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## A view from the roof: magmatic stoping in the shallow crust, Chita pluton, Argentina

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### Abstract

Nearly 2 km of vertical relief and exposure of continuous pluton roof-wall corners around the Chita pluton, northwest Argentina, provides constraints on the 3-D host rock displacement field attending magma emplacement in the shallow crust. The pluton is rectangular in cross-sectional view and consists of weakly to non-deformed granite to granodiorite. Structures in surrounding metasedimentary host rocks are truncated at a knife-sharp contact and are only weakly deflected from their regional orientations. Final emplacement occurred by stoping together with minor doming of the earth's surface. Structural restoration of a cross-section indicates that host-rocks above the pluton may have been domed upwards during emplacement by as much as a few hundred meters, accounting for up to 20% of the exposed pluton volume. The remaining 80% of the space for pluton emplacement was made by downward removal of host-rock from the present level of exposure. Although mechanisms such as floor-subsidence are permissive, late stoping has destroyed evidence for the early emplacement history. However, geometrical constraints provided by exposure of continuous wall-to-roof contacts indicate that early emplacement mechanisms at this level in the crust and immediately below were also dominated by the downward displacement of host rocks through a conduit that now is represented by the solidified pluton.

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### 1. Introduction

The construction and evolution of magma chambers is a fundamental process of crustal growth. Yet, after decades of research the mechanisms of pluton emplacement remain controversial (Pitcher, 1979; Hutton, 1988; Miller et al., 1988; Clemens and Mawer, 1992; Paterson and Fowler, 1993a; Pitcher, 1993; Cruden, 1998; McNulty et al., 2000; Molyneux and Hutton, 2000). Efforts to understand pluton emplacement have been hindered by two critical difficulties. First, the enormous physical scale of plutons allows only limited observation of vertical displacements associated with intrusion (Schwerdtner, 1995). Second, the structural record of pluton emplacement is incomplete. Evidence for early emplacement processes can be destroyed by later

processes such as magmatic stoping (Pitcher, 1993). Additionally, pluton emplacement phenomena display significant natural variation. Tabular, sheet-like, piston-shaped, and stock-like intrusive shapes are common (e.g. Pitcher et al., 1985; Cruden, 1998). Individual plutons show evidence for multiple emplacement mechanisms that vary in space and time (Paterson et al., 1996).

Many of the difficulties in understanding and evaluating emplacement processes can be overcome utilizing observations from pluton roofs and continuous roof-wall intersections. Naturally occurring cross-sections (e.g. Fig. 1), exposing the pluton roof and walls, place crucial boundary conditions on host-rock displacements. While observations from pluton roofs cannot constrain complete emplacement histories, they can establish final emplacement mechanisms and they provide the best geometrical constraints on early emplacement processes (Paterson et al., 1996).

For example, recent controversies have centered on two

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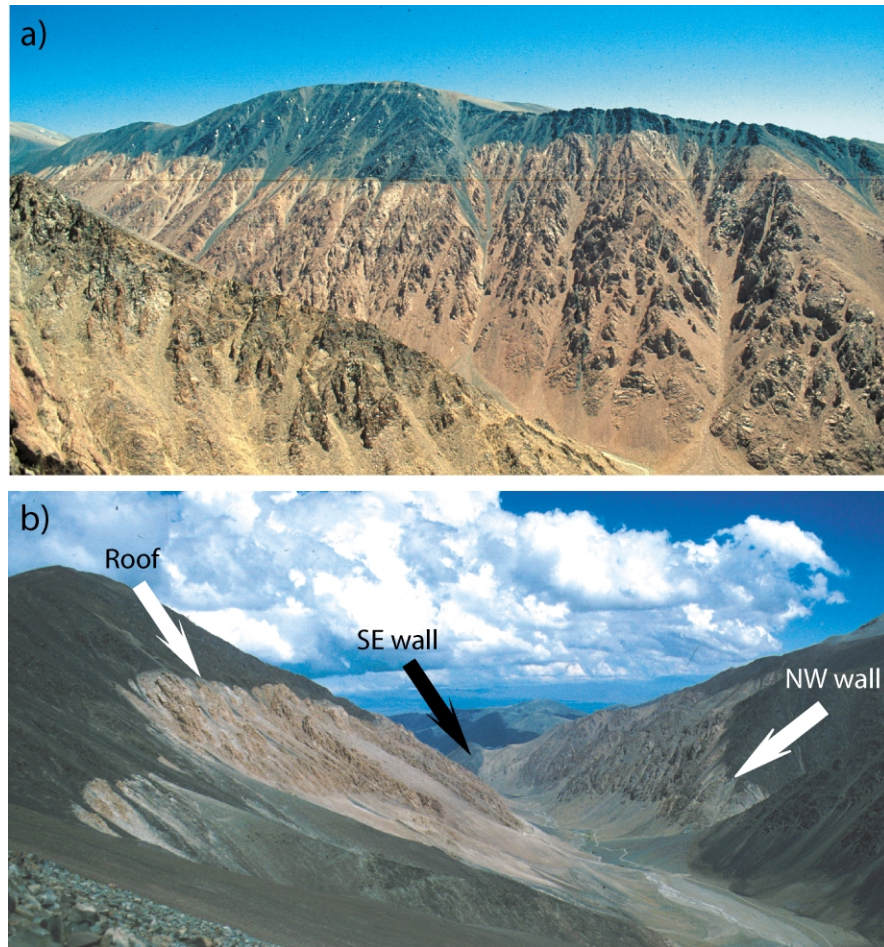


Fig. 1. (a) View looking east-northeast of the roof of Chita granite pluton; summit is 5140 m. (b) View looking southeast, down the long axis of the Chita pluton into the deeply incised Chita Canyon; lowest exposures occur below 3400 m, indicating over 1.7 km of vertical relief within the pluton.

