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In defense of magmatic diapirs

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Abstract

Diapirism as a crustal magma ascent mechanism has been recently criticized. We contend that this reflects an overly simplistic view that diapirs must resemble modeled hot-Stokes diapirs and the perception that magma ascent in dikes is a more problem-free mechanism for the construction of plutons. We describe four Cordilleran plutons that have characteristics much more compatible with diapirs than dike-fed chambers. These plutons were emplaced at depths ranging from ~10 to 30 km and record different parts of diapiric ascent paths. Most ascended during complex visco-elastic flow of host rock during regional deformation, have narrow structural aureoles indicating power-law behavior of host rock, and were constructed of multiple batches of magma, attributes enabling them to ascend greater distances than single hot-Stokes diapirs. Some features of these plutons are not typically attributed to diapirs, and thus we introduce the term visco-elastic diapir for bodies consisting of one or more batches of magma rising together, with length to width ratios <100, surrounded by host rock deforming by brittle and ductile processes, and for which ascent is driven by buoyancy plus regional stress. We conclude that diapirism remains a valid magma ascent mechanism for the crust. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Many types of diapirs have been documented in the geological literature including those consisting of salt (e.g. Jackson and Talbot, 1986), mud (Orange, 1990), and serpentinite (e.g. Carlson, 1984). The existence of mantle diapirs is also supported by modeling (e.g. Marsh, 1982), geophysical data (Hasegawa and Zhao, 1994), and field data from ophiolites (e.g. Nicolas et al., 1988). However, diapirism is increasingly under attack as a magma ascent mechanism in the crust (e.g. Clemens and Mawer, 1992; Petford, 1996; Clemens, 1998). We speculate that there are three principal reasons why this is so:

1. there is confusion about the definition and characteristics of magmatic diapirs and thus uncertainty about what constitutes evidence supporting this ascent mechanism;
2. it has been suggested that ‘diapiric-like’ plutons preserved in the rock record only provide information about emplacement and not ascent; and
3. another model, construction of plutons by magma ascending in dikes, has gained popularity because it is perceived as a relatively ‘problem-free’ ascent mechanism.

We discuss these issues, and then describe four plutons emplaced at different crustal levels in the Cordilleran magmatic arc, which we believe ascended as diapirs. Our goals are to broaden the perspective of what a magmatic diapir might look like, and to make the case that diapirism is still a hypothesis worth evaluating as a magma ascent mechanism in the crust.

2. Definitions and characteristics of magmatic diapirs

According to Petford (1996), the word diapir, taken from the Greek word meaning to pierce, was first introduced by Mrazec (1927). It has since been used informally in regards to plutons to imply the buoyant

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Table 1
Comparison of dikes, hot-Stokes diapirs, and visco-elastic diapirs. Characteristics of hot-Stokes diapirs and dikes are taken from Marsh (1982), Clemens et al. (1997), and Clemens (1998). Note that for dikes we do not treat less well-defined characteristics of dike-fed magma chambers. See text for discussion, although some characteristics are not mentioned, as they are beyond the scope of the paper[1]

	Dikes	Hot-Stokes diapirs	Visco-elastic diapirs
Characteristics of source:			
Hydrous minerals	Must be present	Need not be present	Need not be present
Degree of melting	May be low	More than 30%	More than 30%
Crustal differentiation	Implicit	Not necessarily	Not necessarily
Structural state of host	Fractured, compacted	Exhumed with magma and ductilely deformed	Exhumed with magma and ductilely deformed
Magma supply rate	Must be high	May be low	May be low
Ascent characteristics:			
Dominant mechanism	Along Mode I cracks	Ductile flow	Multiple MTPs
Typical rates	cm to m per s	cm to m per y	cm to m per y?
Rate of ascent controlled by	Buoyancy and magma viscosity	Buoyancy and host rock viscosity	Stress, buoyancy, and host rock rheology
Distance	Any	2 body radii	Variable
Associated with earthquakes	Yes	No	Potentially
Syn-emplacement regional deformation	N/A	N/A	Yes
Dense xenoliths	Will carry up	Sink	Sink
Emplacement characteristics of body:			
Length/width ratio	>100	1	<100
Orientation vs σ_3	Perpendicular	Any	Any
Batches of magma	1	1	Multiple
Connected to source	Yes	No	No
Mixed magma sources	No	Possible	Likely
Differentiation	Only during ascent	After emplacement	During and after emplacement
Duration of construction	10^2–10^4 y	10^5–10^7 y	10^5–10^7 y
Magma viscosity on arrival	10^2–10^5 Pa s	10^5–10^{10} Pa s	10^5–10^{10} Pa s
Kinematics	Center of flow towards tip	Consistent with internal convection	Complex, but mostly pluton center up
Magmatic foliation	Reflects laminar flow	Reflects convection	Typically reflects syn- to post-emplacement regional deformation
Magmatic lineation	Parallel dike walls	Reflects convection	Steep or reflects syn- to post-emplacement regional deformation
Associated eruptions	Fissures and linear chains	Centralized	Centralized
Of host:			
Dominant host rock MTP	Elastic	Ductile flow	Multiple MTPs
Direction host transferred	Towards σ_3	Locally around diapir	Downwards
Control on aureole width	Brittle process zone	T dependent flow	T and strain-rate dependent power-law flow
Kinematics	None	Mostly inner aureole up	Complex, but mostly inner aureole down
Foliation	None	Margin parallel	Complex
Lineation	None	Steep on sides, shallow near roof	Complex
Structures reflect	N/A	Emplacement	Emplacement + regional deformation

[1] MTP = material transfer process, N/A = not applicable, T = temperature.

rise of large elliptically shaped batches of magma. Van den Eeckhout et al. (1986) suggested use of the terms piercing or non-piercing diapirs for bodies of magma which cut through or intrude concordantly into surrounding host rock, respectively.

Diapirism has been the subject of numerous theoretical and experimental studies. Marsh (1982) explored the behavior of spherical or cylindrical 'hot-Stokes' diapirs, in which host rock is heated sufficiently to flow ductilely around the diapir. Strain-rate or power-law behavior of host rock during diapiric rise of magma was examined by Weinberg and Podladchikov (1994). Modeling of diapirs was first presented by Grout (1945) and was later followed by the use of centrifuge techniques (Ramberg, 1981), finite element modeling (Berner et al., 1972; Schmeling et al., 1988), and fluid dynamics experiments (Whitehead and Helfrich, 1991).

