Deformation and magma transport in a crystallizing plutonic complex, Coastal Batholith, central Chile

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ABSTRACT

The Carboniferous–early Permian Santo Domingo complex in coastal Chile (33.5°S) preserves magmatic structures that allowed us to partially reconstruct and compare the deformation histories of two intrusive units within a mid-upper crustal zoned pluton. The oldest history is preserved in the Punta de Tralca tonalite, where microgranitoid enclaves record the emplacement and partial assimilation of mostly mafic magma into an intermediate host. Enclaves record early foliation development by a mechanical sorting and alignment of minerals during hypersolidus flow in melt-rich magma currents, followed by diffusion creep and sliding along melt-coated crystals. Structures in a weaker, tonalitic matrix record compaction, flattening, and near-solids deformation as porous flow, aided by brittle deformation, drained residual melts. These processes produced penetrative S > L fabrics (i.e., planar more dominant than linear fabric) in an increasingly viscous, crystal-rich mush and promoted folding, fracturing, shearing, and crystal-plastic deformation as the mush approached its solids. The deformation disrupted igneous layering and helped mobilize and concentrate melt-rich aggregates, forming diffuse patches and dikes that intruded previously deformed enclaves and matrix and aided pluton differentiation. A different deformation history is recorded by the Estero Córdoba dike, which intruded and interacted comagmatically with the Punta de Tralca tonalite. The dike records how magma flow near stiff boundaries resulted in velocity gradients that drove deformation during magma replenishment. This deformation reset inherited enclave fabrics, increased ductile stretching and winnowing, and formed linear (L>S) fabrics. This example illustrates how different styles of deformation assisted magma movement through a mid-upper crustal magma chamber and highlights the diverse origins and significance of structures generated by deformation in magmas of variable crystal-melt ratios.

INTRODUCTION

Studies of the structure and deformation history of batholiths are essential to our understanding of arc magmatism, orogenesis, and the evolution of continental lithosphere. Batholiths record magma transport and emplacement processes, which are primary mechanisms of transferring heat and mass through the lithosphere. Key questions include (1) how the constituent magmas of batholiths interact, differentiate, and grow and (2) how different styles of deformation influence magma movement and emplacement. Ultimately, the link between deformation and magma transport in a crystallizing pluton may provide insight into the timing, volumes, and styles of silicic arc volcanism.

A great deal of research over the past decade has focused on the physical, petrologic, and temporal relationships between plutonic and volcanic magmas, including the conditions necessary for large volumes of magma to exist in subvolcanic magma chambers (Bachmann et al., 2002; Bachmann and Bergantz, 2004, 2006; Huber et al., 2011; Hodges and Jellinek, 2012; Caricchi et al., 2012; Pistone et al., 2013; Coint et al., 2013). Many studies have concluded that large zoned intrusions are assembled incrementally with small, distinct batches of magma that are emplaced over several million years (e.g., Coleman et al., 2004; Glazner et al., 2004; Bartley et al., 2006; Schaltegger et al., 2009; Coint et al., 2013). Nevertheless, there remains substantial disagreement on whether these small magma batches interact with one another in different settings and, if they do, the nature of these interactions.

One common assumption in some studies of magmatic processes is that magmas move and differentiate mainly as crystal-poor liquids and are the products of an evolution linked to simple cooling prior to volcanic eruption (Bachmann and Bergantz, 2006). However, a growing body of work provides evidence that magmas can crystallize to nearly solid crystal-rich mushes that are then reheated, partially remelted, and remobilized before eruption (Bachmann et al., 2002; Bachmann and Bergantz, 2004, 2006; Yoshinobu et al., 2009; Pistone et al., 2013; Coint et al., 2013). These latter studies suggest that the individual magma batches that make up large zoned magma chambers need not crystallize completely, but instead may be reactivated and interact extensively with one another. A primary mechanism by which these reactivations occur may involve the intrusion of mafic, or possibly even intermediate, magma.
through dikes. The occurrence of microgranitoid enclaves in many magmas supports this hypothesis and provides a potential means for evaluating how the input and resident magmas mixed, mingled, deformed, and differentiated (Hodge et al., 2012; Hodge and Jellinek, 2012; Caricchi et al., 2012).

Another problem related to determining how magmas interact during replenishment events centers on how we use complex igneous structures to reconstruct the history. Despite their potential value, the use of igneous structures to reconstruct the deformation histories of magmatic bodies is commonly difficult. Problems arise because igneous foliations and lineations are easily reset during cooling and exhumation and may only record the final increments of strain as crystal-rich mushes approach their solidi (Benn and Allard, 1989; Ildéfonce et al., 1997; Paterson et al., 1998). In addition, most of the deformation in a magma body may be accommodated by flow in melt, which can leave little to no record (Paterson et al., 1998; Vernon and Paterson, 2006; Memeti et al., 2010; Mamtani, 2014). In general, most objects in plutons and dikes make poor strain markers because their initial shapes are unknown and their final shapes may reflect a wide variety of processes, most of which are spatially and temporally variable (Paterson et al., 2004). The result is that the origin and significance of structures formed during magmatic flow and the deformation of crystal-melt aggregates can be difficult to establish in the field. In particular, reliable criteria are needed to document the kinds of structures that form during transitions from hypersolidus flow in melt-rich magmas to deformation near the solidus where crystal-plastic deformation occurs in the presence of migrating melts (Paterson et al., 1989, 1998; Vernon, 2000; Pawley and Collins, 2002; Vernon et al., 2004; Yoshinobu et al., 2009). These relationships, if established, could be combined with thermal and rheological modeling to more precisely characterize magma behavior.

A potentially promising approach to resolving some of these issues may be in comparisons among mesoscale and microscale structures that record different increments of deformation in crystal-melt aggregates, especially if their relative sequence and local context can be determined. Although obtaining the full rheological and strain history of a crystallizing magma still appears improbable, a close comparison of magma interactions and the deformation mechanisms that result in mineral fabrics, enclaves, and other structures may provide some information on the styles and types of magmatic strains and on the rheological transitions that occur in crystallizing magmas (Paterson et al., 1998, 2004; Pawley and Collins, 2002; Huber et al., 2011; Hodge and Jellinek, 2012; Caricchi et al., 2012; Yoshinobu et al., 2009). One aim of this paper is to test this approach using the Santo Domingo complex (Sinha and Parada, 1985; Sinha, 1987a, 1987b; Wall et al., 1996; Parada et al., 1999) of coastal Chile (Fig. 1). The significance of this example is the rich and well-exposed array of mesoscopic and microscopic structures that preserve different stages of the deformation history of a mid-upper crustal zoned pluton.

In this paper we present the results of a field-based analysis of igneous structures exposed in a 3 km coastal transect across the Punta de Tralca and Estero Córdoba intrusions (Parada et al., 1999) between the towns of Isla Negra and El Tabo (Fig. 1A). As part of this work, we examined outcrops at Isla Negra and completed a 400 m transect across the contacts of the 2 intrusions (Figs. 1B and 2), where we recorded a wide variety of magmatic structures in detail, including mineral foliations and lineations of different age, igneous banding, shear zones, folds, sigmoidal fractures, en echelon tension gashes, boudinage, faults, and dikes (Figs. 3–6). These features, and a domainal preservation of structures, allowed us to establish a relative sequence of events and partially reconstruct the deformation histories of the two units. A comparison of these histories allowed us to examine the following processes: (1) interactions between mafic and intermediate magmas during the replenishment and remobilization of a crystal-rich magma chamber; (2) mechanisms of crystal-melt segregation and expulsion in a viscous, crystallizing magma chamber; (3) microstructures and deformation mechanisms in a crystallizing magma as it transitions from flow in melt-rich magma currents to near-solidus deformation where crystal-plastic deformation occurred in the presence of melt; and (4) patterns of three-dimensional flow and the mechanisms of foliation development in a crystallizing pluton.

To illustrate the results, we divide our data presentation into three sections. First, we define the various categories of igneous structures and describe the different styles of magmatic deformation that occurred within the two intrusions (Figs. 2–6). Second, we report microstructures and other mineral textures that record transitions from hypersolidus flow in melt-rich magmas to crystal-plastic deformation in crystal-rich mushes near the solidus (Figs. 3 and 7). We then compare the characteristics of mineral and enclave fabrics at the contact between the two intrusions to evaluate whether they record different styles and increments of deformation (Figs. 8–11). Our interpretations, and the observations that support them, are summarized in six textural zones (Fig. 12) that describe areas of the plutonic complex that exhibit similar structures and processes. These processes include magma movement in dikes, the mingling and partial assimilation of mafic-intermediate magmas with different effective viscosities, the fracture and shear of crystal-melt aggregates, melt mobilization and reintrusion in a crystallizing magma, melt expulsion to forming a viscous crystal-rich mush, and the late-stage flattening and compaction of that mush. As others have pointed out (e.g., Vernon and Paterson, 2006; Memeti et al., 2010; Mamtani, 2014), similar structures and processes may be common in granitoids, although many dikes and plutons may not record them.

### GEOLOGICAL BACKGROUND

The coastal range of central Chile (lat 33°–34°S) is characterized by Paleozoic to Mesozoic plutons (Hervé et al., 1988), hypabyssal intrusive rocks (Wall et al., 1996), and marine and terrestrial volcaniclastic sedimentary sequences (Vergara et al., 1995). Three plutonic belts, which decrease in age toward the east (Levi, 1973), dominate the batholith (Fig. 1A), i.e., the Santo Domingo, Papudo-Quintero, and Illapel complexes (Parada et al., 1999). Along the coast, the plutonic rocks were emplaced into granitic gneiss and metasedimentary rock of the Valparaíso metamorphic complex (Wall et al., 1996).

The Santo Domingo complex (Figs. 1 and 2) includes two main intrusive units (Sinha and Parada, 1985; Sinha, 1987a, 1987b; Wall et al., 1996) referred to...
here as the Punta de Tralca tonalite and the Estero Córdoba dike (Parada et al., 1999). The Punta de Tralca tonalite is oldest, and is a layered hornblende-biotite intrusion of mostly tonalitic and granodioritic composition that hosts numerous fine-grained mafic and microgranitoid enclaves (to 50% by volume) (Figs. 3A–3D). The close association of the enclaves with mafic dikes led Parada et al. (1999) to suggest that the enclaves represent dismembered dikes that were comagmatic with their tonalite matrix. The younger unit includes a massive, relatively enclave-poor tonalite dike that intrudes the Punta de Tralca tonalite. At its southeastern end, the Estero Córdoba also displays a mix of sheeted granitic dikes interfolded with layers of country rock (Fig. 2).

The Santo Domingo complex appears to range in age from Carboniferous to early Permian. Berg and Charrier (1987) obtained Carboniferous zircon ages from a granitic xenolith in a mafic dike. A U-Pb zircon age of 291 ± 1 Ma (Godoy and Loske, 1988) to 214 ± 1 Ma (Gana and Tosdal, 1996). K-Ar ages on biotite, amphibole, and plagioclase from the gneisses also have yielded Middle–Late Jurassic ages (Cordani et al., 1976; Hervé et al., 1988; Gana et al., 1996). This range suggests that the country rock of the batholith records a complex history of magmatism, metamorphism, and cooling.