aspects associated with construction of batholiths in the upper crust: (1) the role of regional deformation (e.g. Hutton, 1988; Paterson and Fowler, 1993b; Schmidt and Paterson, 2000); and (2) the relative roles of diapirism versus diking in magma ascent and chamber construction (e.g. Clemens and Mawer, 1992; Petford et al., 1993; Paterson, 1994; Weinberg and Podladchikov, 1994; Petford, 1996; Miller and Paterson, 1999; Johnson et al., 2001). Exposures of roofs and roof-wall transitions (e.g. Fig. 1) can provide crucial tests of these models. Strain compatibility requires that lateral dilational opening of host rock walls during faulting must be accommodated by extension or detachment of rocks above the pluton (Paterson and Fowler, 1993b) such that the magnitude of extension and/or detachment of roof rocks provides a measure of the space made by faulting. Similarly, emplacement of magmas as diapirs (e.g. Dixon, 1975; Miller and Paterson, 1999), or via ballooning of a dike fed magma chamber (e.g. Clemens and Mawer, 1992; Petford et al., 1993; Johnson et al., 2001) should produce characteristic deformation patterns in the host rocks (Dixon, 1975; Cruden, 1988). Additionally, recognition of unfaulted, discordant host rock contacts along roof-wall transitions indicates that some amount of

the host rocks was incorporated into the magma chamber. The observation of discordant contacts is often dismissed in the literature and other models are put forth ignoring host rock discordancy and the local presence of host rock xenoliths (e.g. Tikoff et al., 1999; McNulty et al., 2000). However, if some amount of stoping and assimilation occurred, then one implication is that crustal mixing may have occurred throughout the ascent of arc magmas. Thus, balanced cross-section restorations of pluton roofs can help distinguish between emplacement models that rely on faulting, magmatic stoping, as well as characterize the displacement field above a rising diapir.

Below, we document structural relationships around the Chita pluton, Colanguil batholith, northwestern Argentina. It is shown that a fracture-like pluton contact discordantly truncates host-rock structures related to pre-emplacement contractional deformation. We infer that final pluton emplacement was dominated by stoping, together with minor doming of the earth's surface. Early emplacement mechanisms are not known, but geometric constraints indicate that they must have involved predominantly downward displacement of the host-rocks towards the zone of magma generation.

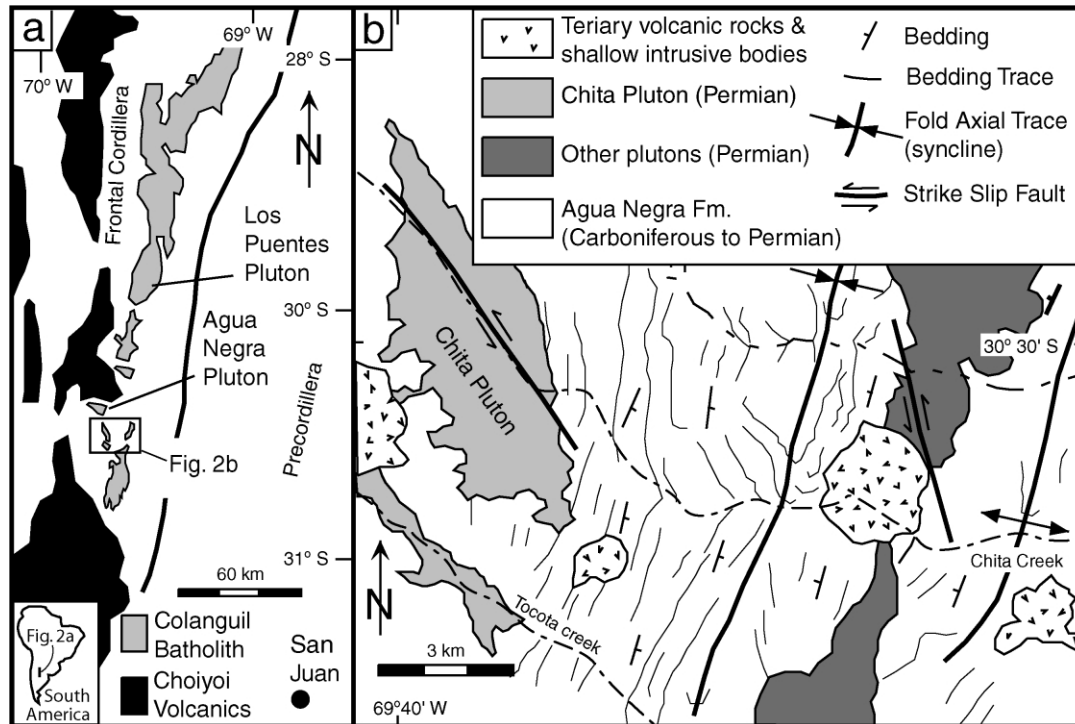


Fig. 2. (a) Location map, after Llambias and Sato (1990). (b) Structural map displaying trends of kilometer-scale folds in the Agua Negra Formation. Dashed lines are form lines on bedding traces from aerial photographs. Air photo interpretations are confirmed by transects in Chita and Bauchazeta creeks. Dips of strata east of the Chita pluton are generally  $<30^\circ$ ; fold axes plunge sub-horizontally (modified from Sato, 1989).