These studies have advanced our understanding of diapirism, but have resulted in an overly simplistic view of both magmatic and host rock processes possible for natural diapirs rising in a heterogeneous crust. Specifically, they simplify or ignore the heterogeneous and strongly anisotropic behavior of the crust; crustal-scale gradients in temperature, pressure, and deviatoric stress; regional deformation synchronous with diapirism; evidence for multiple mechanisms of host rock transfer during magma ascent; and the possibility that a 'diapir' is a wider and evolving part of a through-going magma plumbing system.

For example, these studies conclude that flow instabilities usually result in finger-like bodies that are spherical, rather than sheet-like, in map view, yet recent modeling suggests that ridge-like (sheet-shaped in map view) rather than finger-like flow instabilities will form at pre-existing rigid boundaries, faults, or other lateral changes in material properties, or where regional deformation occurs during diapiric ascent (Talbot, 1977; Ronnlund, 1987; Koyi, 1988; Talbot et al., 1991). Thermal models of diapirs, often used to argue against diapirism, do not incorporate multiple pulses of magma passing into or through chambers and assume overly simplistic host rock flow (Weinberg, 1996). Even so, thermal models still indicate that diapirs can typically ascend a distance of twice their diameter (Marsh, 1982).

Field criteria proposed for magmatic diapirs by some authors also reflect a simplistic view of diapirism. These criteria are commonly based on the assumption that all diapirs are single pulses of magma, have inverted 'tear-drop' shapes, rise through homogeneous host rock undergoing only ductile flow, and preserve magmatic and host rock structures reflecting only ascent processes. For example, Clemens et al. (1997) listed eight field criteria (simplified into three groups below) needed to demonstrate diapiric ascent.

1. At lower levels of a diapir, a high-temperature shear zone, with steep lineation, pluton-side-up kinematic indicators, and rim synclines must be present in host rock around the diapir tail, and a high-temperature, steep lineation must also occur in the diapir.
2. At mid-levels, a high-temperature shear zone with steep lineation and pluton-side-up kinematic indicators must be present along the diapir–host rock contact, and margin-parallel foliation in the diapir, potentially associated with variable kinematics, gives way to steep lineation and no foliation in the diapir core.
3. At high levels, a narrower outward-dipping shear zone displaying down-dip lineation, decreasing temperatures during shear, and pluton-side-up kinematic indicators must be present along the diapir contact; radial lineations should occur in the diapir and increase in intensity towards the margin.

These criteria may fit simple models of hot-Stokes diapirs but may bear little resemblance to natural diapirs. For example, we have presented examples where diapirs may be sheet-like (Paterson and Miller, 1998), preserve magmatic structures that formed *after* ascent (Paterson et al., 1998), and are always associated with varied host rock behavior (Paterson et al., 1996). We therefore suggest that the definition and criteria for magmatic diapirs should not be based on simple hot-Stokes models. The broad definition of Van den Eeckhout et al. (1986) that diapirism is the upwelling of relatively mobile material through or into overlying rock should be retained, and more specific types of diapirs should be delineated where possible.

In this paper, we introduce the term 'visco-elastic diapir' (see Table 1 for characteristics) as an explanation for many diapiric plutons that do not fit the simple hot-Stokes model for diapirs. We use 'visco-elastic' to imply that the host rocks to these diapirs have a complex rheology that ranges from elastic to viscous [see also, Rubin (1993)], including power law, visco-plastic, and other types of behavior, and varies both temporally and spatially during magma ascent. These diapirs are bodies of magma consisting of one or more batches of magma rising together, potentially of any shape but generally with length to width ratios <100, surrounded by host rock deforming by both brittle and ductile processes, and for which ascent is driven by buoyancy plus regional stress.

3. Emplacement vs ascent

Distinguishing between magma ascent and emplacement is to some degree inappropriate as one grades into the other and both require simultaneous move-

