other, the more thorough will be the mixing and the harder it will be to recognize evidence of mixing.

If there is a surprise lesson at Karymsky, it is the lateral extent of dykes that feed central-vent volcano systems, even in modest eruptions. This dyke extends at least two cone radii from the central vent, and perhaps considerably further. Certainly, the
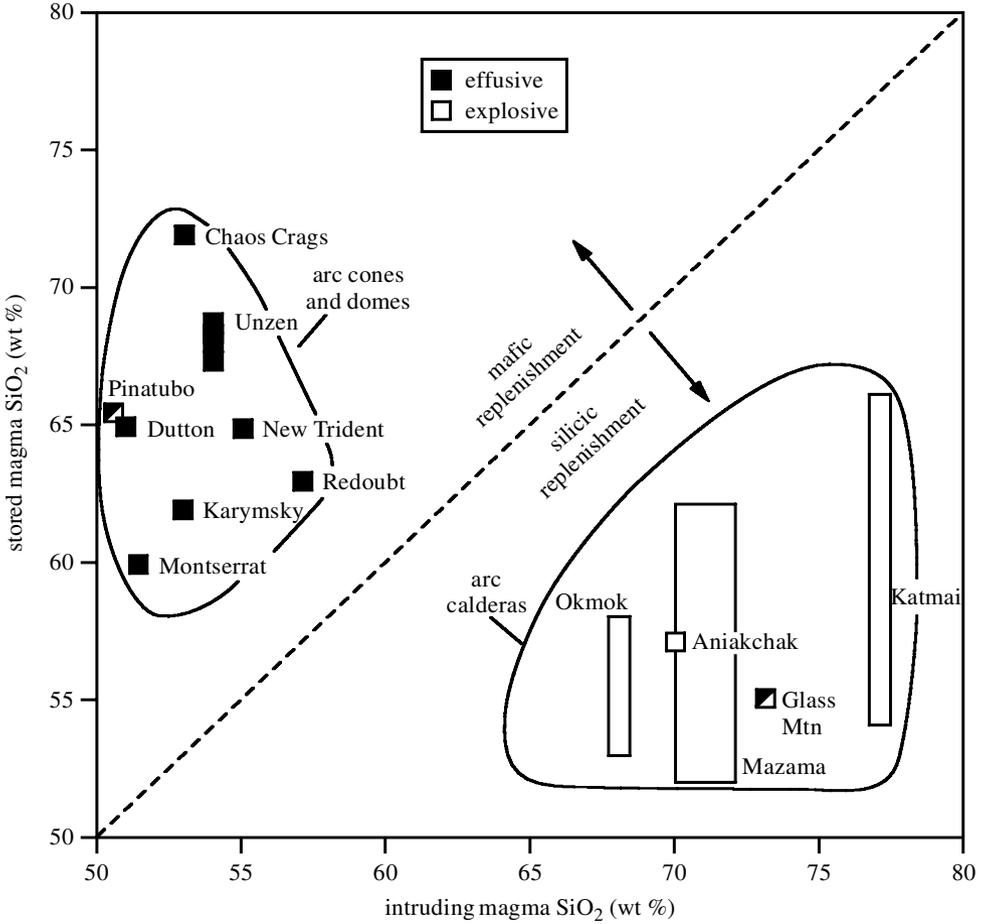
Figure 7. Composition of stored versus composition of intruding magmas, for a number of cases where petrological data can be interpreted to indicate such an encounter. The line $y = x$ divides the field of mafic replenishment (e.g. Karymsky) from silicic replenishment (e.g. Katmai). Data sources are as follows. Chaos Crags, California, USA (Heiken & Eichelberger 1980; Tepley *et al*. 1999); Unzen volcano, Kyushu, Japan (Nakamura 1995; Venezky & Rutherford 1999); Mt Pinatubo, Philippines (Pallister *et al*. 1996); Mt Dutton, Alaska, USA (Miller *et al*. 1999); Soufrière Hills, Montserrat, British West Indies (Murphy *et al*. 2000); Southwest Trident Volcano, Alaska, USA (Coombs *et al*. 2000); Redoubt Volcano, Alaska, USA (Wolf & Eichelberger 1997); Karymsky Volcano, Kamchatka, Russia (this paper); Okmok Caldera, Alaska, USA (Byers 1961); Aniakchak Caldera, Alaska, USA (Dreher *et al*. 1999); Crater Lake, Mt Mazama, Oregon, USA (Bacon 1983); Glass Mountain, Medicine Lake Highland, California, USA (Eichelberger 1975); Novarupta/Katmai/Valley of Ten Thousand Smokes, Alaska, USA (Hildreth 1983). In the mafic replenishment field, we follow the cited authors' conclusions about stored and intruding magmas. For the silicic replenishment field, we suggest a reinterpretation of the cited authors' data based upon the discussion in this paper.