The emplacement depths of plutons within the Santo Domingo complex remain poorly understood. A single hornblende crystallization pressure of 700 MPa reported by Siña (1987b) suggests depths of ~26 km. Chlorite- and epidote-bearing veins that are cut by the El Tabo mafic dike swarm suggest exhumation to upper crustal levels by the mid-Cretaceous (Irwin et al., 1987; Creixell et al., 2009). Fission-track thermochronology confirms that the coastal rocks were at ~4–5 km depth by 102 ± 4 Ma (Gana and Zentilli, 2000). The mafic dikes (Creixell et al., 2006, 2009, 2011) have been attributed to an extensional
tectonic regime that preceded the development of Cretaceous volcaniclastic and marine sedimentary basins exposed to the east (Vergara et al., 1995). Thus, exhumation of the coastal rocks may have occurred concomitantly with subsidence in these basins as arc magmatism migrated eastward.

### REGIONAL STRUCTURE OF THE SANTO DOMINGO COMPLEX

Both the Punta de Tralca and Estero Córdoba intrusions display four categories of multiple magmatic foliations and lineations. From oldest to youngest, these include: (1) aligned hornblende, plagioclase and quartz crystals inside enclaves (SA) (e.g., Figs. 2, 3B, and 3C); (2) a compositional banding defined by flattened, stretched, and aligned enclave swarms and layers of leucocratic matrix material (SB) (Figs. 2–5); (3) a preferred alignment (SC) of primary plagioclase, hornblende, and biotite minerals within dikes and intrusions that cut SB (Figs. 2, 3, and 5); and (4) a magmatic layering (SD) created by sheeted granitoid dikes that are interfolded with layers of country rock at the southeastern end of the Estero Córdoba unit (Figs. 2 and 6). Local crosscutting relationships among these foliations are discussed in the following. Together, all four create a regional structural grain that strikes to the northwest and dips moderately to the northeast (Figs. 1C and 2). The trend of this structural composite grain is discordant to a gneissic foliation in country rock at Las Cruces by a few tens of degrees (Fig. 1D).

Inside the batholith, local discordances among the four categories of igneous foliations also are common. At the southern end of the Punta de Tralca unit (Fig. 1B), igneous layering (striking 328°, dipping 63°NE) is steeper than at its northern end by >10° on average, and locally to 20°. Foliations in the Estero Córdoba dike strike more west and dip more gently than the enclave-rich igneous layering of the Punta de Tralca by ~15° on average, and locally as much as 30°; this latter discordance results from the truncation of igneous layering by the younger dike. These and other discordances reflect deformation during multiple magma injections that aided in establishing a sequence of events.

The alignment of microgranitoid enclaves locally define a northeast-plunging lineation on foliation planes (e.g., Fig. 3G). Hornblende, biotite, and plagioclase crystals also locally are aligned and plunge 50°–60° to northeast on foliation planes, forming mineral lineations (Fig. 1C). Lineation trends in the Punta de Tralca and Estero Córdoba units are statistically identical, although the data are more scattered at the northern end of the Punta de Tralca unit. This pattern suggests that both units record similar bulk flow directions.

### FIELD EVIDENCE OF MAGMATIC DEFORMATION

**Punta de Tralca Tonalite**

**Enclave-Matrix Structures**

Most of the enclaves in the Punta de Tralca tonalite at and south of Isla Negra are composed of plagioclase, hornblende, and interstitial quartz with biotite and minor epidote, titanite, zircon, and apatite. Some mineralogical...
Figure 3. Photographs and sketches showing styles of magmatic deformation in the Punta de Tracla tonalite from coastal outcrops at Isla Negra and areas farther south. All photographs (except A–C, G) are of surfaces oriented perpendicular to the moderately dipping regional S_b igneous banding and a steeply plunging mineral lineation (foliation and lineation orientations shown in Fig. 1C). Photographs in A–C and G are of surfaces oriented perpendicular to S_b foliation and parallel to the lineation. Field of view in A–D, F, and H is 15 cm. Notebook width in E and F is 19 cm. Coin in G is 2.5 cm wide. Fields of view in I and J are 120 cm. Photographs A–G show distributions of plagioclase mineral aggregates inside and outside enclaves. (A) A few evenly distributed grains (white rectangles) in enclaves wrapped by plagioclase accumulations (light gray shading) and external foliations (S_b). (B) Intermediate stage of assimilation where enclave is partially disintegrated into its matrix. Plagioclase phenocrysts are preserved penetrating enclaves (arrows). (C) Enclaves where S_b foliations in the matrix are continuous with those inside enclaves (S_a). (D) Xenolith with wedge-shaped strain shadows composed of plagioclase-rich felsic segregations and xenolith fragments. (E) Sigmoidal en echelon vein sets and microfaults (dashed lines) affecting enclave swarms. (F) Folded enclaves with leucocratic material concentrated in fold hinges. (G) Enclave boudinage with felsic material concentrated in boudin necks. Surface parallels magmatic foliation (S_b). (H) Shear zone with asymmetric schlieren recording sinistral displacements. (I) Dike with an internal flow foliation (S_c) that truncates older external foliations (S_b). (J) Leucocratic pool and protodike with undulose boundaries and a tapered tip truncate enclaves and S_b foliation.
differences, and the presence of xenoliths, suggest that they reflect multiple sources rather than a single homogeneous magma batch.

The tonalite matrix displays greater proportions of euhedral to subhedral plagioclase and biotite crystals and lower abundances of hornblende than the enclaves. Enclave grain sizes are several orders of magnitude smaller than the matrix with the exception of large (to 1 cm long) rectangular lathes of twinned plagioclase. Matrix plagioclase forms thin (≤ 1 cm) accumulations that surround and penetrate the enclaves by different degrees, ranging from a few evenly distributed grains inside enclaves (Fig. 3A) to examples where plagioclase aggregates dominate and the enclaves have partially disintegrated into the matrix (Fig. 3C). Megacrysts frozen at enclave boundaries (arrow in Fig. 3B) record the exchange of material between them prior to their complete crystallization (cf. Parada et al., 1999).

In addition to forming thin accumulations around enclaves, plagioclase crystals show preferred orientations that, along with hornblende and biotite, define magmatic foliations. In some cases foliations in the matrix (S_b) are continuous with those inside the enclaves (S_a) (Fig. 3C), indicating that both enclave and host had similar effective viscosities during deformation. In other examples (Fig. 3D), S_b foliations are deflected around xenoliths and enclaves, forming wedge-shaped strain shadows. Figure 3D shows that minerals are aligned best along the upper and lower surfaces of a hornblende-rich xenolith, forming caps, and less aligned on the ends. The presence of xenolith fragments within the shadows indicates mechanical plucking during flow. These features demonstrate that the enclaves and xenoliths had a range of effective viscosities during magmatic deformation, most likely as a result of variations in grain size, composition, temperature, and melt concentration (e.g., Blake and Fink, 2000).

Fractures, folds, and shear zones involving both enclave and matrix provide further evidence of the range of viscosity contrasts during magmatic deformation (cf. Paterson et al., 1998; Yoshinobu et al., 2009). Sigmoideal fractures, wedge-shaped en echelon tension gashes, veins, and small faults in enclaves are common (Fig. 3E). Extension fractures display tapered tips and are filled with feldspar and quartz aggregations derived from the matrix. Some fractures terminate inside enclaves, suggesting that they initiated at enclave boundaries and propagated inward. Others penetrate through the enclaves and merge with thin (a few crystals wide) zones of tilled feldspar in the surrounding matrix. These latter varieties form en echelon arrays, the lengths of which exceed half the width of the enclave and mark the initial stages of boudinage. The sigmoidal varieties show fracture trends ranging from 30° to 60° clockwise from the trace of the S_b foliation (Fig. 3E). They are widest and steepest at their centers, suggesting the tapered tips are youngest and experienced smaller
rotations compared to the centers. Faults that offset enclave boundaries by a few centimeters show no evidence of cataclasis. High-angle fractures (≈60° relative to the trace of the $S_b$ foliation) show offsets that are antithetic to the deflections of shear zones. Low-angle fractures (0°–30° from foliation) exhibit synthetic offsets. These features formed late in the history of deformation in the unit and when enough solid material had crystallized to accommodate shearing and fracturing (Paterson et al., 1998; Vigneresse and Tikoff, 1999).

Folded enclaves (Fig. 3F) occur in clusters. The folds are asymmetric and filled with crescentic zones of felsic material that are widest in hinges and narrowest on limbs. This felsic material is distinguished from the matrix tonalite by an assemblage of quartz and feldspar minerals, and contains significantly smaller modal abundance of mafic minerals such as hornblende and biotite. These segregations widen into strain shadows and grade smoothly into the surrounding matrix. The shadows, plus the presence of prongs, ears, and tails, record winnowing and stretching during folding and magmatic flow. Elongated and boudinaged enclaves formed on the limbs of some tight folds. Felsic material fills the interboudin partitions (Fig. 3G). Lithic fragments in the partitions, derived from fracturing and ductile flow, record the partial disaggregation of enclaves during boudinage. These patterns suggest that pressure gradients transferred melt into dilational sites around enclaves as they deformed in a crystal-rich mush.

Asymmetric schlieren occur in mesoscopic shear zones as long as several meters (Fig. 3H). The shear zones show across-strike gradients defined by increases in the degree of attenuation of enclaves, decreases in layer thickness, and a deflection of layering and enclaves into thin (1–5 cm) bands where strains appear highest. Within these high-strain zones, the deformation mechanism does not appear to be largely crystal-plastic when observed in outcrop due to the subhedral to euhedral phenocryst forms. Both sinistral and dextral sets occur within subdomains of the tonalite. In high-strain areas, individual enclaves are rotated into alignment with flow banding that truncates older enclaves and $S_b$ foliations.

This diversity and the asymmetry of these structures allowed us to partially reconstruct the kinematics of flow and cross-check senses of shear. These structures include (1) the sense of rotation of $S_b$ foliations and the asymmetry of schlieren and matrix strain shadows in shear zones, (2) fault offsets, (3) sigmoidal fracture sets, (4) en echelon vein arrays, and (5) asymmetric folds. In all cases, the asymmetries are preserved on surfaces oriented perpendicular to both the dominant $S_b$ foliation and the regional, northeast-plunging elongation lineation (Figs. 1C and 4). Few to no asymmetric structures were observed on surfaces perpendicular to foliation and parallel to lineation. Boudinage parallel to the lineation (Fig. 3G) confirms that it is a true stretching direction, although plagioclase minerals often locally show only a weak preferred alignment in this plane where they tumbled around enclaves (Fig. 4B). Extension fractures and strain shadows also show extension across the lineation, indicating that there were two directions of extension during foliation development. The asymmetric structures delineate zones as much as tens of meters wide where shear sense indicators match one another. These zones alternate with one another, defining small cells where material rotated both clockwise and counterclockwise about the northeast-plunging mineral lineation (Fig. 4). Areas of convergence and divergence between cells tend to be steeper than adjacent areas, possibly forming cylindrical pipes. These patterns, and the partitioning of displacements both parallel to and across the lineations, result in a style of deformation characterized by triclinic symmetry (Lin et al., 1998; Iacopini et al., 2007).