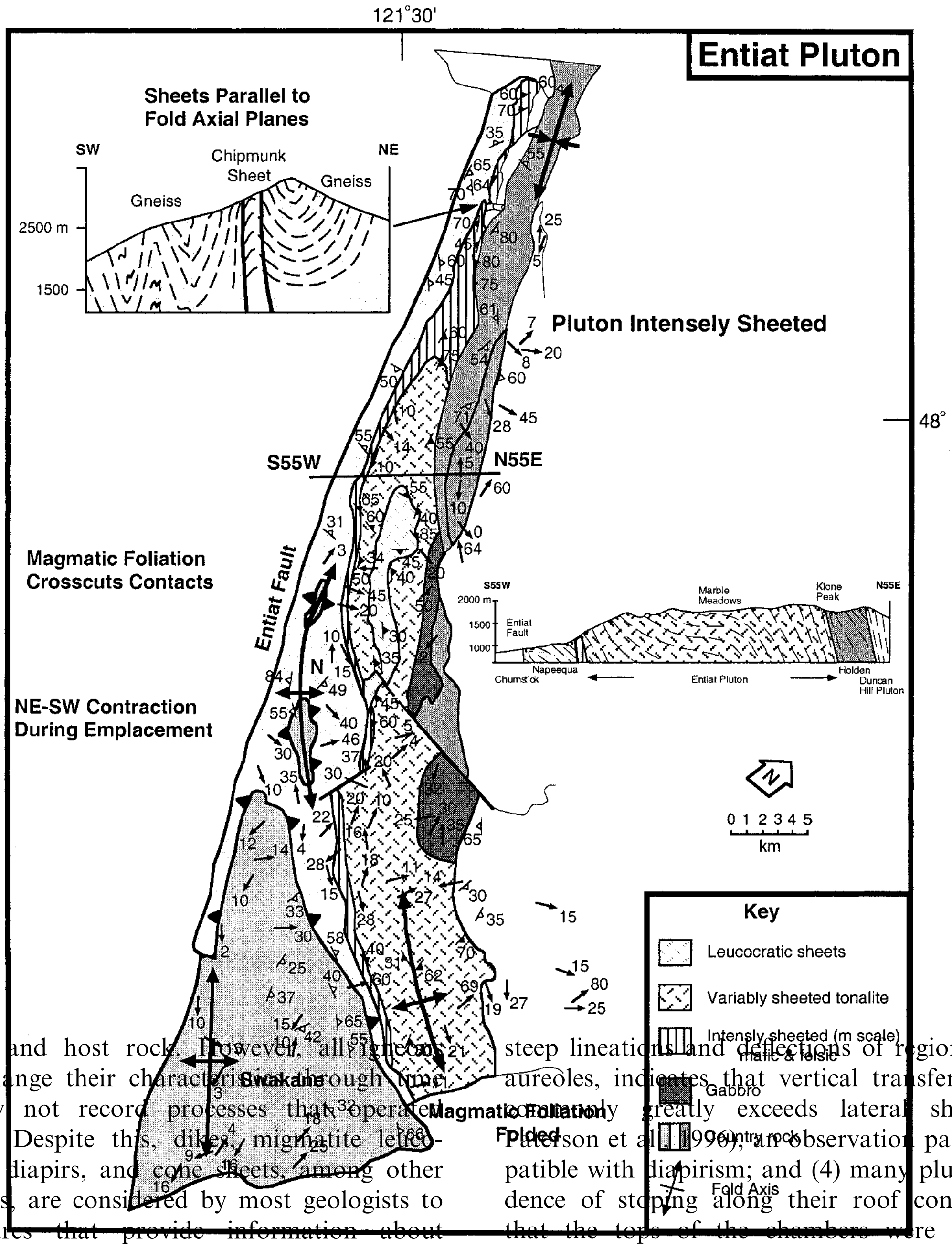

Fig. 1. Sketch map of Mesozoic and Cenozoic plutons in the western part of the North American Cordillera. Note the location of the Cascades core plutons and Half Canyon pluton.

ment of melt and host rock. However, all igneous bodies may change their characteristics through time and thus may not record processes that operated during ascent. Despite this, dikes, migmatite leucosomes, mantle diapirs, and cone sheets, among other intrusive bodies, are considered by most geologists to preserve features that provide information about magma ascent. In contrast, it is often argued that large, elliptical, or spherical 'diapir-like' plutons only record information about emplacement (e.g. Bateman, 1985; Clemens et al., 1997), the argument being that they formed during *in situ* ballooning. This may be true in some cases, but we contend that even if some chamber expansion occurred, most such plutons probably still represent large visco-elastic diapirs for the following reasons: (1) most have magmatic foliations in their margins, indicating they had not reached their solidus before final ballooning/emplacement and thus were still hot and probably buoyant; (2) if these bodies had sufficient energy to heat and displace host rock during expansion, then they probably had enough energy to continue ascent; (3) field evidence, including steep lineations and deflections of regional markers in aureoles, indicates that vertical transfer of host rock commonly greatly exceeds lateral shortening (e.g. Paterson et al., 1996), an observation particularly compatible with diapirism; and (4) many plutons show evidence of stoping along their roof contacts implying that the tops of the chambers were still ascending during final solidification.

3.1. Magma ascent in dikes: the alternative model?

An increasingly popular mechanism of magma ascent is transport in dikes, a mechanism for which there are extensive field examples and theoretical models (Lister and Kerr, 1991; Clemens and Mawer, 1992). Controversy arises, however, when dikes are assumed to feed large elliptical to spherical bodies, a hypothesis for which there are much less field data and no theoretical models. We are troubled by several aspects of this hypothesis.

1. Large volumes of magma are needed at depth to

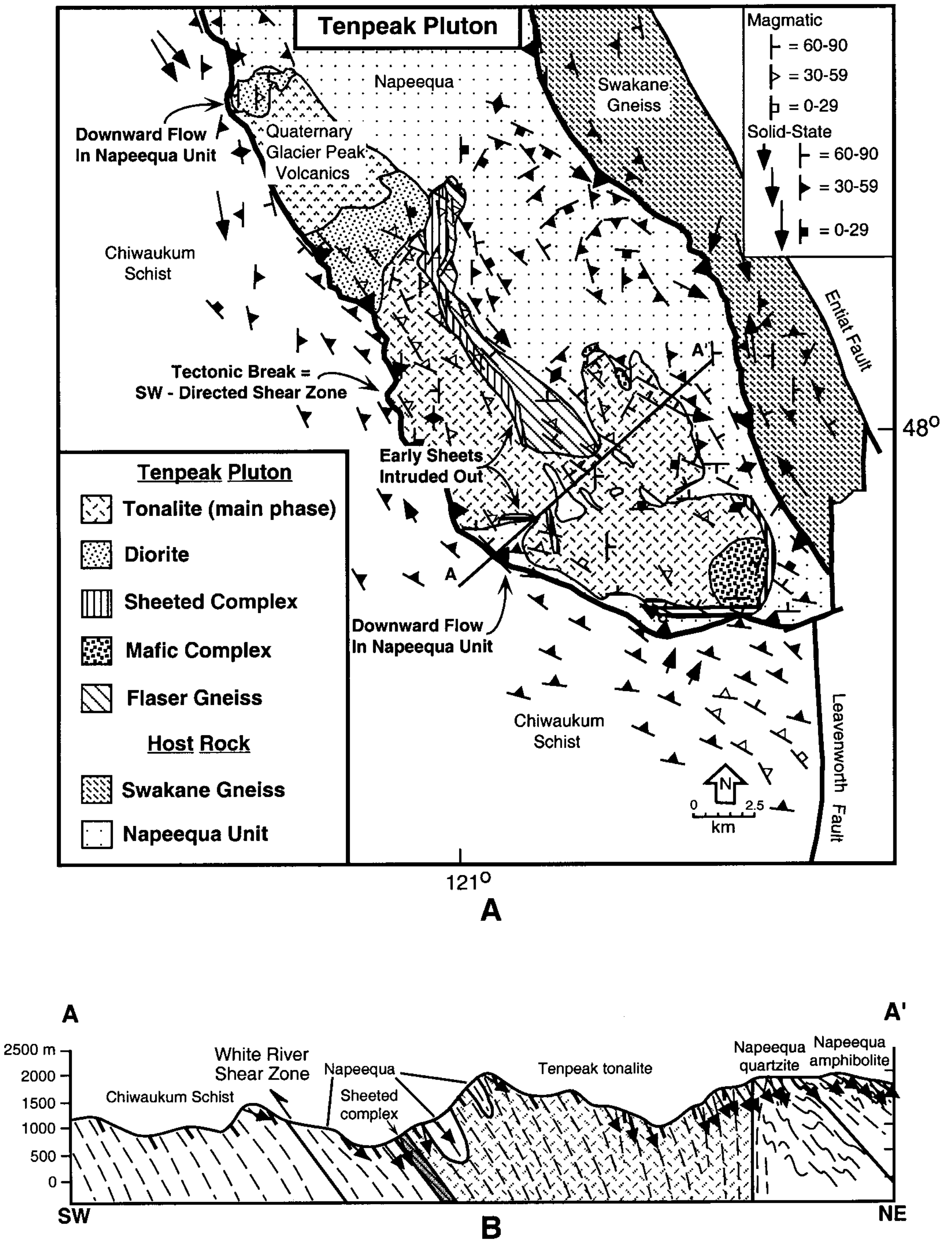

Fig. 2. (a) Geologic map of the ~30 km deep Tenpeak pluton showing simplified structural data and highlighting main features relevant to ascent and emplacement. (b) Cross-section through the pluton and its southwestern and northeastern structural aureoles. Dashes at topographic surface show dip of measured foliation and lighter-weight dashes are foliation traces. Arrows indicate plunge of lineation. Note that the inward dip of the southwest contact is compatible with the lower half of an asymmetric diapir.

feed and maintain an open dike long enough to construct a large pluton. If such volumes exist then they are likely to rise as a diapir (Weinberg, 1996).