## 2. Geologic setting

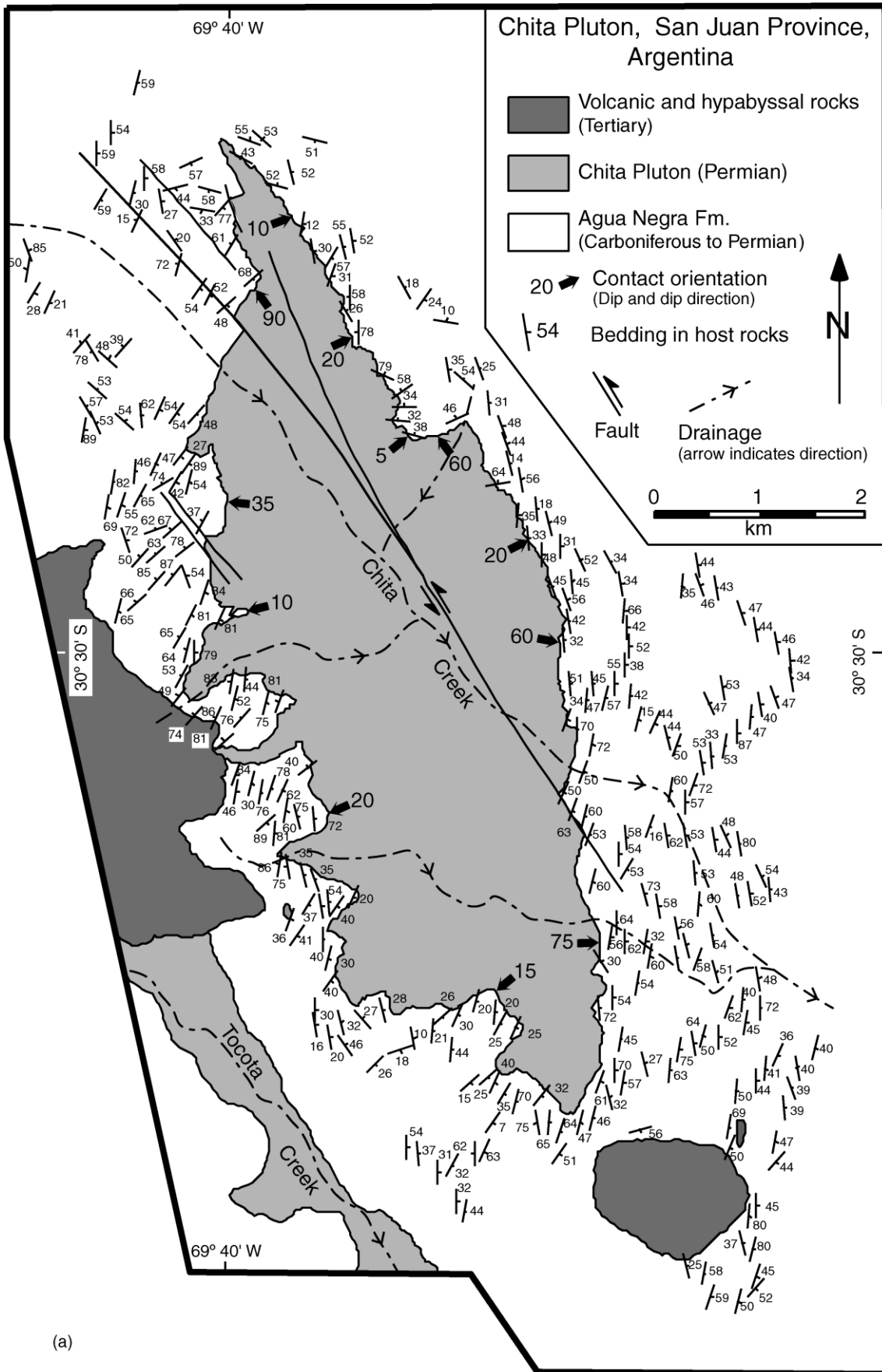
### 2.1. Colanguil batholith

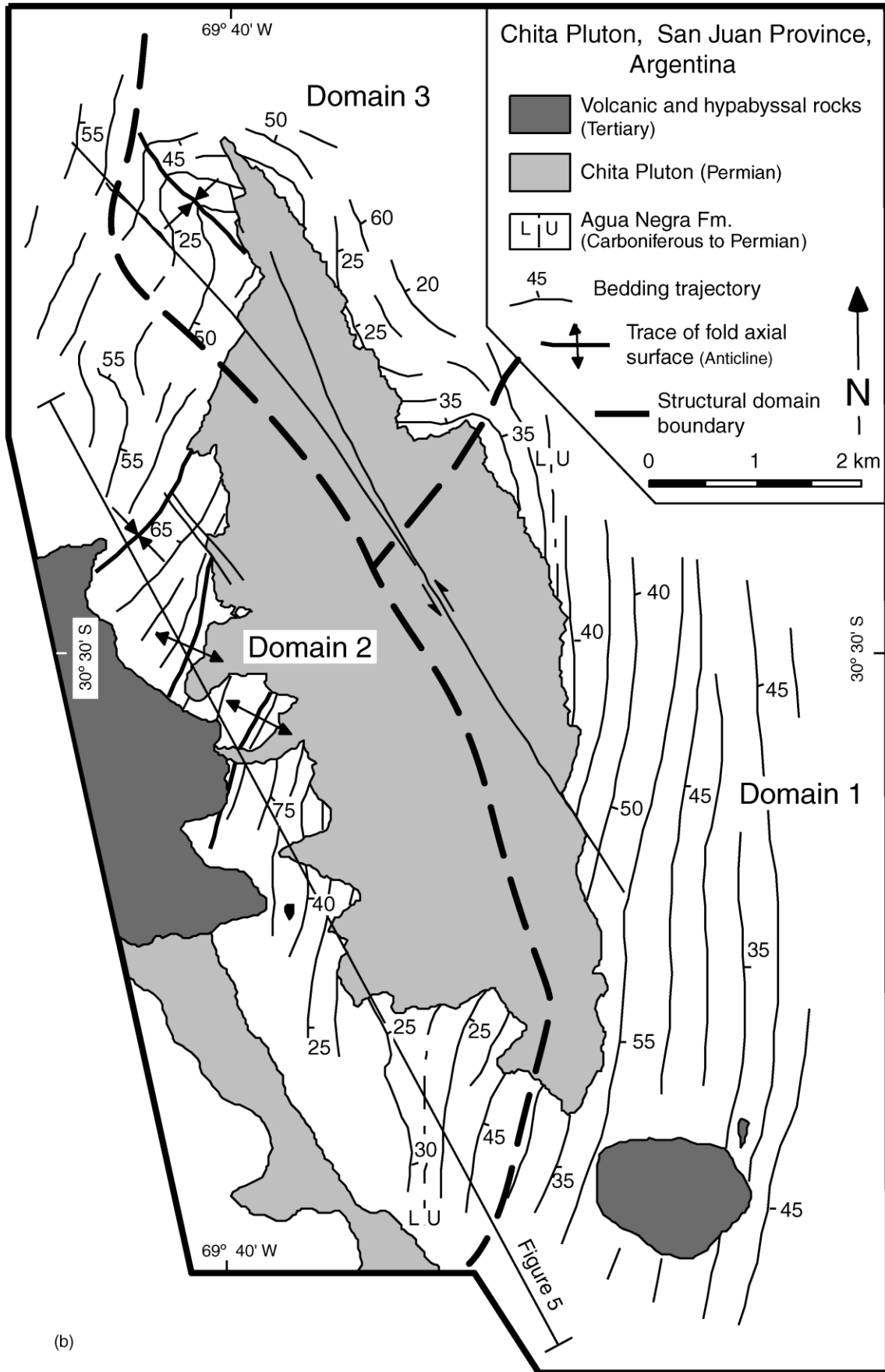
The Permian Colanguil batholith is located in the Frontal Cordillera, western Argentina, and consists of Late Paleozoic to Triassic (and Jurassic?) composite plutons that intruded into their own volcanic ejecta and previously deformed Paleozoic strata (Fig. 2; Llambias et al., 1987; Mpodozis and Kay, 1992). This elongate, north–south-trending batholith crops out for approximately 220 km between  $29^\circ$  and  $31^\circ$ S latitude, and is 10–30 km wide. Plutons in the batholith consist chiefly of amphibole- and/or biotite-bearing granodiorites, granites and leucogranites, with minor associated diorite. Compositionally the batholith is calcalkaline, metaluminous to weakly peraluminous, and relatively potassic, with initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios between 0.705 and 0.713. Five Rb–Sr age determinations from the batholith fall between 264 and 247 Ma (Sato et al., 1990). Plutons of the Colanguil batholith locally intrude rhyolite and dacite ignimbrites of the Permian Choiyoi Group that constitute probable eruptive equivalents of the plutonic rocks. These flat-lying volcanic deposits form an elongate belt located 5–20 km west of the batholith (Fig. 2; Sato