![Figure 5](image_url)

Figure 5. (A) Sketch of outcrop at site 11IN01B (Fig. 1B) showing the contact between the Punta de Tralca (left) and Estero Córdoba (right) tonalites. View is of a surface oriented perpendicular to the $S_b$ foliation and the regional northeast-plunging lineation (YZ plane). Note different shapes, orientations, and alignment of enclaves in each unit. Dashed lines highlight $S_b$ foliation surfaces. Small box in the Estero Córdoba dike shows the location of C. (B) Photograph of $S_b$ foliation in the Punta de Tralca tonalite. (C) Photograph of $S_c$ foliation and narrow channels that record the flow and an exchange of material between the two units parallel to $S_b$. 
Melt Reintrusions and Dike Networks

Virtually all of the structures that affect both enclave and matrix in the Punta de Tralca tonalite (e.g., Figs. 3E–3H) exhibit accumulations of the leucocratic matrix in dilational sites, including strain shadows, fold hinges, interboudin partitions, tension gashes, and faults. Many of these accumulations are distinguished texturally and compositionally from other matrix material by higher abundances of K-feldspar, plagioclase, and quartz, and lower abundances of biotite and hornblende. These concentrations display a variety of shapes and sizes, ranging from diffuse globular patches to thin ($\leq 2$ m) dike networks with irregular margins (Fig. 3J) to dikes with straight, planar boundaries. All intrude previously deformed enclaves and matrix, including those involved in folds and shear zones, indicating that they are among the youngest features in the unit.

The felsic concentrations exhibit systematic changes in geometry and texture with increasing size. Accumulations between 1 cm and 1 m long truncate both enclaves and matrix material at one end while grading smoothly into the host matrix without sharp boundaries at the other end. Their margins typically show undulating, scalloped geometries and most do not entrain enclaves, suggesting only minor flow. In contrast, meter-scale dikes and accumulations entrain enclaves and display new flow foliations ($S_x$) that truncate older external ones everywhere along their length (Fig. 3I). Many of the large concentrations form approximately planar zones, although their margins locally are undulose.
and scalloped. The ends of these zones display apophyses with tapered ends (Fig. 3J), suggesting that they propagated as fractures within the crystallizing host. A continuum appears to exist between these incipient dikes with diffuse, undulating boundaries and well-developed dike networks with straight planar boundaries that cut across the foliation defined by igneous layering and enclaves ($S_B$). The youngest dikes show few enclaves and granodioritic compositions. These observations suggest that the small patches record the pooling of melt-crystal aggregates during the early stages of mobilization. Transportation away from these pools via dike propagation likely occurred during the last stages of crystallization.

**Estero Córdoba Dike**

**Northwestern Contact**

At site 11N01B (Figs. 1B, 2, and 5) a diffuse, nonplanar contact between the enclave-rich Punta de Tralca tonalite and the younger Estero Córdoba dike is well exposed (Fig. 5A). The Estero Córdoba dike contains inclusions of the Punta de Tralca tonalite, and in a few places truncates igneous layering ($S_B$) in the older rocks. Foliations composed of tilted plagioclase and aligned biotite locally parallel the contact and truncate some enclaves while flowing around others. Leucocratic dikes emanate from the younger tonalite (Fig. 5A), cutting through the Punta de Tralca tonalite. In other places along the same contact, both the young intrusion and its enclave-rich host share a common magmatic foliation that parallels $S_B$. These zones form narrow channels (Figs. 5A, 5C) where enclaves and plagioclase crystals are preserved crossing the cuspatte boundary between the two units, suggesting that they were conduits for material exchange. Inclusions of the Punta de Tralca tonalite within the dike support this conclusion. These observations imply that temperatures were high enough and emplacement rates were slow enough to allow the two units to exchange material as they crystallized and deformed together.

A comparison of structures within the two units reveals differences in the relative age and character of foliations. In the Punta de Tralca tonalite, the dominant foliation is a pervasive, relatively uniform igneous layering ($S_B$) (Fig. 5B). Foliations inside ($S_B$), and outside ($S_B$) the enclaves are parallel (e.g., Figs. 3C and 5B). The enclaves are all aligned and display uniformly oblate shapes. These observations indicate that the enclaves and their matrix share deformation history and had similar effective viscosities at the time the foliations formed.

In contrast, inside the Estero Córdoba dike, schlieren and fieldspar accumulations align into foliations ($S_B$) that are discordant to foliations in channels that parallel $S_B$ (Figs. 5A, 5C), implying a clockwise (top to the southeast) rotation of material about an axis parallel to the mineral lineation. The enclaves are stretched, winnowed, and broken, implying a combination of semi-rigid rotation, fracturing, and ductile distortion within a weak, melt-rich matrix.

The youngest features include late, hornblende-bearing felsic dikes that cut $S_B$ foliations. Some dikes display undulose contacts but, unlike the older Estero Córdoba dike, do not record mixing or mingling with the enclave-rich Punta de Tralca tonalite. Most contacts are sharp and truncate enclaves. Long (1–2 cm) clots of hornblende form flow foliations within the dikes at high angles to foliations in host rock. Some dikes show drag along their margins, further suggesting that they intruded when both older units mostly had solidified.

**Southeastern Contact**

The southeastern end of the Estero Córdoba unit is characterized by sheeted granitoid dikes interleaved and interfingered with screens of country rock (sites 11N03A–11N03C, Figs. 1B, 2, and 6). Megacrystic granodiorites, granites, and hornblende-biotite tonalites make up the granitoid sheets. Xenoliths, which appear to be derived from the wall rock, occur throughout this zone. The incorporation of xenoliths that are completely disconnected and surrounded by intrusive rock in Estero Córdoba unit suggests that stopping could have been an important process late in the history of the pluton. The wall rock, which is best exposed at Las Cruces (Fig. 1A), is a combination of gneiss, slate, biotite schist, and calcareous gneiss that forms part of the Valparaíso metamorphic complex (Fig. 1B).

The orientations of deformed dikes and the alignment of minerals within the granitoid sheets define a magmatic layering ($S_B$) that is distinct from later stage crosscutting dikes containing $S_C$ foliations observed elsewhere in the unit (Fig. 6). $S_C$ foliations are deflected around flattened schlieren with pressure shadows. Inside xenoliths, older mineral foliations are tightly folded and truncated at their margins, indicating that they were more viscous than the matrix. At site 11N03A (Figs. 1B, 2, and 6), the dikes and layers show various stages of boudinage, from pinch-and-swell to broken, isolated biotite-rich pods. Felsic segregations fill the hinges of folds, and even the most highly stretched and attenuated layers exhibit little mesoscopic evidence of crystal-plastic deformation. These features, including synmagmatic folds of granitc dikes and country rock and the $S_B$ layering, compose a structural style that is absent in the unit farther north. The interfolding and parallel mineral lineations (Figs. 1C, 1D) suggest that the Estero Córdoba dike and Valparaíso metamorphic complex locally shared a history of ductile deformation during intrusion.

**DEFORMATION MICROSTRUCTURES**

**Enclaves in the Punta de Tralca Tonalite**

Enclaves in the Punta de Tralca tonalite display continuous foliations ($S_B$) of dark green and brown hornblende intergrown with plagioclase-quartz aggregates. The boundaries between these phases commonly are irregular with rounded corners, mutual indentations (arrows, Fig. 7A), and protrusions that disrupt the strong shape-preferred orientations exhibited by large plagioclase phenocrysts. The aggregates consist of polygonal grains that contain smaller rounded grains and inclusions of quartz and feldspar within them (Figs. 7A, 7B). Concentrations of quartz inclusions at plagioclase grain boundaries indicate that the two minerals grew together (arrows, Fig. 7B).
Figure 7. (A–C) Deformation microstructures in an enclave of the Punta de Talca tonalite. Q—quartz, pl—plagioclase, hb—hornblende, bt—biotite, ks—microcline. (D) Tonalitic matrix of the Punta de Talca tonalite. Box shows tapered pressure shadows of biotite on plagioclase crystals. (E–I) The Estero Córdoba tonalite. All images are shown with crossed polars except F, which is in plane light. Boxes in E and H show location of images in G and I, respectively. See text for discussion and significance of arrows.
Many grains also are internally strain free and exhibit no crystallographic preferred orientations. These microstructures suggest that crystal-plastic adjustments of grain boundaries changed the shapes of aggregates initially aligned by magmatic flow. The rounded corners and amoeboid shapes indicate that the adjustments did not take place when the crystals were suspended freely in a magma body; instead, they appear to have occurred by diffusion along grain boundaries, through crystals, and/or by diffusion-accommodated sliding (Vernon, 1970; 2004).

Differences in the dihedral angles formed by triple junctions between plagioclase, quartz, and hornblende crystals suggest disequilibrium among phases and provide additional evidence that grain boundary adjustments by crystal-plastic deformation modified the shapes of aggregates in the presence of melt. Some quartz on quartz grain boundaries show 120° dihedral angles at triple junctions (Fig. 7B), indicating that these aggregates were hot long enough for crystal interfaces to adjust to minimize their interfacial free energy (Vernon, 2004). Boundaries involving plagioclase-quartz, hornblende-quartz, and hornblende-plagioclase crystals show small dihedral angles (arrows, Figs. 7A, 7B), including 60° angles in three grain junctions between quartz, plagioclase, and hornblende (Fig. 7B). These small angles indicate that these grains were not in textural equilibrium and suggest the presence of residual interstitial melt (Jurewicz and Watson, 1985). Hornblende also shows an interstitial geometry consisting of arms and pendants that partially surround quartz crystals (arrow, Fig. 7A). Other evidence of melt includes beads of equant, randomly oriented, strain-free quartz and feldspar grains that formed along grain boundaries and fill the intervening spaces between fractured primary plagioclase crystals (Fig. 7C). Dihedral angles of the tips of grain boundary melt films are <60°. This string-of-beads texture results from the crystallization of melt as cooling rates slow, which creates melt rims on quartz and feldspar grain boundaries, through crystals, and/or by diffusion along grain boundaries, possibly aided by the presence of melt (Vernon et al., 2004). Late fractures cut across multiple grains and are filled with small quartz and feldspar crystals (Fig. 7D). Plagioclase is sericitized along its edges in fractured zones. These microstructures record fluid infiltration accompanied by brittle deformation and the growth of secondary minerals late in the history of solidification.