2. Most large bodies in magmatic arcs are tonalite to granodiorite and their chemistries commonly indicate both significant mantle and crustal components (e.g. Frost and Mahood, 1987; Sisson et al., 1996). If these are dike-fed bodies, then a mechanism is needed by which a dike can tap both crustal and mantle sources and then thoroughly mix these

sources before reaching the emplacement level. Mixing of magmas from dikes with different sources at the emplacement level requires vigorous convection, and some workers question whether this is likely in granitoid magma chambers at mid to upper crustal levels (e.g. Marsh, 1988).

3. We do not understand the mechanics by which a dike will form in the ductile lower crust and then feed a large magma chamber, expanding by ductile processes in the relatively cold and strong upper crust. If the dike cannot continue to crack and propagate upwards then we contend it should form a sill or laccolith at shallow levels. Indeed, McCaffrey and Petford (1997), among others, argue that this is the case for some plutons, but many large elliptical to spherical plutons, particularly in arcs, do not have this geometry (e.g. Buddington, 1959; Paterson et al., 1996).
4. Since magma flow rates in dikes are fast, fast strain rates are needed at the level of emplacement to make space for the magma (Paterson and Tobisch, 1992), and this again must occur in the relatively cold, strong upper crust.
5. If magma ascends episodically by diking, as proposed by Petford (1996), then thermal models indicate that typical cooling and crystallization rates should result in sheeted complexes, rather than large magma chambers, except in regions of high ambient temperatures (Hanson and Glazner, 1995; Yoshinobu et al., 1998).

Given these problems with constructing large dike-fed magma chambers and the inconsistencies between ballooning models and field data described above, we conclude that diapirism should be considered as a valid working hypothesis for large elliptical and spherical plutons.

In the following sections, we describe four arc plutons in the North American Cordillera (Fig. 1) that we interpret to represent diapirs emplaced over a wide range of crustal levels (~10–30 km). Three of these plutons are part of the Cretaceous and Paleogene magmatic arc of the Cascades core, Washington, which was constructed across accreted oceanic and arc terranes. The fourth was emplaced farther south at shallow levels into the Cordilleran miogeocline, which is underlain by Precambrian basement. In addition to providing examples of magma chambers constructed over a wide range of crustal depths, these plutons represent a broad range of magma compositions and were intruded into many types of host rock. These case studies, therefore, are most relevant to magmatic arcs, but we believe they also provide general insights into magma ascent in most tectonic settings.

4. Examples of diapirs

4.1. Deep-crustal diapir—Tenpeak pluton

The 91–92 Ma Tenpeak pluton was emplaced at ~30 km depth [800–1000 MPa (Dawes, 1993; S.M. DeBari, written communication, 1998)] into the amphibolite- and quartzite-dominated Napeequa unit and the amphibolite-facies pelitic and psammitic Chiwaukum Schist of the Cascades core (Fig. 2). This pluton is elliptical in map view (aspect ratio ~3.8:1), with an eastern lobe. The outer parts of the pluton are marked by a discontinuous zone of sheeted and mingled gabbro and tonalite. Larger bodies of tonalite make up most of the pluton interior, and truncate and intrude out much of the sheeted zones. Abundant enclaves indicate that mafic magma continued to be emplaced during intrusion of the tonalite. Host rock inclusions, up to 1 km wide, are widely scattered but particularly common as meter-scale tabular rafts in sheeted zones. Petrological studies demonstrate that the mafic rocks represent mantle-derived magmas, whereas the tonalites formed by mixing of mantle and crustally derived melts (Dawes, 1993; DeBari et al., 1998). Crustal melting probably occurred at 1500–1600 MPa (DeBari et al., 1998), and thus the tonalitic magmas rose ~20 km, or about 2.5 times the pluton diameter, to their site of emplacement.

Moderate to strong magmatic foliation and lineation are well developed in the pluton (Fig. 2). They are variably overprinted near host rock contacts by a syn-emplacement, largely margin-parallel, high-temperature subsolidus fabric. Mineral lineation has moderate to high pitches throughout the pluton.

A narrow structural aureole is defined by deflections of regional host rock structures, which outside of the aureole record NE–SW contraction associated with SW-directed shear and NW–SE stretching (Miller et al., 1997). As the south and southwest contacts of the pluton are approached, moderately NE-dipping foliation and lithologic contacts between units steepen, bending downward in a zone 500 m to locally 1 km wide (0.09–0.18 body radii), and fold axes and subhorizontal mineral lineation swing to a down-dip orientation. These features and pluton-side-up (reverse shear) kinematic indicators in the pluton margin all suggest downward flow of host rock in the aureole during rise of the pluton. Structures similarly steepen in a 500-m-wide aureole (0.09 body radii) next to the steep northeast contact of the pluton, but kinematics are complex. Pluton-side-up indicators in the Tenpeak imply that host rock has moved downward adjacent to at least part of the eastern lobe, but host-rock-side-up (SW-vergent) shear in the pluton is recorded in some planar segments of this contact. We infer from these relationships that regional SW-directed shear domi-