crustal structure along which it was intruded is of the size-scale of several volcanic centres. Clearly, we should think of dykes, rather than mere fingers of magma, as the intruders in replenishment events. Furthermore, we should not assume that flank

vents are only 'parasitic' to the main cone and lack deep connections to magma sources. Their deep connections may in fact be more direct than those of the central vent.

More importantly though, the observations at Karymsky suggest a radical interpretation for the Katmai system and with it the possibility that another field of systems exists in figure 7. The minimum extent of the Katmai dyke is even greater: at least three cone radii from the central vent. What if this intrusion had been less extensive so that it released all of its contents into the Katmai chamber without venting separately? The rhyolitic magma, being much less dense than the stored magma, would have risen rapidly through the Katmai chamber and ponded at the roof. But this magma was less dense than even the Katmai edifice and shallow basement. Rapid inflation of the reservoir combined with loss of buoyancy of the roof would lead to caldera collapse, in this case with all the magma venting around and through the collapsing roof block. We postulate that this is exactly what happened at neighbouring Aniakchak Caldera (Dreher *et al.* 1999), at Okmok Caldera (Byers 1961) further down the chain, and, probably, at many other discontinuously zoned voluminous arc eruptions, as suggested in figure 7. What these sites have in common is the simultaneous eruption of 'normal' andesite and a homogeneous, unusually silicic, and unusually crystal-poor rhyodacite or rhyolite. The main products of direct interaction are volumetrically subordinate banded pumices in which steep concentration gradients in melt compositions—not just in crystals as in the enclave–host assemblage—are preserved. If enclaves are produced by contact between mafic and silicic magmas over days, then these eruptions bear witness to pre-eruption contact that spanned no more than hours. No evidence of prolonged contact in a zoned chamber is to be found.

Such a replenishment trigger is consistent with the observed characteristics of arc caldera eruptions. Weinberg & Leitch (1998) have shown that introduction of a viscous buoyant magma to a chamber can produce a rapidly rising diapir with minimal interaction with its surroundings. Spera (1984) has shown that evacuation of a chamber proceeds from magma that is near the conduit intake to magma that was initially far from the conduit intake, rather than a top-to-bottom tapping that turns chamber stratification upside down. Hence, the eruption would tap silicic diapir and then andesitic chamber magma: no clean stratification may ever have existed in these chambers, even though a clear chemical stratification of deposits is produced.

We would assume that this silicic intruder ultimately owes its existence to basalt injections, perhaps by partial melting of crust with basalt-advected heat at a deeper level (see, for example, Huppert & Sparks 1988; Bergantz 1989; Koyaguchi & Kaneko 1999). There is geochemical evidence for blending of mantle and crustal melts in andesites, which might be expected to occur at the site of crustal melting (see, for example, Hildreth & Moorbath 1988). Here, we suggest that crustal melt may at times collect into discrete bodies and mix with its mafic associates only later at shallow depth, if at all. The chemical zonation of eruption products that has been viewed as evidence of efficient shallow fractionation may instead be evidence of extremely inefficient mixing.

This topic deserves much further discussion that is beyond the scope of the present paper. For now, we note that a persuasive case for mafic dyke intrusion can be made at Karymsky; that the same logic points toward a silicic dyke trigger at Katmai; and that many other arc calderas may share Katmai's origin.

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