The biotite that fills spaces between plagioclase grains forms tapered overgrowths on lenticular and bent plagioclase crystals (box in Fig. 7D). The overgrowths exhibit oblate shapes and form a part of the S₁ foliation. In some of the overgrowths, and along the boundaries between large plagioclase crystals, biotite and chlorite are sheared, suggesting that they accommodated relative motion between grains. The shear bands are defined by shredded cleavage, broken fragments, and subgrains, suggesting slip on cleavage planes. The presence of oblate shapes and the alignment of pressure shadows on plagioclase crystals suggest that flattening, compaction, and mineral growth contributed to the development of S₁ foliations as interstitial liquids were removed from crystalline networks.

**Estero Córdoba Dike**

The Estero Córdoba dike (Figs. 1 and 2) contains plagioclase and biotite with variable amounts of quartz, microcline, hornblende and epidote. At site 11IN01B (Figs. 1B, 2, and 5), biotite aggregates form foliations (S₁) that wrap twinned plagioclase crystals. Most of the biotite is bladed and shows little to no optical evidence of kinks, bent lattices, or other internal deformation, even where they bend around large plagioclase crystals. The exception to this occurs in a few small areas between large, unstrained plagioclase grains where biotite shows slip along cleavage planes and local shear band boudinage. The shear bands form tapered aggregates where biotite crystals are thinned, shredded, and stretched (arrow a in Fig. 7F). Similar microstructures have been reported in other deformed tonalites where they have been used to infer sliding along grain boundaries, possibly aided by the presence of melt (Vernon et al., 2004).

Plagioclase crystals are variably aligned. Some of the largest grains display two different types of fractures. One type occurs entirely within single plagioclase crystals, ending at their boundaries (Figs. 7E, 7F). A second type forms pull aparts (arrow and box in Fig. 7E). Many of these fragments display irregular edges that match other grains on the opposite side of the fracture. Quartz, microcline, and minor hornblende and epidote filled the intervening...
pockets between the grains. This texture, the granitic composition of the fill, and the interstitial relationships among adjoining plagioclase megacrysts suggest that these pockets collected residual melts (e.g., Vernon et al., 2004).

Highly irregular, cuspatelike grain boundaries and small (<120°) dihedral angles (Figs. 7G, 7H) in aggregates involving plagioclase, quartz, microcline, and hornblende indicate disequilibrium, also suggesting that these phases crystallized from residual melts (Jurewicz and Watson, 1985; Holness and Sawyer, 2008). Other evidence includes straight crystal faces of coexisting plagioclase and K-feldspar against quartz (Fig. 7H), overgrowths of late K-feldspar on primary, twinned plagioclase (arrow, Fig. 7E), and plagioclase pieces stranded as inclusions in melt pockets between fractured plagioclase crystals (arrow, Fig. 7I) (Vernon, 2004). These microstructures suggest the formation of cracks by melt-enhanced hydrofracturing and the pseudomorphing of granitic melts in pockets by late magmatic phases.

A number of pockets between fragments of plagioclase show lobes where vermicular intergrowths of quartz and potassium feldspar replaced plagioclase (arrows, Fig. 7I). These myrmekites record mineral reactions in low-strain sites that were sheltered by large, rigid grains of plagioclase (Hamner, 1982). The dendritic grain shapes suggest a slowing of diffusion rates (Vernon, 1968) relative to those that accompanied changes in the shapes of plagioclase and quartz aggregates in the enclaves. Plagioclase also shows evidence of crystal-plastic recrystallization while new crystals of quartz and potassium feldspar were growing from melt in low strain pockets. Grain boundary bulging and groups of small, strain free grains concentrated along grain boundaries (arrows, Fig. 7H) suggest that some melt crystallized along grain boundaries and may reflect sliding on melt-coated grains (Vernon, 2004).

In the melt pseudomorphs, K-feldspar shows subgrains, deformation bands, and scalloped grain boundaries (arrow, Fig. 7G), suggesting that recrystallization occurred by dislocation creep at temperatures >500 °C (Tullis et al., 2000). Large quartz grains in melt pockets show chessboard extinction, a blocky subgrain structure that is common in granulites and migmatites (Kruhl, 1996; Garlick and Gromet, 2004) and granitoids (Paterson et al., 1989; Vernon, 2000) deforming near solidus temperatures. The exact temperatures this pattern records is dependent on water content, strain rate, and other factors, but generally ranges from 400 to 700 °C (Vernon, 2004). Other relatively low temperature, subsolidus deformation textures include deformation lamellae in quartz (Fig. 7I), lenticular deformation twins in plagioclase (Figs. 7E, 7H), and K-feldspar and tartan twinning in K-feldspar (Fig. 7G). The concentrations of the latter microstructures vary with local strain.

**Fabric Analysis**

**Approach**

Most attempts to measure magmatic strains in granitoids encounter problems because the assumptions required to use standard methods of strain analysis frequently are violated (Paterson et al., 2004), i.e., (1) strain is homogeneous over the scale of the measurements, (2) markers deform passively with their matrix, (3) the initial three-dimensional shapes and orientations of markers can be reasonably established, (4) marker shapes are relatively uniform, and (5) all markers share a common deformation history. In addition, the use of minerals is complicated because their orientations are easily reset and they do not record deformation accommodated by melt (Paterson et al., 1998). Enclaves carry another set of problems related to temporal and spatial variations in how they form and respond to deformation. Their final shapes and orientations are influenced by many processes, including initial shapes, variable viscosities, a competition between strain and interfacial energies, and deformation that may involve internal strain or rigid rotations in a magma body (Paterson et al., 2004). These and other problems preclude the use of mineral and enclave populations as accurate strain markers.

In a detailed consideration of these issues, Paterson et al. (2004) suggested that comparisons among the characteristics of igneous layering, mineral fabrics, and enclave fabrics, including internal mineral alignment, may provide qualitative information on the changing styles and kinematics of magmatic strains. We tested this approach at site 11IN01B (Figs. 1B and 5) by comparing the orientations and distributions of two populations of enclaves and plagioclase minerals in the Punta de Tralca and Estero Córdoba units using three different techniques. The techniques included raw measurements of mineral alignment in three dimensions and analyses of the preferred orientations (b) and shape fabrics (R) using the center to center (Fry, 1979; Erslev, 1988) and R/φ (Dunnet, 1969; Lisle, 1985) methods (see Appendix 1). Rather than attempt to calculate true finite strains, our goals were to evaluate (1) whether plagioclase and enclave orientations and distributions in the Punta de Tralca tonalite are compatible with interpretations of the late compaction and flattening of a crystal-rich mush, and (2) if inherited enclave fabrics in the Estero Córdoba dike were reset during magma emplacement or if they retained some memory of their previous history within the Punta de Tralca tonalite. The application of these techniques in this context highlights systematic variations that may reveal differences in the deformation history between the two units.

Achieving these goals appears possible at site 11IN01B because the relative age, relative viscosities, three-dimensional shapes, and structural context of the mineral and enclave fabrics are clear. The presence of narrow channels (Figs. 5A, 5C) where enclaves and plagioclase crystals are preserved crossing the cuspatelike boundary between the two units, and inclusions of the Punta de Tralca tonalite within the dike, indicates that enclaves in the Estero Córdoba dike were derived from the Punta de Tralca tonalite. This relationship allowed us to evaluate how entrainment in the dike affected the shapes of enclaves whose initial conditions could be reasonably established. The relative uniformity of enclave shapes and parallel mineral and enclave lineations in each unit also simplified the comparisons. The three techniques used, which emphasize different aspects of the fabrics, provided a means to evaluate sensitivities. The goals we chose also allowed us to avoid assumptions of passive deformation and permitted us to compare fabrics that incompletely record different increments of deformation.
Applications

We measured the orientations of 1729 plagioclase crystals in 2 hand samples that show the typical characteristics of each unit at site 11IN01B. These included a penetrative $S > L$ fabric shared by both enclaves and matrix material in the Punta de Tralca tonalite and stretched and aligned minerals and enclaves in the Estero Córdoba dike (Fig. 5). The measurements were obtained from polished rock surfaces (Fig. 8A). Code modified in Webber (2012, 2014) statistically fit ellipses to the traces of grain outlines (Fig. 8B) and tabulated their eccentricities and orientations. Orientations were measured from three mutually perpendicular planes, defined with respect to foliations and lineations measured in the field (Fig. 8C). The results are plotted as probability density functions (Figs. 8D–8F and 9A–9C), which describe the relative likelihood that each mineral will take on a given orientation within each plane. Circular standard deviations (Fisher, 1996) of the distributions provide a measure of the degree of mineral alignment for each plane.

For the center to center technique, we created normalized Fry (1979) plots (Erslev, 1988) from the centroids of plagioclase minerals on three perpendicular faces (Figs. 8G–8I and 9A–9C). For each plot, the apogee and perigee of the central voids were selected to determine the axial ratio of the sectional fabric ellipse. Three sectional ellipses (Figs. 10D, 10E) allowed us to construct a fabric ellipsoid using algebraic methods described by Owens (1984), Robin (2002), and Launeau and Robin (2005). This ellipsoid provided a measure of the distribution of the grains in three dimensions. Several fits were compared to assess errors (Appendix 1).

We applied the $R_f / \phi$ method (Lisle, 1985) to both mineral and enclave populations in the two units. For minerals, we used the same grains as those used in the Fry analyses and probability density functions. Measurements of enclaves were completed from photographs of outcrop surfaces of known orientation. All photographs were taken perpendicular to, and at the same distance from, the outcrop using a customized camera mount (Webber, 2012). This procedure minimized edge distortions and other data collection errors. The absence of prongs, ears, and other irregularities allowed us to reasonably approximate enclave shapes and orientations with ellipses. Harmonic means of shape ratios ($R_s$) and vector means of their orientations (Figs. 8J–8L) were used to compare results (Webber, 2012, 2014). A series of fabric ellipsoids were obtained using the same methods described above.

Results

For the mineral fabrics in the Punta de Tralca tonalite, all three analytical techniques yielded similar results (Fig. 8). The raw measures of plagioclase alignment (Figs. 8D–8F) show a slightly more pronounced peak and lower circular standard deviation in the XZ plane, indicating the minerals are slightly more aligned on the XZ plane. This is confirmed by the normalized Fry (1979) plots (Fig. 8G–8I and 9A–9C), which show a slightly more pronounced peak and lower circular standard deviation in the XZ plane, indicating the minerals are slightly more aligned on the XZ plane. The results of the two methods are nearly identical and show similar oblate fabric ellipsoids (plotted in Fig. 10C). CSD—circular standard deviation; $H_m$—harmonic mean.

Figure 8. (A) Photograph of plagioclase crystals surrounding a small enclave in a sample of the Punta de Tralca tonalite (XZ face shown). Dashed red line shows trace of $S_b$ foliation. (B) Fitted ellipses. (C) Block diagram illustrating the three perpendicular planes used as a reference frame in the analysis. (D–F) Probability density histograms of plagioclase populations measured on the three perpendicular faces. Plots show the greatest mineral alignment in the XZ plane, the weakest alignment in the XY (foliation) plane, and moderate alignment in the YZ plane. (G–I) Results of a normalized center to center (Fry) analysis of plagioclase populations on the three perpendicular faces. (J–L) A sectional $R_f / \phi$ analysis of the same mineral populations. Results of the two methods are nearly identical and show similar oblate fabric ellipsoids (plotted in Fig. 10C). CSD—circular standard deviation; $H_m$—harmonic mean.
sections oriented parallel to lineation and perpendicular to foliation. The YZ plane shows weak alignment and the XY (i.e., foliation) plane shows none. The lack of alignment in XY suggests that the plagioclase orientations partly reflect local tumbling and flow around semirigid enclaves, such as that illustrated in Figure 4B. Alignment in both the XZ and YZ planes is compatible with late compaction.