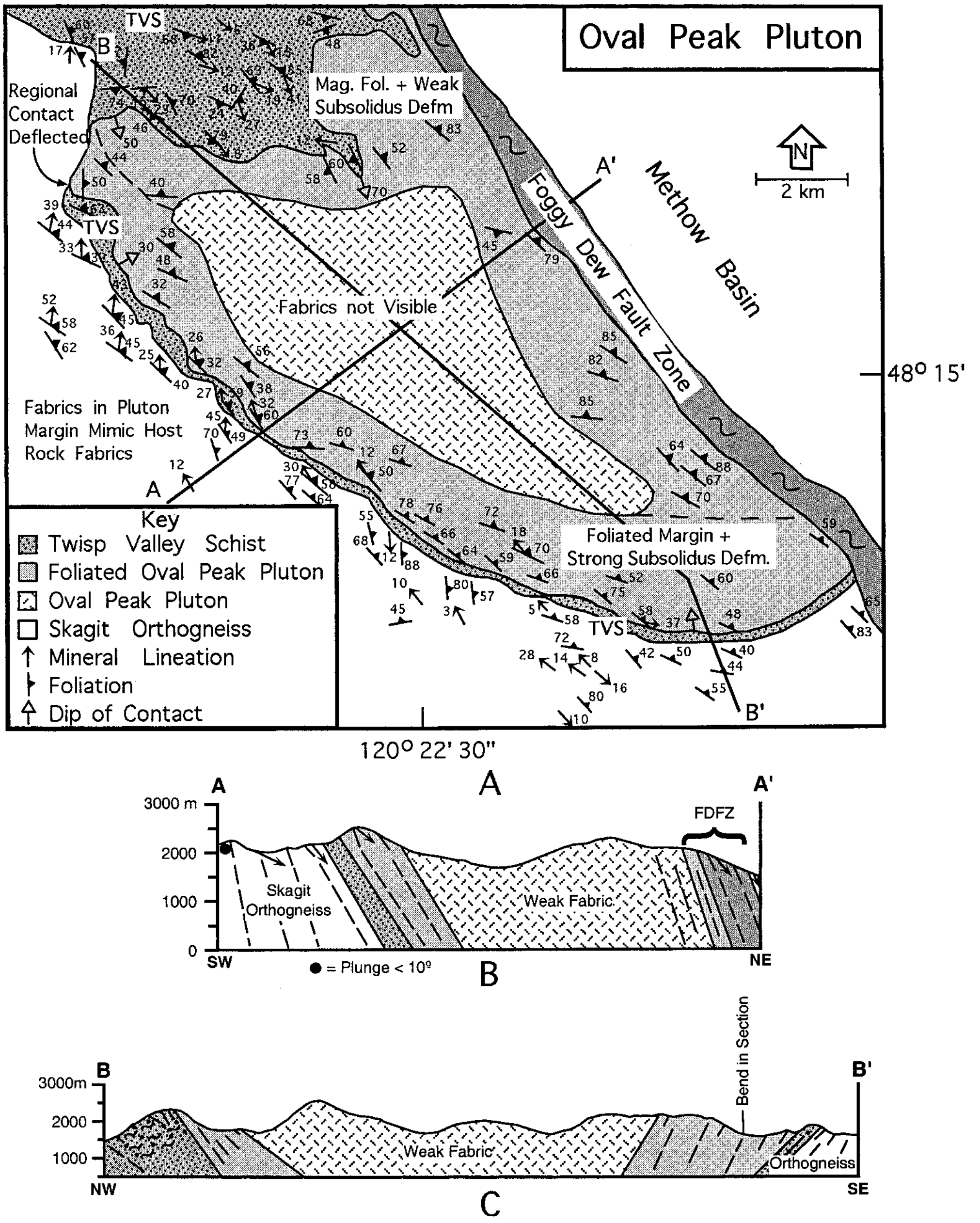

Fig. 3. (a) Geologic map after Miller and Bowring (1990) of the mid-crustal Oval Peak pluton. Dashed line within foliated margin of the pluton separates rocks with moderate to strong subsolidus foliation from those with weak subsolidus foliation. (b) SW–NE section through the pluton. Note steepening of lineation (arrows) in southwest aureole. Dashes at topographic surface show dip of measured foliation. FDFZ = post-emplacement Foggy Dew fault zone. (c) NW–SE section showing inward dips of pluton, which combined with southwest margin suggests an elongate funnel truncated by the Foggy Dew fault zone.

nated over, or outlasted, downward flow in parts of the northeast aureole. At the northwest end of the pluton, the margin is at high angles to the Napeequa–Chiwaukum boundary (Fig. 2). This boundary is only deflected in a narrow aureole where the regionally structurally higher Napeequa unit has been bent downward and westward.

The pluton has the shape of the lower part of an asymmetric diapir (Fig. 2b) and we suggest that it was constructed by multiple magma batches rising in a diapir during regional contraction. Downward transport of host rock was an important process during ascent, and downward movement also occurred in the region now occupied by the pluton, as indicated by the stoping out of sheeted zones by larger tonalite batches and by the numerous host rock inclusions. The downward ductile flow, stoped blocks, moderate to steep lineation in the pluton and aureole, curvature of sheets around the south and southwest margins, and orientation of the sheets and the pluton at a high angle to the