et al., 1990). Sub-horizontal orientation of the volcanic strata at present-day elevations slightly above the plutonic rocks suggests that the exposed portions of the Colanguil batholith were emplaced at very shallow crustal levels ( $< a$  few kilometers), and also rules out significant post-volcanic regional tilting.

The plutons we have studied intrude weakly metamorphosed, moderately deformed sedimentary rocks of the Upper Carboniferous to lower Permian Agua Negra Formation (280–290 Ma; Gonzalez, 1981). These clastic sedimentary rocks consist of quartz-rich sandstones and shales that were deposited in a shallow marine environment and reach approximately 2 km in thickness. Construction of the Colanguil batholith and associated volcanic rocks occurred after west-directed reverse faulting and open folding during the Permian San Raphael orogeny (Fig. 2; Llambias and Sato, 1990). The plutons cut these contractional structures and volcanic rocks of the Choiyoi Group rest unconformably on the Agua Negra Formation. Thus, deformation associated with the San Raphael event in the vicinity of the Colanguil batholith is bracketed between 280–290 and 265–247 Ma, with 280–270 considered to be its most probable age (Llambias and Sato, 1990; Sato et al., 1990).

Fig. 3. (a) Simplified geologic map of the Chita granite pluton showing drainage patterns, pluton contact orientations, and bedding orientations in the Agua Negra Formation. (b) Bedding strike trajectories and major fold axes. Thick dashed lines denote boundaries between structural domains described in text. Thin dashed line in Agua Negra Formation shows transition from shale-dominated (lower; L) to sand-dominated (upper; U) strata.





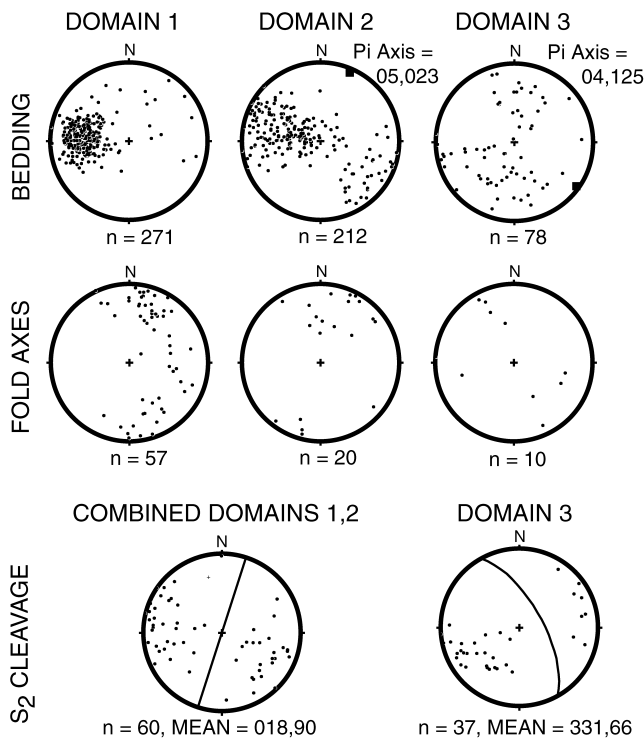


Fig. 4. Equal area stereographic projections showing poles to bedding surfaces, trend and plunge of minor fold axes, and poles to  $S_2$  cleavages as separated by structural domain. Domain boundaries are given in Fig. 3b. Pi axes = pole to best-fit-great-circle to bedding poles, and approximate axes of the major folds.

## 2.2. Chita pluton

Exposures of the Chita pluton occur along the canyons of Chita creek and Tocota creek and are presumably joined together in the near subsurface (Figs. 2 and 3). Exposures spanning  $> 1.5$  km of topographic relief reveal a pluton with a sub-horizontal roof and steeply dipping walls (Fig. 1). Shallowly dipping contacts along the canyon sides represent the pluton roof (average dips  $0^\circ$ – $20^\circ$ ). North-striking pluton wall contacts dip  $50^\circ$ – $80^\circ$  outwards from the pluton center. Thus, the true map-view shape of the pluton is probably elliptical with 3:1 aspect ratio, long axis trending N to NNE, and with an area of approximately  $50 \text{ km}^2$ .