The normalized Fry (Figs. 8G–8I) and R/φ (Figs. 8J–8L) plots both show that the most mineral alignment occurs in the XZ plane, little to no alignment occurs in the YZ plane, and no detectable alignment occurs in the XY plane. The fabric ellipsoids using both techniques show similar slightly oblate shapes (Fig. 10C). A comparison of the orientations of foliation (XY) planes and lineations (X directions) calculated from the mineral fabric (Fig. 10B) approximately match those measured in the field (Fig. 10A), suggesting that the ellipsoids are reasonably oriented. The shapes also are compatible with a small increment of late near-solidus, melt-present, compaction.

Plagioclase mineral orientations in the Estero Córdoba dike (Figs. 9A–9C) are similar to those in the Punta de Tralca tonalite (Figs. 8G–8I), except with slightly better alignment in the YZ and XY faces. The better alignment could reflect the smaller population size. The Fry technique (Figs. 10D–10F) was not sensitive to these subtle differences and yielded an oblate fabric ellipsoid similar in shape and orientation to that in the Punta de Tralca tonalite (Fig. 10C). Calculated foliations and lineations (Fig. 10B) also match measured ones (Fig. 10A) reasonably well and mimic the slight discordances observed at the outcrop. These similarities and the weak distortions suggest that the mineral foliations, like those in the Punta de Tralca, mostly are sensitive to the last increments of compaction.

We measured the axial lengths and orientations of 203 enclaves on three faces in each unit (Fig. 5A). Each face contained a population size of between 30 and 44 enclaves (Fig. 11). The sectional ellipsoids in both units all show the highest degree of alignment and distortion on surfaces oriented parallel to lineation and perpendicular to foliation.

In the Punta de Tralca tonalite, all enclaves show preferred alignments and oblate shapes, and a fabric ellipsoid that is more distorted than those recorded by the mineral fabrics (Figs. 10C, 10D, 10F). Like the raw mineral measurements and Fry analyses, the R/φ plots also show maximum alignment in the XZ plane and weak alignment in the other two planes (Figs. 11A–11C). In contrast, enclaves in the Estero Córdoba dike display highly distorted prolate shapes, even though their orientations are the same as both mineral and enclaves in the Punta de Tralca tonalite (Fig. 10). The axial ratios of sectional ellipses are generally higher in the dike than in the older tonalite, especially in the XZ plane (Fig. 11). The differences in the two units are illustrated in the Nadai plot in Figure 10C. The low dispersions (Fig. 11) and reasonable ellipsoid fitting errors (Fig. 10C) (Appendix 1) in each unit reflect the relatively uniform populations. The fabric ellipsoid from the Punta de Tralca tonalite plots within the oblate field (υ = 0.46) and has a low magnitude of distortion (κ = 0.73). The fabric ellipsoid from the dike plots within the prolate field (υ = -0.24) and is more distorted (κ = 1.36). This result is surprising because of the textural evidence from the outcrop showing that enclaves in the dike were derived from the older tonalite and yet they record no evidence of their prior oblate shape. This suggests that the enclave fabric in the dike has been reset by flow during intrusion. The differences between the mineral and enclave fabrics in both units also suggest that they record different increments of the deformation, most likely as a result of viscosity contrasts.

**DISCUSSION**

The data we report in this paper, combined with the work of others (Siña and Parada, 1985; Siña, 1987a, 1987b; Wall et al., 1996; Parada et al., 1999), allowed us to reconstruct the history of magmatism and deformation in the Punta de Tralca tonalite and the Estero Córdoba dike (Figs. 1B and 2). We use structural relationships preserved within the two units to examine the following processes: (1) interactions between mafic and intermediate magmas, (2) mechanisms of melt segregation and expulsion from a crystallizing pluton, (3) microstructures that record rheological transitions as the magmas crystallized, and (4) flow patterns and igneous fabric development during magma chamber replenishment and reactivation.

**Mafic and Intermediate Magma Interactions During Magma Chamber Rejuvenation**

The Punta de Tralca unit (Figs. 1B and 2) records the intrusion of multiple batches of mostly mafic magma into an intermediate host and the variable mixing and mingling of those magmas. The mafic intrusions, which are now represented by enclave swarms, depict the replenishment, thermal rejuvena-
tion, and remobilization of a crystal-rich magma chamber by the injection of magma through dikes. This process is important in arc systems because it governs how magma bodies in the middle and upper crust grow and differentiate (Couch et al., 2001; Bachmann et al., 2002, 2007; Hodge et al., 2012; Hodge and Jellinek; 2012; Caricchi et al., 2012). In addition, the injection of hot mafic magma into cooler, more silicic magma chambers may trigger eruptions in shallow magma reservoirs (Feeley and Dungan, 1996; Bachmann and Bergantz, 2004, 2006; Huber et al., 2011). We use the mineral textures recorded by enclaves to interpret how the input and resident magmas interacted as the pluton differentiated and crystallized.

Some of the principle features of the Punta de Tralca unit include (1) enclaves that show strong preferred orientations and variable degrees of deformation and assimilation with their tonalitic and granodioritic host (Figs. 3A–3C); (2) multiple generations and types of foliations that record deformation processes ranging from the rotation and alignment of crystals suspended in melt-rich magma currents to near-solidus deformation in crystalline aggre-

![Figure 10](image-url)
categories of foliations are represented in zones 1–3: (1) the preferred alignment of hornblende, plagioclase, and quartz minerals ($S_a$) inside enclaves (Figs. 3B, 3C), (2) flattened and stretched enclaves entrained in the leucocratic matrix of their host, forming alternating light and dark colored bands ($S_b$) (e.g., Fig. 5B), and (3) mineral foliations ($S_c$) composed of aligned hornblende, biotite, and plagioclase crystals within leucocratic dikes and other intrusions that cut $S_a$ and $S_b$ (e.g., Fig. 3I). Crosscutting relationships among these foliations, and comparisons of features inside and outside enclaves, allowed us to define three different types of interactions between the enclaves and their matrix.

Zone 1 (Fig. 12) represents areas where enclaves display the lowest viscosity contrasts and highest crystal contents, and are mostly assimilated into their tonalitic matrix (Fig. 3C). Foliation internal ($S_a$) and external ($S_b$) to the enclaves are parallel and grade smoothly into one another across enclave boundaries, forming the regional $S_b$ layering (Fig. 5B). This parallelism indicates that the two foliations formed together under similar conditions, most likely during final deformation of the matrix. The zone records the fewest number of plagioclase-rich, leucocratic dikes and patchy accumulations in the unit. Stretched and flattened enclaves form a penetrative oblate $S > L$ shape fabric (Figs. 5B, 10C, and 10D), which forms the dominant structure. Most prongs, ears, and other protrusions on enclaves (in the XZ plane) appear to have been removed by winnowing during flow and/or flattening. Microstructures indicate that both enclaves and matrix share a history of late-stage crystal-plastic recrystallization that accompanied flattening and occurred in the presence of melt. These features suggest that both the enclaves and their matrix in this zone share a similar, mostly ductile deformation history. This history was acquired at a stage when both magmas were highly viscous, crystal rich, and deforming near their solidi.

Zone 2 displays enclaves with moderate to high viscosity contrasts relative to their matrix (Figs. 3A, 3D, 3G). Foliation internal to the enclaves ($S_a$) commonly are oblique to, and cut by, matrix foliations ($S_b$). Some late crystal-plastic recrystallization of quartz-feldspar aggregates occurred but was weak enough to avoid obliterating evidence of earlier hypersolidus flow in a melt-rich magma. Evidence of brittle and ductile deformation affecting both enclaves and matrix material is abundant, and includes shear zones, folds, fractures, boudinage, and faults (Fig. 3E–3H). Collections of plagioclase-rich leucocratic material are preserved in pressure shadows, fold hinges, shear zones, and boudin necks, some of which truncate $S_a$. These features indicate that most of the enclaves in this zone behaved as rigid or semirigid objects during deformation and magma mingling. Although some deformation, such as fracturing and shearing, was shared by both enclaves and matrix, the enclaves mostly record a deformation history that differs from that of their matrix.

Zone 3 is marked by the appearance of mesoscale (from several centimeters to several meters wide) leucocratic felsic and tonalitic accumulations and dikes with internal flow foliations ($S_a$) that truncate enclaves and other ($S_a$ and $S_b$) foliations (Figs. 3H–3J). The largest dikes form interconnected networks and channels, and are among the youngest features that make up the unit. The variety of orientations and angles created by dike apophyses suggests that
Figure 12. Left: Illustration of structures observed in six textural zones viewed on surfaces oriented perpendicular to the regional northeast-plunging elongation lineation (YZ plane). References to figures with example relationships are shown on left axis. Center: Summary of structures that characterize each zone. Right: Summary of processes interpreted from the analyses and observations. Enclaves have been enlarged to emphasize their structure. Magmatic foliations (S_A, S_B, S_C, S_D) and other relationships are described in the text.
these intrusions did not undergo most or all of the flattening, compaction, and crystal-plastic deformation that dominated zone 1, and do not share the same deformation history as the enclaves and matrix. We interpret the abundant leucocratic accumulations in this zone to represent residual crystal-melt aggregates that were separated from their tonalitic host and remobilized during synmagmatic deformation. Similar features have been reported in other zoned magma chambers (Vernon and Paterson, 2006; Yoshinobu et al., 2009; Pignotta et al., 2010; Coint et al., 2013).

On the basis of these relationships, we interpret zones 1–3 to record different degrees of mafic-intermediate magma assimilation. The variable interactions most likely were controlled by differences in the density, temperature, composition, and effective viscosity of the enclaves and their tonalitic host (cf. Hodge et al., 2012; Hodge and Jellinek, 2012; Caricchi et al., 2012). The varieties of leucocratic felsic and tonalitic accumulations that surround and intrude the enclaves to varying degrees record different stages in the mobilization and expulsion of melt from the magma chamber. This removal of melt resulted in a differentiated, viscous crystal-rich magma mush. In the following we use enclaves to varying degrees record different stages in the mobilization and expulsion of leucocratic felsic and tonalitic accumulations that surround and intrude the mush, allowing the folds, fractures, and shear zones to form and be preserved (Paterson et al., 1998; Vernon and Paterson, 2006; Bachmann and Bergantz, 2004; Yoshinobu et al., 2009; Huber et al., 2011). This is because aggregates of touching feldspar crystals with an interstitial liquid allow the transmission of differential stresses (Vigneresse and Tikoff, 1999). The crystal concentrations most likely resulted from a combination of crystallization below the rigid percolation threshold (Vigneresse et al., 1996), a mechanical sorting of crystals at rheological boundaries, and the removal of interstitial melt. All of these processes would have increased the viscosity of the mush, allowing the folds, fractures, and shear zones to form.