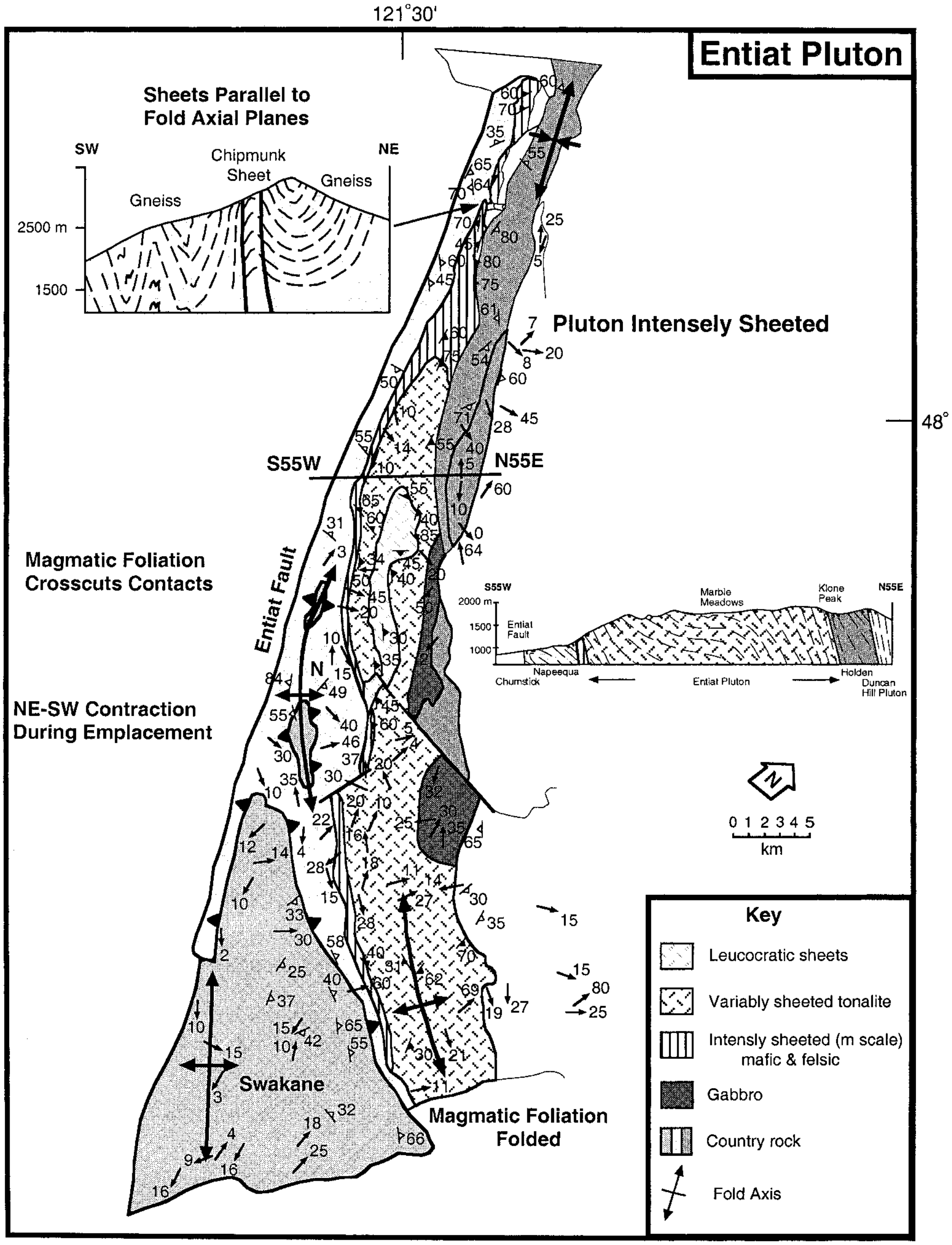

Fig. 4. Geologic map and cross-sections of the mid-crustal Entiat pluton emphasizing simplified structural data and main features relevant to ascent and emplacement. N = Napeequa unit, dashes indicate foliation traces.

regional shortening direction all argue against diking associated with elastic fracturing as the dominant ascent mechanism. Instead, they are compatible with diapiric ascent through host rocks that range from viscous to elastic in rheology.

4.2. Examples of mid-crustal diapirs

Two plutons intruded at similar mid-crustal depths (500–700 MPa) in the Cascades core illustrate the range of characteristics of plutons that we interpret to have ascended as diapirs. These are the elliptical (aspect ratio ~2.2:1), 65 Ma Oval Peak pluton and the highly elongate (aspect ratio ~10:1), 73 Ma Entiat pluton (Miller and Bowring, 1990; Paterson and Miller, 1998).

4.2.1. Oval peak pluton

The Oval Peak pluton is compositionally homogeneous, consisting mostly of biotite tonalite. Weakly foliated rocks make up the core of the pluton and, as described in detail by Miller and Bowring (1990), this magmatic fabric is progressively overprinted toward the southwest and south contact in a 1- to 2-km-wide zone of syn-emplacement, moderate to strong high-temperature subsolidus foliation (Fig. 3). Weak subsolidus mineral lineation occurs within 50 m of the contact. In the north, foliation intensifies to a lesser extent, and in the northeast, the pluton is truncated by the post-emplacement Foggy Dew fault zone.

The mostly amphibolite-facies host rocks include the Twisp Valley Schist, a correlative of the Napeequa unit, which forms a <300-m-wide envelope around the foliated margin and a larger mass north of the pluton. Tonalitic and granodioritic orthogneisses of the Skagit Gneiss lie outboard of the schist. Foliation near the pluton generally parallels pluton contacts, which dip moderately inward in the south, west, and north, and in three dimensions define an elongate, truncated funnel (Fig. 3b and c).

The structural aureole of the Oval Peak pluton ranges in width from ~200 m to perhaps 2 km, or 0.02–0.23 body radii, where it is most clearly defined at the ends of the pluton by deflection of foliation from its northwest regional trend into parallelism with pluton contacts. The most distinctive regional marker to enter the aureole is at the north end where the western contact of the Twisp Valley Schist bends westward for 3 km beginning ~2 km from the pluton (Fig. 3). The schist pinches out for a short distance, reappears along the southwest margin of the Oval Peak, and wraps around the southern end.

Most of these and other observations support diapiric emplacement, including: (1) overprinting of magmatic fabrics by subsolidus foliation in the margin; (2) the funnel-like shape of the pluton, suggestive of the lower half of a diapir; (3) deflection of foliation and regional marker(s) in the aureole; (4) down-dip lineation and reverse (pluton-side-up) shear in parts of the southwest margin and host rocks (Miller and Bowring, 1990); and (5) the roughly elliptical shape in map view of the pluton.

Although ballooning of a dike-fed magma chamber can explain some of these observations, it is difficult to reconcile with the compositional homogeneity and sparsity of sheeting. The pluton is elongate perpendicular to the inferred regional shortening direction during emplacement, which is not the orientation expected for dikes. Furthermore, strong subsolidus deformation should occur in the margins of a ballooning pluton, but the intensity of such deformation in the south and southwest margins is moderate and the northern margin shows even weaker subsolidus fabrics. Finally, the pluton is unlikely to have been constructed by magma ascending through dikes into dilational cavities in a fault zone. A ductile shear zone was probably active along the southwest margin during emplacement, but the pluton does not lie in a dilational fault jog, and a shear zone does not extend along or from the northern end of the pluton (Miller and Bowring, 1990).

4.2.2. Entiat pluton

In contrast to the Oval Peak, the highly elongate Entiat pluton consists of many compositionally and texturally defined, moderately to steeply dipping, cm- to km-scale sheets (Fig. 4; Paterson and Miller, 1998). Mafic sheets occur mainly in the margins and in the northwest tip region where they are intruded by, or mingle with, sheets of the dominant tonalite. The numerous thin sheets in the northwest end give way to a few 500-m- to 2.5-km-wide sheets of tonalite in the broader southeastern part of the pluton.