The Chita pluton consists of relatively homogeneous pale-orange colored, generally medium-grained granite, with 27–42% quartz, 30–40% perthitic orthoclase, 22–33% sodic plagioclase ( $An_{6-27}$ ), and accessory biotite,

fluorite, zircon, opaques and apatite (Sato, 1989). Neither magmatic nor solid-state foliations or lineations were observed. In thin section, the rock exhibits primary igneous textures, or textures associated with metasomatic alteration, overprinted by minor sub-solidus deformation. Deformation microstructures include undulose and patchy extinction in quartz and potassium feldspar. Fluid inclusion data suggest crystallization at less than 100 MPa (Sato, 1989). Mirolitic cavities are locally common. Such evidence for shallow emplacement level is consistent with the stratigraphic thickness of Agua Negra Formation host rocks (2 km), and with the nearby occurrence of flat-lying, probable eruptive equivalents of the Choiyoi Group volcanics.

Localization of late magmatic fluids and mineralization beneath the inferred roof contact suggests that the pluton has not been tilted. Below this contact, sub-horizontal compositional layers of pegmatite, aplite, and biotite-rich rhythmic schlieren occur in a zone a few meters thick. Uppermost portions of the pluton locally show intense metasomatism and greisen-type alteration with muscovite, molybdenite and quartz-fluorite veins (Sato, 1989). Scarcity of similar features along the steep pluton walls is consistent with ponding of late volatile-rich fluids beneath the pluton roof.

## 2.3. Host rock lithology and structure

The Agua Negra Formation comprises a coarsening upward sequence of interbedded quartz-rich sandstone, mudstone, and lesser conglomerate. In eastern, stratigraphically higher portions of the field area, prominent sandstone marker beds delineate the large-scale structure. Primary sedimentary structures are widely preserved and include bedding ( $S_0$ ), graded bedding, cross-bedding, ripples, and load casts in the sandy rocks, laminations and oscillation ripples in the mud rocks, and pebbles in the conglomerates. Younging indicators show that the section is everywhere upright. Hornfelsic contact metamorphism affects host rocks within several tens of meters along the pluton margin, and in a wider zone, up to a few hundred meters thick above western portions of the pluton roof. The highest grade rocks contain abundant biotite; cordierite is present locally.

The host rocks contain structures that predate and postdate emplacement of the Chita pluton. Two fold sets were mapped (Figs. 3b and 4). the first fold set is prominent in the map area and is parallel to the regional structural grain

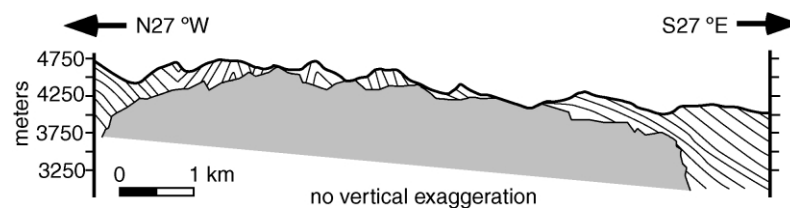


Fig. 5. Geologic cross-section of the Chita granite pluton (location in Fig. 3b). All relationships shown are exposed in the canyon of Chita creek, and have been projected laterally for short distances onto the line of section. The discordant pluton contact truncates host-rock bedding and folds shown as lines within the host rock.



shown in Fig. 2. Folds are open to tight and are upright with axes plunging gently to NNE ( $\pi$  axis =  $5^\circ$ ,  $023^\circ$ ). Minor folds are commonly W-vergent. It is not known whether this asymmetry relates to local shear-sense on the limbs of kilometer-scale folds, or to overall vergence of regional contractional structures. The second fold set consists of a single map-scale, open, upright, gently SE-plunging syncline ( $\pi$  axis =  $4^\circ$ ,  $125^\circ$ ) and associated minor folds. Both fold sets deform bedding ( $S_0$ ) and a bedding-parallel cleavage ( $S_1$ ).

Bedding orientations in the Agua Negra Formation are shown in Figs. 3 and 4. The data have been divided into three structural domains. Bedding in domain 1 dips homoclinally eastward, and defines the limb of a kilometer-scale syncline (Fig. 2). In domain 2, fold limb dips steepen and fold wavelength decreases from kilometers to several hundreds of meters. Domain 3 is defined by the SE-plunging syncline (fold orientation set two). Although minor folds show scattered orientations (Fig. 4), average orientations are sub-parallel to major fold axes in domains 2 and 3. Minor folds from both orientation sets occur in domain 1.

Two cleavages were mapped in the host rocks. An early, bedding-parallel, continuous slaty cleavage ( $S_1$ ) occurs widely in mud rocks of the Agua Negra Formation, but is weakly developed or absent in the sandstone. Where most intensely developed,  $S_1$  is associated with layer-parallel extension and boudinage of sand horizons. A second set of variably developed axial planar cleavages (collectively termed  $S_2$ ) are associated with both fold orientation sets and cut bedding and  $S_1$  (Fig. 5). In domain 1, axial planar cleavage tends to be weakly developed, and is expressed as a spaced, straight to anastomosing cleavage in fold hinge zones; pencil structures defined by cleavage/bedding intersection are common. In domains 2 and 3, axial planar cleavage is locally intensified and manifested as a penetrative slaty cleavage. When plotted by structural domain (Fig. 4),  $S_2$  shows significant scatter that is related to cleavage refraction between the sandstone and mudstone beds. In domains 1 and 2,  $S_2$  cleavage lies parallel to the dominant regional structural grain, with average strike  $018^\circ$ , and sub-vertical dip. Domain 3 axial planar  $S_2$  cleavage shows average strike and dip of  $331^\circ$ ,  $66^\circ$ NE.

Pre-emplacement faults primarily accommodated E–W contraction and apparently relate to the San Raphael orogeny. Only one map-scale, N-striking, E-dipping thrust

Fig. 6. Photographs of roof-wall transitions around the southern contact of the Chita pluton. (a) Shallowly dipping bedding truncated at roof-wall corner. (b) View of roof-wall transition. Road in foreground is at 3400 m while the roof crops out above 4500 m, indicating over 1100 m of exposure at this locality. Note jagged wall contact. (c) View from road looking obliquely up, to contact shown in lower half of (b). Note large xenolith (long dimension  $\sim 80$  m; noted with white arrow) within margin of Chita pluton adjacent to angular host rock contact. Black lines within pink granite are mafic dikes, white lines within gray host rocks are granitic dikes.