The results from other field studies, experiments, and numerical modeling indicate that a variety of brittle and ductile deformation mechanisms can promote the draining of melts from between crystals (Jurewicz and Watson, 1984; Dell’Angelo and Tullis, 1988; Gleason et al., 1999; Rosenberg and Berger, 2001; Sawyer, 2001; Yoshinobu et al., 2009; Huber et al., 2011). In the Punta de Tracla unit, fractures (Fig. 3E), the collection of leucocratic material in low-pressure sites around enclaves (Figs. 3D, 3E, 3G), and remnants of melt pockets between broken plagioclase crystals (Figs. 7E, 7I) suggest that this process involved porous flow aided by microfracturing. The initial formation of microfractures may have occurred by a process similar to that described by Huber et al. (2011); in their model, density differences between melts and crystals, and the low compressibility of both, lead to a local increase of pressure where melts are concentrated. Microfracturing relieves the overpressure because of the high density of cracks that leads to a loss of strength. This process unlocks the rigid mush and promotes the movement of melt. The tapered tips (Fig. 3J), sigmoidal shapes (Fig. 3E), and en echelon geometries of the fractures we observed imply an increasingly viscous host where local increases in magma pressure and/or strain rate promoted further brittle deformation and fracture propagation (Blake and Fink, 2000; Paterson et al., 2004). Pressure gradients, generated as melts accumulated and enclaves deformed, also aided in the transfer of melt into dilational sites around folds.

Melt Mobilization and Removal From a Crystallizing Pluton

The mechanisms by which felsic and tonalitic melts in the Punta de Tralca unit were mobilized and expelled are recorded well by mesoscale structures that affect both enclaves and the regional SB layering in zone 2 (Fig. 12). In this zone, fractures, folds, and shear zones all disrupt SB (Figs. 3E–3H), indicating that they formed late in the deformation history of the magma. These structures reflect deformation in viscous, crystal-rich mushes where enough solid material (~45–50 vol% crystal) was present to enable fracturing and shear zones to form and be preserved (Paterson et al., 1998; Vernon and Paterson, 2006; Bachmann and Bergantz, 2004; Yoshinobu et al., 2009; Huber et al., 2011). This is because aggregates of touching feldspar crystals with an interstitial liquid allow the transmission of differential stresses (Vigneresse and Tikoff, 1999). The crystal concentrations most likely resulted from a combination of crystallization below the rigid percolation threshold (Vigneresse et al., 1996), a mechanical sorting of crystals at rheological boundaries, and the removal of interstitial melt. All of these processes would have increased the viscosity of the mush, allowing the folds, fractures, and shear zones to form.

The results from other field studies, experiments, and numerical modeling indicate that a variety of brittle and ductile deformation mechanisms can promote the draining of melts from between crystals (Jurewicz and Watson, 1984; Dell’Angelo and Tullis, 1988; Gleason et al., 1999; Rosenberg and Berger, 2001; Sawyer, 2001; Yoshinobu et al., 2009; Huber et al., 2011). In the Punta de Tracla unit, fractures (Fig. 3E), the collection of leucocratic material in low-pressure sites around enclaves (Figs. 3D, 3E, 3G), and remnants of melt pockets between broken plagioclase crystals (Figs. 7E, 7I) suggest that this process involved porous flow aided by microfracturing. The initial formation of microfractures may have occurred by a process similar to that described by Huber et al. (2011); in their model, density differences between melts and crystals, and the low compressibility of both, lead to a local increase of pressure where melts are concentrated. Microfracturing relieves the overpressure because of the high density of cracks that leads to a loss of strength. This process unlocks the rigid mush and promotes the movement of melt. The tapered tips (Fig. 3J), sigmoidal shapes (Fig. 3E), and en echelon geometries of the fractures we observed imply an increasingly viscous host where local increases in magma pressure and/or strain rate promoted further brittle deformation and fracture propagation (Blake and Fink, 2000; Paterson et al., 2004). Pressure gradients, generated as melts accumulated and enclaves deformed, also aided in the transfer of melt into dilational sites around folds.

Melt mobilization and removal was accompanied by compaction and flattening. In zone 1, mineral reactions that occurred during near-solidus, H2O-saturated crystallization or late hydrothermal alteration formed oblate biotite pressure shadows around large plagioclase laths and destroyed most melt pseudomorphs within SB (Fig. 7D). Some biotite crystals are sheared, suggesting that they accommodated sliding between the larger plagioclase grains as melt was extracted. Strain shadows and fracture sets show two perpendicular directions of extension within the XY plane of SB (Fig. 4), further suggesting flattening. In addition, the S > L mineral fabrics (Figs. 10C, 10F) and the uniformly oblate enclave shapes (Figs. 10C, 10D) in zone 1 evoke flattening. Because enclaves and mineral fabrics commonly record different deformation increments, and enclave shapes can reflect a variety of processes (Paterson et al., 2004), the uniform patterns in zone 1 suggest that the flattening occurred late, at a time when enclaves and matrix shared foliations and viscosity contrasts between them were low. The occurrence of crystal-plastic deformation mechanisms in both enclaves and matrix in this zone also suggests that the flattening occurred when the magma had mostly crystallized and was deforming close to its solidus.

In summary, the mobilization and removal of residual felsic and tonalitic melts from within the Punta de Tralca unit was accomplished through a combination of compaction, porous flow, internal fracturing, synmagmatic ductile deformation, and flow within dikes. These processes all helped drain melts into dilational sites of folds, boudins, fractures, and other structures and resulted in the formation of the highly viscous, crystal-rich magma mush that dominates zone 1. These interpretations agree well with those of other studies (e.g., Bachmann et al., 2002; Bachmann and Bergantz, 2004; Yoshinobu et al., 2009; Huber et al., 2011) suggesting that significant portions of some plutons in arc settings are compacted, high-strength cumulate-rich bodies that can be reactivated through a combination of synmagmatic brittle and ductile deformation mechanisms.

Rheological Transitions in Crystallizing Magmas

The rheological transitions that occur as magmas mingle, crystallize, and differentiate play important roles in how these materials migrate and solidify within the crust. A comparison of mineral microstructures in the Punta de
Tralca and Estero Córdoba units highlights the different transitions these two magmatic bodies underwent. Both units preserve a progression from hyper-solidus flow in melt-rich magmas to deformation close to the solidus where crystal-plastic processes occurred in the presence of melt. However, the Estero Córdoba dike preserves a richer array of deformation structures that suggest high melt fractions and less evidence of crystal-plastic recrystallization than the Punta de Tralca rocks. The dike shows an abundance of crystallization microstructures, including microfractures (Figs. 7E, 7F), melt pseudomorphs (Figs. 7E–7H), K-feldspar overgrowths on primary plagioclase (Fig. 7E), and inclusion-rich melt pockets between fractured grains (Fig. 7I). These and many other features are well preserved and lack the late hydrothermal reactions that destroyed most of the crystallization microstructures and melt pseudomorphs in the Punta de Tralca tonalite. This suggests that the Estero Córdoba dike was less viscous, richer in melt, cooled more quickly, and underwent less late-stage flattening and compaction than the viscous crystal-rich mush into which it intruded. Some of the best evidence of magma flow involving the rotation and alignment of crystals suspended in a melt-rich magma is preserved inside enclaves in the Punta de Tralca tonalite. Plagioclase accumulations that surround and penetrate enclaves by varying degrees (Figs. 3A–3C) record the comagmatic exchange of material between matrix and enclaves during flow. Thin (≤1 cm) layers of tiled crystals between enclaves and matrix (Figs. 3A, 3G) connote the presence of an interstitial liquid (Vernon and Paterson, 2006). These textures, and evidence of initially high viscosity contrasts, suggest that mechanical sorting by the addition of crystals at and across enclave boundaries during magma flow contributed to mineral alignment within Sx.

Other microstructures preserved inside enclaves, especially in zone 1, record the transition to near-solidus deformation in crystalline aggregates where crystal-plastic deformation occurred in the presence of small amounts of migrating melt. Amoeboid grain shapes, strain-free quartz and plagioclase, rounded grains, and other features (Figs. 7A–7C) indicate that the shapes of quartz-plagioclase aggregates initially aligned by magmatic flow were modified by diffusion creep (Vernon, 1970, 2004), dislocation creep, and finally late hydrothermal mineral reactions. Interstitial hornblende between feldspar and quartz (Fig. 7A), small dihedral angles in three-grain junctions between quartz, plagioclase, and hornblende (Fig. 7B), and the string-of-beads textures (Fig. 7C) suggest that melt crystallized along plagioclase grain boundaries and that some sliding occurred on melt-coated grains (Garlick and Gromet, 2004; Holmes and Sawyer, 2008). Thus, the minerals that define Sx inside enclaves also record a transition from flow in a melt-rich magma to near-solidus deformation, where crystal-plastic deformation mechanisms contributed to the formation of Sx as melt was expelled.

These observations are important because they demonstrate that crystal-plastic deformation in quartz-plagioclase aggregates occurred while the Punta de Tralca tonalite, and to some degree the Estero Córdoba dike, were deforming above their solidi. Their occurrence suggests the possibility of using experimentally-derived flow laws to estimate the rheologies of magmas with variable crystal-melt fractions in natural granitoids. An interesting area of research would be to combine the microstructures we describe and flow laws for high-temperature creep in quartz and plagioclase to estimate how magma rheology changes as plutons crystallize. Some studies utilized this approach for various continental (Pawley and Collins, 2002) and oceanic (Yoshinobu and Hirth, 2002) settings. The approach could significantly augment current methods, which mostly employ combinations of field observations and information on the temperature, chemical composition, and volatile content of the magmas (Yoshinobu et al., 2009; Caricchi et al., 2012; Hodge and Jellinek, 2012).

**Magma Flow Patterns and Fabric Development**

**Punta de Tralca Tonalite**

Mesoscale structures preserved within the Punta de Tralca tonalite provide information on the three-dimensional geometry of flow patterns that accompanied pluton crystallization and the draining of melts to form a crystal-rich mush. Figure 13 illustrates conceptually how some of this flow may have occurred. The diagram shows a pattern whereby material rotated about the regional northeast-plunging mineral lineation during bulk transport parallel to the lineation through a network of rigid or semirigid enclaves and crystals. The

![Diagram illustrating a type of helicoidal flow resulting in cells of material that rotate about the direction of bulk transport illustrated in Figure 4. The bulk transport direction parallels a steeply plunging mineral lineation. Displacements occur parallel to and across this lineation, resulting in a style of deformation that exhibits triclinic symmetry.](image-url)
flow appears helicoidal, but also may simply reflect a type of sluggish convection in a crystallizing intermediate magma body after it was replenished and thermally rejuvenated by the input of mafic magma.