Moderate to strong magmatic and locally subsolidus foliation and lineation overprint sheets. Foliation defines meso- and map-scale upright, NW-trending magmatic folds (Paterson and Miller, 1998). Lineation generally plunges gently and trends NNW–SSE parallel to host rock lineation and axes of magmatic folds. However, in the southern part of the southwest margin lineation has a down-dip orientation associated with pluton-side-up reverse shear (Hurlow, 1992; Paterson and Miller, 1998).

A highly variable structural aureole occurs in host rock units, which are dominated by amphibolite, schist, quartzite and tonalitic orthogneiss. Near the southwest margin, fabrics intensify and regional foliation and host rock markers steepen and bend downward into parallelism with the moderately to steeply NE-dipping pluton contact in a 500-m- to 1-km-wide (0.12–0.24 body radii) aureole. In contrast, deformation intensity does not increase significantly adjacent to the steep northeast contact and segments of this contact are discordant to the folded but commonly gently dipping host rock foliation. Foliation in host rocks directly in front of sheet tips at the northwest end of the pluton define upright, gently plunging syn-emplacement folds (Fig. 4). Magmatic foliation in some sheet tips defines folds continuous with those in the host rock. Sheet walls are oriented parallel to the axial planes of the host rock folds, cut across host rock anisotropy in fold hinges, and are not folded.

These relationships from the pluton aureole place significant limits on emplacement mechanisms. The discordance of parts of the contact implies that stoping removed some of the inner aureole. The lack of deflection of regional markers outside the narrow aureole requires that lateral displacements were restricted to the aureole, or to the area now occupied by the pluton, and that any lateral expansion and shortening of host rock was compensated for by vertical material transfer. Regional contractional deformation may have also played some role, but its magnitude is difficult to constrain.

The abundant sheets and overall sheet-like shape of

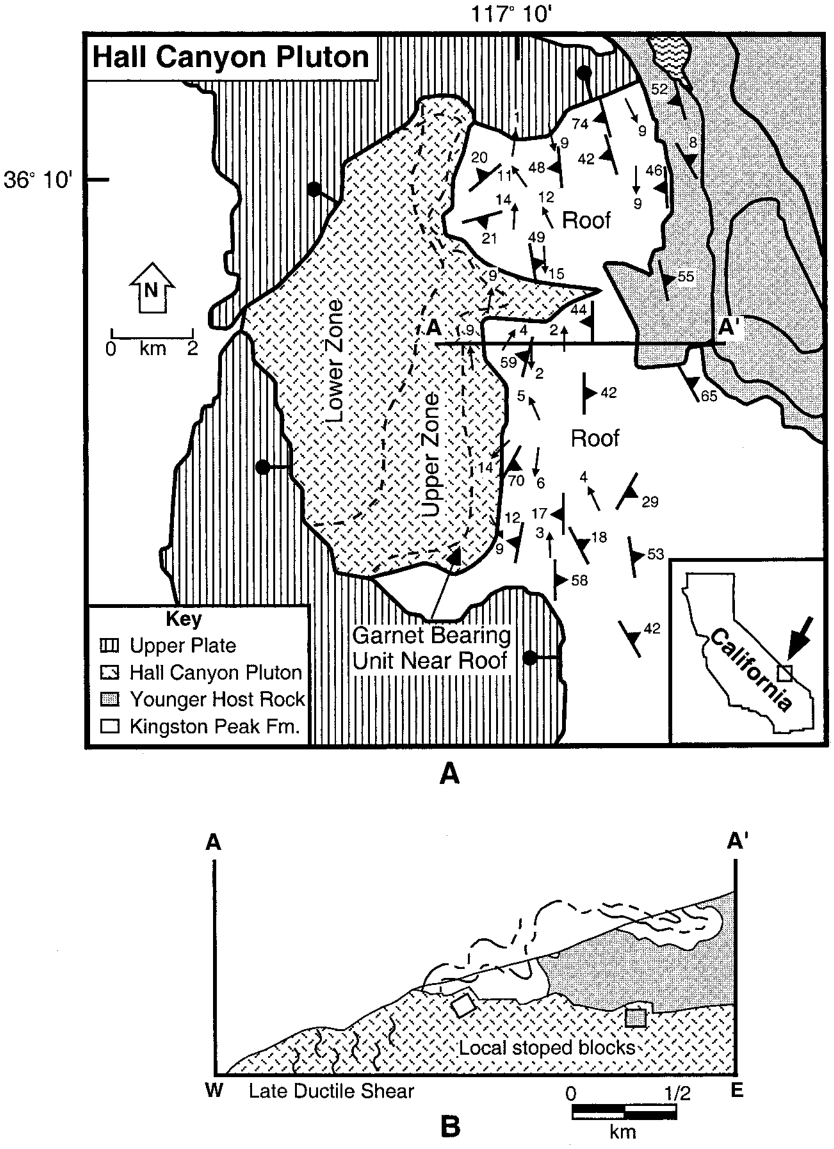

Fig. 5. (a) Geologic map simplified from Crossland (1995) and Mahood et al. (1996) emphasizing main body of upper-crustal Hall Canyon pluton. (b) Cross-section through main body of Hall Canyon pluton; note truncation of host rock folds by roof contact and stoped blocks below roof.

the Entiat pluton make a dike ascent mechanism appealing, but several characteristics of the sheets and pluton argue against a simple diking model: (1) the sheets have length/width ratios ranging from ~6 to >75, and narrow, blunt tips, geometries intermediate between those of dikes and elliptical diapirs (Paterson and Miller, 1998); (2) no faults or fractured process zones extend in front of tips, and host rocks at the tips and sides of the pluton underwent complex ductile flow, rather than fracturing, during emplacement; (3) sheet margins are more curviplanar than is typical of dikes; (4) magmatic foliation patterns are not typical of dikes; and (5) the sheets are oriented at high angles to the regional shortening direction and we infer σ_1, rather than σ_3 as predicted by elastic dike models.

We conclude that the Entiat pluton is constructed of multiple diapiric pulses with sheet-like shapes controlled by rise in anisotropic crust during regional contraction (Ronnlund, 1987; Talbot et al., 1991; Paterson and Miller, 1998). We propose that initial, predominantly mantle-derived (Dawes, 1993) mafic sheets rose from deep magma ridges and that these mafic magmas were progressively overwhelmed by larger bodies of tonalitic magma that contained greater amounts of crustal melt.