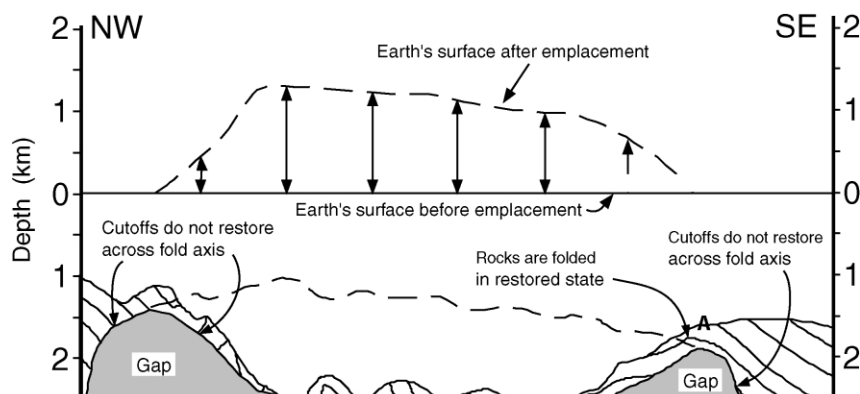


Fig. 7. Restoration of cross-section in Fig. 5. The upper diagram depicts the amount of upward deflection of the earth's surface that is required to account for the intruded area in cross-section (Fig. 5). If all space for the pluton was created by roof uplift then bedding cut-offs should restore and no gaps should be encountered. Note large gaps and unmatched bedding cut-offs. Note the map-scale anticline (A) that should be evident on the east-southeast side of the pluton. The cross-section implies a significant space problem; large amounts of host rock are missing. See text for details.

fault was observed. This fault has Agua Negra Formation in both the hanging wall and footwall and is bedding parallel for much of its trace. However, at one locality, the fault cuts down-section across at least 150 m of footwall strata, suggesting that it may have cut a pre-existing fold. In contrast, outcrop-scale west-vergent thrust faults and associated hanging-wall folds are common.

The pluton is cut by brittle, SE-striking, sub-vertical post-emplacement fault system with up to 500 m of sub-horizontal, left-lateral displacement. Many smaller SE-striking left-lateral faults offset the pluton contact at various locations (Fig. 3).

#### 2.4. Pluton/host-rock contact relations

The knife-sharp intrusive contact of the Chita pluton discordantly cuts across structures and bedding in the host rocks from map- to thin-section scales (Figs. 1 and 6). Both  $S_1$  and  $S_2$  cleavages are overprinted by hornfels texture in the contact aureole, indicating that they are older than the pluton, consistent with the observation of truncation of folds by the pluton. Locally,  $S_1$  is preserved in the inner contact aureole where it is cut by the pluton. Trajectories of host-rock structures show weak to no deflection from regional orientations (generally  $< 10^\circ$ ; Figs. 3b and 5). No map-scale gradients of emplacement-related ductile deformation were observed.

Sub-horizontal roof contacts can be traced continuously into subvertical wall contacts (Figs. 5 and 6). At outcrop-scale, the pluton contact consists of long, gently curvilinear contact segments that join at sharp corners, making steps and jogs at the scale of centimeters to a few hundreds of meters (Figs. 5 and 6b). Adjacent to the contact, undisrupted bedding surfaces in sand horizons, and pebbles with low axial ratios and bedding-parallel orientations in conglomerate indicate low intensities of ductile defor-

mation. There is no discernible evidence for shear or host-rock assimilation along the contact.

Within the pluton, swarms of small host-rock xenoliths occur near the host rock contact, and a few large xenoliths occur within a few hundred meters of the pluton roof (Fig. 6b and c). However, such xenoliths make up  $< 1\%$  of the exposed outcrop area. At the eastern pluton margin on the north side of Chita creek, several stoped blocks have been preserved in various stages of separation from the host-rock walls (Fig. 6). Internal structures within one large block are rotated relative to structures in adjacent host rocks, indicating complete separation from the walls. Pluton-derived dikes are locally abundant in host-rocks near the eastern pluton contact, but around other contacts of the pluton, dikes are uncommon. The dikes commonly cut across host-rock bedding, cleavage, and joints, showing little evidence for dike orientation controlled by host-rock anisotropy.

### 3. Discussion

#### 3.1. Constraints on emplacement mechanisms

Structural relations around the Chita pluton provide constraints on final pluton emplacement mechanisms. For example, the lack of ductile deformation at the roof and undeflected regional host-rock structures excludes strain fields typical of diapirs (e.g. Ramberg, 1981), hot-Stokes diapirs (e.g. Marsh, 1982), power-law diapirs (e.g. Weinberg and Podladchikov, 1994) or emplacement by ballooning (Dixon, 1975; Bateman, 1985; Schwerdtner, 1995). The physical continuity of the host-rock roof and walls rules out ring-faulting (e.g. Corry, 1988), while the lack of extension or detachment of the roof rocks precludes lateral dilational opening of the host rocks, whether linked to regional faults (e.g. Hutton, 1988), or to intra-arc extension (e.g. Hamilton,