The rotational pattern of flow (Figs. 4 and 13) explains the distribution and style of all late asymmetric structures (Fig. 3E–3H) we observed that define alternating cells of clockwise and counterclockwise displacements across the mineral lineation (i.e., in the YZ plane) in zones 2 and 3. This style of flow is reminiscent of deformations that commonly occur in transpressional shear zones where triclinic symmetry is achieved through combinations of flattening and a kinematic partitioning of displacements both parallel to and across the mineral stretching lineation (Lin et al., 1998; Marcotte et al., 2005; Iacopini et al., 2007). In simple steady-state noncoaxial flow, the vorticity vector is parallel to one of the axes of instantaneous strain, giving the flow monoclinic symmetry (Iacopini et al., 2007, 2010; Xypolias, 2010). However, if the vorticity vector has a direction that is oblique to any of these axes the flow has a triclinic symmetry (Jiang and Williams, 1998). In the Punta de Tralca unit, the orientations of plagioclase crystals within the tonalitic matrix are compatible with a type of complex rotational flow: their distribution within the XZ plane and the lack of preferred orientations in the XY and YZ planes (Fig. 8) are consistent with the tumbling and rotation of crystals as they move through a matrix of rigid or semirigid enclaves. This process, or something similar to it, could have effectively drained melts, thereby increasing effective viscosities and aiding compaction.

The geometry of the flow illustrated in Figures 4 and 13, or something similar to it, may also explain patterns observed in other magmatic and partially molten bodies. Hippert (1994), for example, reported foliation and lineation patterns in migmatitic diapirs in the Baçao complex of southeastern Brazil that thermally rejuvenated by the input of mafic magma. Despite these examples, however, there remains a dearth of information in the literature on helical and other complex rotational flows in convecting magma chambers. This suggests that either these flow types are rare, poorly preserved, or simply understudied. One potential problem with helical flow is that it may be unstable or represent a precursor to turbulent flow (Moffatt and Tsinober, 1992; Scolfield and Huq, 2010). Turbulent convection appears difficult to achieve in a viscous melt flowing through a framework of solid crystals (Bachmann and Bergantz, 2004). Internal fracturing linked to magma overpressurization, which can break up and weaken the crystalline framework (Huber et al., 2011), or the addition of volatiles in wet magmatic systems (Bachmann and Bergantz, 2006), may help overcome these problems. These processes potentially could help promote complex flow in magmas by allowing thermally rejuvenated mushes to convect. Our study highlights the need for three-dimensional fabric analyses to document the geometry of three-dimensional geometries of flow in crystallizing plutons.

In addition to rotational flow through a matrix of enclaves, we suggest that channelized flow in dikes, resulting in the formation of $S$ foliations and drag along dike margins, was important in zone 3 (Fig. 12). Other investigations of how dikes might be linked to melt segregation in migmatites have produced two end-member models. The first, called the rivulets-feeding-rivers model, involves the formation of a self-organized network of veins and dikes operating simultaneously that increases in capacity and decreases in number, forming a fractal geometry (Weinberg, 1999; Tanner, 1999; Brown, 2004). The second, known as the stepwise accumulation model, forms local melt-conductivity pathways through the draining and closure of small veins into larger dikes such that conductivity is spatially and temporally transient (Bons et al., 2009). Crosscutting relationships among dikes in the Punta de Tralca tonalite suggest that a single melt conductivity network where magma transportation operated simultaneously at a variety of scales is unlikely. Our observations support a stepwise accumulation model while highlight the important role of brittle and ductile deformation in segregating and mobilizing increasingly felsic melts within a crystallizing host.

**Estero Córdoba Dike**

The Estero Córdoba dike (Figs. 1B and 2) records the intrusion of a melt-rich tonalitic magma into an already highly viscous crystal-rich mush, represented by the Punta de Tralca rocks. This intrusion records processes by which a rigid crystal-rich mush deforming near its solidus was reactivated and mingled comagmatically with a melt-rich dike of intermediate composition (Fig. 5). Furthermore, relationships preserved on the southeast side of the dike (Fig. 6) record the transfer and ponding of melt-rich material at the margin of the magma chamber near its contact with metamorphic host rock.

The key features of the Estero Córdoba dike include (1) a diffuse, nonplanar northwestern contact with the Punta de Tralca tonalite, into which it intrudes (Fig. 5); (2) many local foliation discordances (Fig. 10A) and textural evidence
of magma mingling and the comagmatic exchange of enclaves and minerals in narrow channels (Figs. 5A, 5C); (3) evidence of significant differences in the viscosities of the two units; (4) L > S flow foliations (S_1) that are discordant to foliations in the channels (Figs. 5A, 5C); (5) enclaves that record deformation by ductile distortion, winnowing, and a semigrigid rotation of material within a weak, melt-rich host; (6) young dikes that intruded after the main dike had cooled and mostly solidified; (7) a southeastern contact, representing the margin of the magmatic system, where sheeted dikes are interfolded and mixed with country rock of the Valparaíso metamorphic complex.

The geometric relationships among these features are illustrated in textural zones 4–6 of Figure 12. Zone 4 includes the northwestern contact and is dominated by flow foliations (S_1) and other structures that are unique to the younger dike. Both zones 5 and 6 show structures at the southeastern end of the unit. Zone 5 exhibits interfolded and stretched granitoids, which form a distinctive magmatic layering (S_0) absent in the rest of the unit. Country rock in zone 6 comprises gneiss, slate, biotite schist, calcareous gneiss.

On its northwestern side (Figs. 1B and 2), the Estero Córdoba dike records an exchange of material with the Punta de Tralca tonalite (Figs. 5A, 5C) in narrow channels. This exchange of material, along with the local sharing of foliations, indicates that temperatures were high enough and emplacement rates were slow enough to allow the two tonalites to mingle as they crystallized and deformed together. Parallel lineations formed by both stretched enclaves and aligned plagioclase phenocrysts (Fig. 10A) further suggest that both units record similar bulk flow directions. This interpretation is in agreement with numerical and analogue models of crystal alignment in a flowing magma that suggest that as crystal contents increase, the heterogeneous size distribution of natural crystals and contact interactions tend to generate fabrics with a lineation that tracks directions of magmatic flow (Arbaret et al., 2000).

A comparison of mineral and enclave fabrics in each unit at site 111N01B (Fig. 5) yielded interesting information. In the Punta de Tralca tonalite, these show differences in the age, amount, and style of deformation. As expected (e.g., Vernon and Paterson, 2006), these differences are accentuated in areas where viscosity contrasts are high, such as in zone 2, and are reduced in areas of low viscosity contrast, such as zone 1. Zone 2 enclaves record the earliest stages of deformation when mechanical sorting and mineral alignment in melt-rich magma currents formed S_0. In zone 1, enclaves record a history most similar to the matrix mineral foliations, which mostly show only the last stage of deformation. This shared history is reflected in areas (e.g., Fig. 5B) where S_0 and S_1 foliations are parallel and show fairly uniform oblate shapes (S > L) shape fabrics (Figs. 10C, 10D, 10F). However, even in these latter areas, the shape fabrics created by the enclaves and mineral populations are significantly different (Fig. 10C). These observations support the conclusions of others (Paterson et al., 2004) who showed that enclaves and mineral foliations in plutons tend to record different parts of the deformation history. The implication is that parallel foliations often record widely different processes, ages, and origins (cf. Pawley and Collins, 2002).

The differences in age and style of deformation recorded by enclaves and mineral foliations are even more pronounced in the Estero Córdoba dike. The orientations and distribution of plagioclase minerals in the unit are identical to those in the Punta de Tralca (Fig. 10C). However, enclave shapes are very different (Figs. 10C, 10D), despite identical orientations and parallelism with mineral lineations (Figs. 10A, 10B). These patterns illustrate how mineral foliations in crystallizing plutons are easily reset and typically record only the last phase of deformation (e.g., Paterson et al., 1998, 2004; Pignotta et al., 2010; Coint et al., 2013).

A close examination of the size fractions of minerals that make up the S_2 foliations provides additional information on the mechanisms of fabric resetting. Only the largest fraction (0.5–1 cm) of plagioclase crystals are aligned and contribute to forming S_2. In contrast, smaller grains that fill the spaces between megacrysts (e.g., Fig. 7E) are mostly equant, show less alignment, and appear to reflect in situ crystallization. This process, combined with the fragmentation of larger grains and mineral rotation in melt, effectively reset the strain memory of the fabric. This interpretation agrees with the models of Arbaret et al. (2000), who showed that different size fractions of feldspar in granites record different parts of the strain history. With increasing crystal content, the largest megacrysts tend to evolve closer to the strain ellipsoid than small grains. We suggest that future work comparing the orientations and distributions of different mineral size fractions could prove useful for understanding parts of the strain history.

Our comparison of enclave populations in the two units also yielded an unexpected result. Observations of shared foliations and evidence that both enclaves and minerals crossed the contact at site 111N01B suggest that the enclaves in the Estero Córdoba were derived from the Punta de Tralca. We therefore expected the enclaves in the former unit to retain some memory of the oblate shapes and history of flattening in the latter. Viscosity contrasts and the likelihood that most of the strain accompanying dike emplacement was accommodated by flow in melt increases the probability of this retention. However, the enclaves in the Estero Córdoba record no hint of the oblate shapes and flattening that dominates the Punta de Tralca tonalite. Instead they form a strong L > S fabric and uniformly prolate shapes (Figs. 10C, 10E). This result suggests that the enclaves also were reset, and their prior history erased, by ductile stretching, shearing, and winnowing during dike emplacement. The evidence of high strains also supports predictions (e.g., Barrière, 1981; Vernon and Paterson, 2006) that magma flow near stiff boundaries drives deformation and sorting. This type of deformation in a flowing, melt-rich magma appears to be a primary mechanism for generating linear fabrics in granitoids.

One of the pitfalls of using enclave populations to reconstruct deformation histories is that statistical averaging can increase errors and mask differences if the enclaves exhibited a wide variety of initial shapes (Paterson et al., 2004). The strong differences we obtained from the two units that persist after a consideration of the errors (Fig. 10C) (Appendix 1) appear to partly reflect the relative uniformity of shapes and orientations in the two populations we selected (note the low dispersions in Fig. 11). The pattern confirms that both
enclaves and mineral populations have short memories that make them poor strain markers (Paterson et al., 2004). However, the example also shows that the paired use of enclaves and mineral structures can be informative because the combination reveals information on timing and kinematics of flow and the effects of different processes on the behavior of minerals and the evolution of foliation types. The utility of this approach, as suggested by Paterson et al. (2004), demands information on the relative age, initial conditions, and context of the structures. As we illustrate here, some of these properties can be reasonably established using crosscutting relationships and textural features preserved in outcrops. However, they do not provide a true determination of finite strain.