4.3. Upper-crustal diapir—Hall Canyon pluton, Panamint Mountains, SE California

The 73 Ma Hall Canyon pluton was emplaced at

~10 km depth (Labotka, 1981) into the Proterozoic Kingston Peak Formation in the Panamint Mountains (Fig. 5a). This weakly elliptical (aspect ratio ~1.5 to 2.0:1) composite body consists of a lower, relatively homogeneous biotite–muscovite granodiorite phase and an upper muscovite ± garnet granite phase (Nibler, 1991; Mahood et al., 1996). The geochemistry of these phases indicates that they originated from two different crustal sources, with little to no mixing between phases except in a narrow, intervening zone of mingling and sheeting (Griffis, 1986; Nibler, 1991; Mahood et al., 1996). Mahood et al. (1996) concluded that the magmas may have formed by partial melting of metapsammites and rocks of intermediate composition, and depths to likely source regions suggest the magmas rose ~10–20 km, or one to two body diameters.

Magmatic fabrics are poorly developed and we have not recognized any consistent patterns in the field. Solid-state structures occur in a post-emplacement dextral shear zone that cuts the western part of the pluton (Crossland, 1995) and is in turn cut by a W-dipping detachment fault that down-drops part of the roof and the granite phase (Mahood et al., 1996). In this down-dropped section, hundreds of stoped blocks of tens of meters to centimeter scale are common below the roof contact and are locally found farther into the pluton. Stoped blocks are also locally preserved below the roof of the main (footwall) part of the pluton (Fig. 5b).

The studies of Crossland (1995) indicate that roof-rock schists preserve four generations of ductile structures, which are dominantly small- to large-scale, W-vergent folds with subhorizontal axes and variably dipping axial planes, all of which are cut by the pluton contact (Fig. 5b). The irregular, stepped shape of the roof contact is striking, and sharp, ~90° changes in orientation occur on the scale of tens to hundreds of meters (Fig. 5b). Faults do not extend into the pluton or host rock from these stepped segments. Also, no ductile deformation associated with emplacement is observed along the contact, nor are older structures in the schist deflected as the roof contact is approached (Fig. 5b). Therefore, stoping must have been the dominant emplacement mechanism at the exposed crustal level (Crossland, 1995).

Field evidence rules out emplacement by ballooning or faulting, or as a laccolith (Crossland, 1995). The markedly silicic magma compositions and sparsity of sheeting are inconsistent with magma ascent in dikes, so we suggest that the Hall Canyon pluton represents what some diapirs look like as they reach shallower crustal levels, even though we see little evidence of the types of criteria required for diapirism by some authors. At these levels, multiple batches of magma may still be recognizable in the chamber, magmatic fabrics are increasingly poorly developed, and stoping becomes an increasingly important and commonly dominant material transfer process during final emplacement resulting in discordant stepped margins.

5. Discussion and conclusions

We have described four plutons, from a range of crustal levels, that are most compatible with ascent as visco-elastic diapirs. These plutons differ from each other and from 'textbook' hot-Stokes diapirs to variable extents, but all, or most, share several important features.

1. They ascended during complex flow of their host rock during regional deformation, with the possible exception of the Hall Canyon pluton.
2. Emplacement occurred by a variety of brittle and ductile material transfer processes, but downward transfer of host rock dominated in all cases. Indeed, the downward flow in structural aureoles and pluton-side-up kinematic indicators in the deep and mid-crustal examples are some of the strongest evidence for diapirism.
3. The narrowness of the ductile aureoles at all depths indicates that host rocks approximated power law, rather than Newtonian materials during at least the final stages of ascent.
4. All of the plutons, except possibly the Oval Peak, were constructed by multiple batches of magma. This suggests that pre-heated pathways existed for later batches of typically more felsic magma. Preheating and power-law behavior of host rocks would enable these diapirs to ascend farther than modeled hot-Stokes diapirs (Marsh, 1982; Weinberg, 1996) and ascent of more than one body diameter is indicated by petrological data for the Tenpeak and Hall Canyon diapirs.
5. All of these plutons are elongate perpendicular to the regional shortening direction during emplacement, and at least locally cross cut host rock anisotropy. Besides providing evidence that these bodies are unlikely to be assembled from dikes, this geometry indicates that visco-elastic diapirs can have any orientation relative to regional stress fields and in many cases are at high angles to σ_1, as discussed by Paterson and Miller (1998) for the Entiat pluton.

These examples show that visco-elastic diapirs may exhibit a wide range of characteristics. Differences partly reflect contrasts in host rock properties at different crustal levels. However, differences may occur even at similar crustal levels, as exemplified by the homogeneous, elliptical Oval Peak pluton and the heterogeneous, sheeted Entiat pluton.

We emphasize that our examples of visco-elastic diapirs indicate the shortcomings of placing restrictions on internal and host rock processes in diapirs based solely on simplistic models. Diapirs may consist of multiple pulses of magma entering and/or leaving the magma chamber. Internal processes may be complex, as illustrated by the Hall Canyon pluton where convection in the lower phase, fractionation and upward migration of melts in the upper phase, and local sheeting and mingling between phases are all documented by Mahood et al. (1996). The characteristics of diapirs may also change over time while being affected by regional deformation. Furthermore, displacement of host rock during ascent occurs by multiple processes, and host rock may be displaced in any direction.

We conclude with some philosophical thoughts regarding the rejection of diapirism because field observations of hypothesized diapirs do not fit simple experimental and numerical models. We certainly agree that it is necessary to quantify observations and use these observations to develop mechanical models, but we contend that this is a meaningless endeavour if not done in the context of the rock record. It is valid to question whether the rock record only records information about emplacement, but in every example presented above, the magma chambers were still moving up and host rock down when the systems were 'frozen'. Thus, we suggest that it is more appropriate to ask how far these diapirs ascended by the processes indicated by their frozen configuration. It is also valid to argue that the rock record for diapirism is incomplete, but we suggest that different plutons record different parts of diapiric ascent paths. If true, we can obtain as complete an understanding of diapirism as other ascent mechanisms by looking at examples of diapirs at different crustal levels, as we have done. This is illustrated by the deep Tenpeak pluton, which possibly represents part of a throughgoing diapiric magma plumbing system that fed much shallower plutons of similar age in the Cascades arc. It is also justifiable to argue that magma ascent in dikes is sometimes problematic and may function best in tandem with diapirs. Finally, it is equally valid to argue that the rock record indicates that dike-fed ballooning is a much less convincing mechanism than diapirism for reasons outlined above and by Paterson and Vernon (1995). In short, we argue that diapirism remains a viable and likely mechanism for ascent of magmas in the crust and should be considered as valid a mechanism as diking.

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