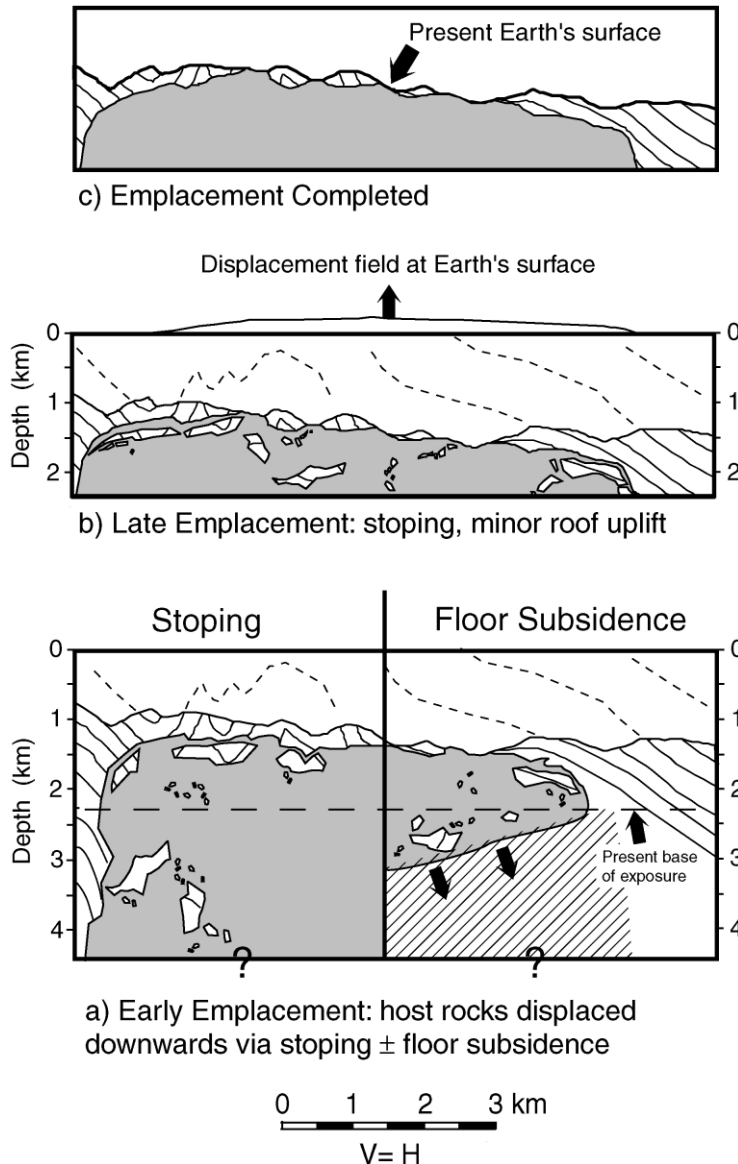


Fig. 8. Interpretation, to scale, showing three time steps in the emplacement of the Chita pluton. (a) Early pluton emplacement dominated by downwards displacement of host rocks. Diagonal-ruled area represents zone of ductile deformation that should accommodate floor subsidence. Although the early mechanisms are unconstrained, both stoping and floor-subsidence are permitted. Magnitude of surface doming is represented by changes in elevation of the pluton roof contact between the last two time steps, and by displacement of the upper cross-section boundary in the upper time step. (b) Final emplacement (middle time step) was accommodated by stoping with possible minor roof uplift. (c) The present day section. See text for discussion.

1995). Lastly, the fracture-like nature of the intrusive contact and the lack of migmatitic aureoles are inconsistent with appreciable host rock assimilation at the host rock contact. Therefore, it is concluded that the 3-D truncation of bedding and structures by the pluton requires removal of host-rock material from the present level of exposure. Structural and stratigraphic continuity of the roof and walls establishes a boundary condition indicating that the bulk of the missing material must have been displaced downwards through a conduit that is now represented by the solidified pluton.

Roof uplift and/or doming associated with laccolith formation are viable emplacement mechanisms at this depth. We have restored a cross-section through the Chita pluton in order to evaluate possible host rock doming above

the pluton roof during emplacement and to estimate the amount of displaced host rock material (Fig. 7). Validity of the restoration depends on assumptions that available mapping adequately characterizes regional structural trends distal from the pluton, and that any deviations from regional trends adjacent to the pluton were caused by pluton emplacement. The restoration was performed using the computer program GEOSEC version 4.1 (see Kligfield et al., 1986). Doming was simulated by a vertical simple shear algorithm. Although doming may have involved mechanisms other than vertical shear (e.g. inclined shear, flexural slip), use of alternative folding models does not significantly affect the results given below.

The restoration illustrates three main problems with a

roof-uplift interpretation for emplacement of the Chita pluton. First, at roof-to-wall transitions and along dozens of smaller steps and jogs, the pluton contact changes orientation abruptly without corresponding changes in orientation of host rock bedding (Figs. 5 and 6). Thus, bedding cutoffs cannot be closed across the contact jogs, resulting in large gaps in the restored section (gaps shown represent 25% of the cross-section area of the pluton; Fig. 7). Hundreds of meters of stratigraphic section have been cut away along the pluton walls, as documented by truncation of sandstone marker horizons on the east side of the pluton and by discordant bedding trajectories on the west side (Figs. 3b and 5). Second, lowering of roof rocks in the restored section creates a large anticline above the eastern end of the pluton (predicted amplitude > 700 m; predicted wavelength > 2 km; predicted bedding deflection ~ 60°; Fig. 7). If the pluton had intruded and unfolded an older anticline, the continuation of this fold (out of the plane of section in Fig. 7) should be exposed immediately north of the pluton's eastern margin (Fig. 3a). Mapping and air photos show homoclinal, east-dipping sand horizons (Figs. 2 and 3), thus such a fold does not exist. Third, bedding, fold axes and fold axial surfaces are virtually undeflected from regional orientations in the vicinity of the pluton (< 10°; Figs. 3b and 5). If roof doming had been significant, these older structures would be strongly deflected near the pluton.

Based on these observations and reconstructions of the Chita pluton, our preferred model for magma chamber construction is shown in Fig. 8. Magmatic stoping is inferred to have been the dominant process during final stages of magma chamber construction. This explains: (1) fracture-like, discordant intrusive contacts; (2) the lack of penetrative ductile deformation in the host rocks; (3) the large quantity of missing host-rock material; and (4) downward removal of the missing material. Based on deflections of host rock markers in the roof (e.g. bedding), we estimate that roof rocks above the center of the pluton have been domed upwards by 250 m (accounts for 15% of pluton's cross-section area), an amount consistent with observed 0°–10° deflections of host-rock strata and structures adjacent to the Chita pluton (Fig. 8). Although surface doming could have been slightly greater than is shown in Fig. 8, we argue that doming could not have accommodated more than a few tens of percent of the pluton's volume. Therefore, approximately 80% of the host rock space presently occupied by the Chita pluton must have been produced by downward displacement of the host rocks.