The southeastern end of the Estero Córdoba dike (zone 5, Fig. 12) exhibits a structural style that is absent farther north. At sites 11IN03A–11IN03C (Figs. 1B, 2, and 6) sheets of compositionally diverse granitoids are interfolded with one another and with layers of country rock, suggesting the incremental emplacement of multiple batches of increasingly felsic dikes. The presence of synmagmatic folds, xenoliths, and stretched screens of country rock (Figs. 6 and 12) also suggest that the dike and the Valparaíso metamorphic complex locally share a deformation history. Pignotta et al. (2010) reached a similar conclusion for the Jackass Lakes pluton in the central Sierra Nevada batholith using analogous structures. Other work has shown that the differential movement of magma next to cooler country rock can accentuate deformation along pluton margins (Vernon and Paterson, 2006). In this interpretation, magma replenishment may cause the magma to expand, resulting in flattening of both the pluton margin and its wall rock.

On the basis of these relationships we suggest that most, if not all, of the structures in zone 5 are the youngest in the Estero Córdoba dike and reflect the last stages of magma emplacement at its margin. In addition, the comagmatic history of the Punta de Tralca and Estero Córdoba units indicates that melt was present in the oldest parts of the system (zones 1–3) as melts near the margin (zones 5–6) were emplaced. In this context, zone 4 may represent a transfer zone that fed dike emplacement in the outer parts of the magma chamber. The type of zonation appears similar to that described by Coint et al. (2013) for the Wooley Creek batholith in the Klamath Mountains; this batholith also shows three main compositional and temporal zones: a lower zone formed from multiple batches of gabroic through tonalitic magmas, a central dike-rich zone that underwent mixing with the lower zone, and an upper zone, which is youngest and composed of tonalite to granite. These zones suggest that large interconnected magma chambers are relatively common in continental arc systems and provide further evidence that plutons are assembled from numerous, incrementally emplaced batches (cf. Glazner et al., 2004). However, the individual magma batches need not crystallize completely, but instead may interact comagmatically (cf. Coint et al., 2013). In these systems, the injection of intermediate magma into a highly viscous, crystal-rich mush as dikes appears to be able to provide enough heat, melt, and mechanical energy to sustain the magma chamber and help mobilize and expel felsic melts toward the outer or upper reaches.

CONCLUSIONS

The Punta de Tralca tonalite records the intrusion of multiple batches of relatively mafic magma into an intermediate host through dikes. Microgranitoid enclaves in the unit exhibit variable degrees of assimilation with a tonalitic and granodioritic host and preserve mesoscale and microscale structures that record rheological transitions as the crystallizing mush approached its solidus. In areas of high viscosity contrast between enclaves and matrix, internal ($S_a$) and external ($S_b$) foliations typically are discordant, indicating that the structures record different increments of deformation. Mineral microstructures and field relationships show that $S_b$ in these zones is oldest and formed by a combination of (1) the rotation and alignment of crystals suspended in a flowing magma, (2) mechanical sorting during flow by the addition of matrix crystals at and across enclave boundaries, and (3) high-temperature diffusion creep and sliding on melt-coated grains as melts crystallized and were expelled. The occurrence of crystal-plastic deformation suggests the possibility of using experimentally derived flow laws to estimate the rheologies of magmas with variable crystal-melt fractions in future studies.

In areas of low viscosity contrast, enclaves were mostly assimilated by their matrix. Internal ($S_a$) and external ($S_b$) foliations are parallel and grade smoothly into one another, forming a regional compositional banding. This parallelism indicates that the two foliations formed together during final deformation of the matrix. Magmatic shear zones, faults, folds, sigmoidal tension gashes, and boudinage disrupt this regional layering, indicating that they also formed late in the deformation history when enough solid material was present in a crystal-rich mush to enable fractures and shear zones to form. The draining of melts to form the crystal-rich mushes increased the mechanical coupling between enclaves and their matrix and promoted compaction, crystal-plastic deformation, and flattening, which resulted in penetrative $S > L$ mineral and enclave fabrics. These structures may provide key insight into the mechanisms responsible for the extraction of melt from a crystalline mush to produce phenocryst-poor rhyolitic eruptions (e.g., Bachmann and Bergantz, 2004). These mechanisms may partially control the timing, volume, and style of Andean volcanism.

Concentrations of leucocratic, quartz-rich material intruded previously deformed enclaves and matrix within the Punta de Tralca tonalite. These accumulations exhibit changes in geometry, texture, and composition with increasing size, from small globular patches of tonalite and granodiorite that grade smoothly into the tonalite host to granitic dikes with internal flow foliations ($S_b$) that entrain and truncate enclaves and older flow foliations. Gradational contacts between the concentrations and their host indicate that melt-rich magma was able to pool within a crystal-rich mush. The accumulations escaped most or all of the flattening and late near-solidus strains are recorded by both enclaves and matrix. We interpret these as residual melts that were mobilized and concentrated by brittle and ductile deformation. They support a stepwise accumulation model for the pluton.
where melt escaped as the host crystallized and aided compaction of the crystal-rich mush.

The Estero Córdoba dike records the processes by which a rigid, crystal-rich mush deforming near its solidus was reactivated further and mingled comagmatically with an intrusion of intermediate composition. The dike records a structural style and history that differs from those of the Punta de Tralca tonalite, even though the two units were comagmatic. The two intrusions display local foliation discordances and evidence of material exchange in thin channels. Parallel lineations formed by both stretched enclaves and aligned mineral aggregates suggest that both units record similar bulk flow directions. Field relationships and mineral microstructures suggest that the dike was richer in melt and underwent less flattening, less compaction, and less crystal-plastic deformation than the more viscous crystal-rich mush of the Punta de Tralca tonalite. The presence of synmagmatic folds, stretched dikes, flattened xenoliths, and deformed screens of gneiss suggest that dike emplacement involved ductile and brittle deformation, sheeting, and the material transfer of country rock.

Mineral orientations and distributions in the dike are identical to those in the Punta de Tralca tonalite and confirm that mineral foliations are easily reset. The in situ crystallization of new minerals, the fragmentation of plagioclase megacrysts, and crystal rotation within a melt-rich magma were the primary resetting mechanisms. Different size fractions of minerals in granitoids record different parts of the strain history, with the largest megacrysts recording more strain than smaller grains. Consequently, a comparison of the orientations and distributions of mineral size fractions should prove useful for evaluating these histories in the future.

Field relationships indicate that enclaves in the northwest part of the Estero Córdoba dike were derived from the Punta de Tralca tonalite. Despite this origin, and similar orientations, these enclaves retain little evidence of their prior history, which was nearly erased by deformation during dike emplacement. A comparison of mineral and enclaved fabrics in the two units illustrates how intrusion of the Estero Córdoba dike resulted in velocity gradients that drove deformation, increased ductile distortion and winnowing, and resulted in linear (L > S) fabrics. The results highlight the utility of three-dimensional fabric analyses in documenting the geometry of flow in crystallizing magmas.

This study provides further evidence that large interconnected intrusive bodies are assembled from many incrementally emplaced batches that need not crystallize completely and, instead, may interact comagmatically. Relationships preserved in the Punta de Tralca unit suggest that significant portions of plutons in arc settings may be compacted, high-strength cumulate-rich bodies that can be reactivated by the emplacement of magma through dikes and combinations of symmagmatic brittle and ductile deformation. In these systems, the injection of intermediate magmas into highly viscous, crystal-rich mushes through dikes also appears to be able to provide enough melt and energy to sustain the magma chamber and help mobilize and expel felsic melts upward and outward toward the roof and margins of the system.

APPENDIX 1. FABRIC ANALYSES AND ERROR ASSESSMENT

Fabric Analysis Methods

The normalized Fry method (Fry, 1979; Erslev, 1988) produces a polar plot of the center to center distances and angles for each pair of objects that is normalized by the combined lengths of their mean semiaxial diameters. An undeformed, randomly packed aggregate of objects produces a point cloud outside a central void of unit radial length. Through deformation, nearest-neighbor lengths become closer in shortening directions and farther apart in lengthening directions. This anisotropy is reflected by an elliptical central void that is taken to be a two-dimensional strain ratio if the assumptions described in the text are satisfied.

The Rf method (Ramsay, 1967; Dunnet, 1963; Lisle, 1985) determines the axial ratio of a sectional strain ellipse by statistically investigating the relationship between the eccentricities of deformed elliptical objects and their orientations. The method involves determining the orientations of deformed objects after iteratively applying a finite increment of inverse strain parallel to the vector mean of long axis orientations. This iterative process is carried through a geologically reasonable range of strain ratios, from which a chi-squared test for uniform object orientation also is applied. The inverse strain ratio that produces the most uniformly distributed population of object orientations is taken as the sectional strain ratio, subject to the validity of the assumptions described in the text.

To obtain a three-dimensional ellipsoid, the sectional methods are applied to at least three faces oriented at high angles to each other in order to constrain the inverse shape matrix of Shimamoto and Ikeda (1976) and Wheeler (1986), following the method in Robin (2002) and Launae and Robin (2005). This procedure allows for a parameterization of fabrics using the orientations and normalized lengths of a triaxial ellipsoid. These parameters can then be used to investigate the shape symmetry of the fabric in terms of prolate versus oblate geometry following Lodé’s (1926) parameter and the magnitude of distortion given by the octahedral shear strain (Ramsay and Huber, 1983).

Error Assessment

A comprehensive investigation of all errors involved in three-dimensional strain analysis is beyond the scope of this contribution. However, some understanding of the variability of our analyses of enclave fabrics is important for a comparison and interpretation of the results. The approach implemented here follows the procedure of Mookerjee and Nickleach (2011), which involves an assessment of how perturbations of sectional data influence the parameters of fitted ellipsoids. Mookerjee and Nickleach (2011) addressed this variability by constructing a random bivariate normal distribution of strain ratios and orientations as a function of the variance-covariance of the sectional Rf and n parameters. Sections that display less dependence between these parameters produce a larger range of strain ratios and orientations. Random samples from these distributions then are used to construct a population of ellipsoids that describe the possible analysis error.

Despite its utility, this approach may be biased in situations involving a comparison of analyses from populations that exhibit different variances in initial axial ratios. To address this scenario, we implemented a modified procedure of the error analysis that involves making two assumptions: (1) the observed distribution of object axial ratios and orientations is representative of the population for a given section and (2) the sample variance of harmonic means of axial ratios approximates the sample variance of the sectional strain ratio. The first assumption is important because we assessed error by randomly sampling from a two-dimensional kernel density estimation (Venables and Ripley, 2002) of object ratios and orientations for each section. The kernel density estimation grid is evaluated through axial ratios from 1% to 15% beyond the maximum observed axial ratio at a resolution of 0.05. Object orientations are evaluated through 180° at a 0.5° resolution. This distribution is randomly sampled 50 times taking n objects at a time, where n is the original observed population size. Consequently, sectional fabric deformations made from originally larger populations will reflect lower variance and more confidence about the sectional results. Conversely, sections with fewer objects will display greater variance and lower confidence. From the 50 sampled populations a measure of the variance of the strain ratio and lengthening direction is made. Considering that computational efficiency is compromised by applying an iterative destraining and chi-squared test to each sample population in order to calculate a series of strain ratios, we simply calculated the harmonic mean of axial ratios following assumption two. The variance-covariance
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