Magmatic stoping destroyed evidence for the early emplacement history. For example, it is possible that early emplacement of the Chita pluton involved ductile mechanisms within the host rocks, and that the deformed aureole rocks were subsequently removed as stoped blocks. However, preservation of the roof-wall transitions and vertically extensive wall exposures (Fig. 6) require that if such ductile aureoles were generated earlier in the emplacement history, then these aureoles would have to

be characterized by very high strain zones (e.g. Fig. 8a). Otherwise, we would expect to see evidence for ductile deformation adjacent to the walls of the pluton. Given the shallow level of emplacement, we suspect that host rock temperatures were probably not high enough and/or durations of heating not long enough to induce plastic deformation mechanisms that would accommodate formation of a high strain, ductile aureole.

The structural relations around the Chita pluton, as well as other plutons within the Colanguil batholith (e.g. Yoshinobu et al., 1995) establish a vertical host rock transport direction. In the broadest sense, construction of these plutons was accommodated by foundering of host rocks to levels below the present exposure. In Fig. 8 we depict early emplacement by two possible mechanisms: (1) stoping; and (2) subsidence of the host-rock floor and shearing away of host rocks along the pluton walls (e.g. Cruden, 1998). Both mechanisms effectively remove the plutonic 'space problem' to lower levels. However, geometric constraints provided by the extensive vertical exposure, truncated structures in the host rocks, lack of any tilted layering or other 'depositional' structures within the pluton (e.g. Wiebe and Collins, 1998), and lack of any pervasive ductile deformation in the host rocks of the Chita pluton lead us to conclude that stoping was the dominant mechanism at this level in the crust.

### 3.2. The efficacy of stoping

Theoretically, stoping should be an efficient mechanism to remove host rocks. From Daly (1933) onwards, various authors have concluded that thermal stresses adjacent to magmas are sufficient to shatter relatively cold, upper-crustal host rocks (e.g. Marsh, 1982; Furlong and Meyers, 1985; Clarke et al., 1998). Stokes-settling models predict rapid sinking of stoped blocks if they exceed a critical size (tens to a few hundred meters) that depends on magma viscosity and block/magma density contrast (Shaw, 1965; Marsh, 1982). Stoping is subject to geometrical and thermal limitations, as the pluton becomes choked with blocks if it ascends for a distance greater than two pluton diameters (Marsh, 1982). However, ascent of the Chita pluton by stoping for the final 2 km or more (i.e. 0.5 pluton diameter) is compatible with these geometrical and thermal constraints.

The lack of preserved host rock xenoliths within the Chita pluton attests to the apparent efficiency by which the discordant, fracture-like contact must be produced and the blocks removed. Where, then, are the 'graveyards of stoped blocks' (e.g. Marsh, 1982; Clarke et al., 1998)? This is a critical question in that discordant, unfaulted pluton-host rock contacts are common throughout the crust (e.g. Barnes et al., 1986; Saleeby, 1990; Paterson et al., 1996), yet stoped blocks are relatively rare. We suggest that even if stoping was the last emplacement-related processes before final crystallization, there is no a priori reason why the

blocks should be preserved in the pluton. The rate of block foundering is dependent on magma rheology, block size, and block density (Shaw, 1965; Paterson and Miller, 1998). Recent thermal and mechanical models suggest that sinking rates may be quite fast and that the viscosity of the magma may be sufficiently low to allow blocks to rapidly sink below the level of initial detachment (McLeod and Sparks, 1998; Paterson and Okaya, 1999). Refractory blocks are denser and prone to faster sinking rates, whereas less dense blocks (i.e. those not yet depleted by melting) are more prone to melt during convective heat transfer. In either case, thermal stresses will contribute to the overall disaggregation of blocks contained within the magma. Recent work by Clarke et al. (1998) on a metasedimentary block in the South Mountain batholith, Nova Scotia, indicates that continued disaggregation via thermal cracking, melting, and melt reinjection may aid in the ‘disintegration’ of the block into more digestible sizes. Thermal and mechanical modeling suggests that convective heat transfer adjacent to blocks 1–10 m in area may provide the necessary heat to aid in the mechanical and thermal disintegration of these blocks (Paterson and Okaya, 1999). Such a model may explain the apparent chemical contamination in many plutons by isotopically ‘crustal’ sources (e.g. Walawender et al., 1990; Green, 1994). Future studies should involve detailed geochemical and petrographic traverses at the outcrop and map scale, to evaluate the nature of potential chemical gradients associated with the disaggregation and mixing of stoped material (e.g. Clarke et al., 1998) and the potential existence of xenocrystic material.

#### 4. Conclusions

Continuous roof and roof-wall exposures of the Chita pluton, Colanguil batholith, NW Argentina provide constraints on the 3-D displacement of host rocks during magma chamber construction in the shallow crust. The pluton is rectangular in cross-section, having a gently dipping roof and steeply outward-dipping walls. Structures within the host rock adjacent to the pluton primarily reflect pre-emplacment regional contraction and show little evidence for emplacement-related, ductile deformation. These host-rock structures are truncated along a fracture-like intrusive contact and are only weakly deflected from their regional orientations. Widely preserved primary sedimentary structures indicate weak penetrative deformation within the contact aureole. Cross-section restoration of the Chita pluton suggests that host-rocks above the pluton may have been domed upwards during emplacement by a maximum of a few hundred meters, accounting for approximately 20% of the exposed pluton volume. The remaining 80% of the space for pluton emplacement was made by downward removal of host-rock from the map plane. We infer that magmatic stoping dominated emplacement of the pluton, and that late stoping destroyed evidence

for the early emplacement processes. Preservation of an essentially intact host rock envelope around the pluton roof and walls provides a geometrical boundary condition indicating that early pluton emplacement processes must also have involved some type of foundering of host rock material.

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