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Roof and walls of the Red Mountain Creek pluton, eastern Sierra Nevada, California (USA): implications for process zones during pluton emplacement

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Abstract

The Red Mountain Creek pluton has a sub-circular outline in map section, generally flat roof, and steep sides. The pluton roof sharply truncates host rock markers, has a highly irregular geometry with rectangular steps, and passes continuously into a steep wall. The roof–wall transition is not offset by faults and shows no evidence of extensive diking or synemplacement ductile strain, which requires that the pluton roof and its wall remained attached to each other and were not faulted or ductilely deformed during emplacement of the pluton. We propose that the exposed section through the Red Mountain Creek pluton may represent the crestal portion of a vertically extensive piston-shaped plutonic system, the upper part of which was largely emplaced by magmatic stoping although other material transfer processes may have previously operated during emplacement. Characteristics of the pluton roof presented in this paper as well as in other papers on pluton roofs directly rule out some emplacement models commonly applied to plutons in the Sierra Nevada, place limitations on other models, and fit well the expected characteristics of visco-elastic diapirs around which variable material transfer processes largely displace host rock downwards. In the upper-crustal plutons, the most widespread preserved process of downward transport of host rock was magmatic stoping.

Keywords: Pluton; Emplacement; Pluton roof; Magmatic stoping; Sierra Nevada

1. Introduction

Understanding of various aspects of pluton emplacement in magmatic arcs and orogenic belts is crucial to constrain a wide range of lithospheric processes since voluminous magmatism may drive heat flow (and thus metamorphism), control crustal rheology and regional deformation, as well as contribute to significant vertical mass exchange within the crust. Correct models of pluton emplacement are thus of great importance for evaluation of mechanisms and time- and length-scales of growth of continental crust in arcs and orogens.

Despite the scientific interest of plutons for several hundred years, no general consensus on pluton emplacement has been reached as yet. Instead, rather contradictory interpretations of emplacement, inferred three-dimensional shapes, and suggested vertical extents are applied, sometimes even to the same pluton. The reason for this is partially due to the complex nature and great variability of plutons but is largely due to the lack of three-dimensional exposures. Our understanding of pluton construction is commonly biased by very limited observations along pluton walls in two-dimensional horizontal map sections through plutons where their upper parts have been eroded off and their floors are not exposed leaving the three-dimensional shape and vertical extent largely a matter of speculation. The nature of contacts and aureoles near tops of plutons may differ remarkably from the sides as a result of changing depth (Buddington, 1959) or, alternatively, structures near the tops better reflect the dominant material transfer processes (i.e. MTPs of Paterson and Fowler, 1993) during ascent and emplacement, whereas pluton sides reflect more complex effects of continued heating, complex strain patterns, and later post-emplacement elastic rebound around plutons.

We are therefore faced with a challenging issue of how to rigorously test various pluton emplacement models within the limited ‘observation window’ that is usually significantly smaller than the vertical and horizontal scale at which plutons occur in the crust. From this perspective, we suggest that the

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best 'test sites' for placing constraints on emplacement processes are pluton roofs, that is, wall-rock in front of the magma path, and roof–wall transitions in the upper parts of plutonic systems. In our view, since any given emplacement mechanism results in rather different characteristics of the roof and roof–wall transition in a pluton, many ambiguities in interpreting emplacement are eliminated in cases where the pluton roof and particularly roof–wall transitions are preserved.

Assuming that magma is largely ascending upwards, and in some cases laterally at emplacement sites, then roof and intact roof–wall transitions can be viewed as the 'process zones' during ascent/emplacement, such as those previously described at dike tips (Rubin, 1995). It is in these regions that information is preserved on how host rock is displaced during rise/growth of magma chambers. One challenge in trying to evaluate magma ascent/emplacement is the recognition that many large plutons and batholiths have grown incrementally over time (Wiebe, 1996; Vigneresse and Bouchez, 1997; Miller and Paterson, 2001; Coleman et al., 2004). Thus it is necessary to search for evidence of multiple 'emplacement events' and to keep in mind that later magma pulses may intrude into earlier pulses, the latter of which thus become host rock to the younger pulses.

In the present paper, we examine the pluton roof and roof–wall transition of the Red Mountain Creek pluton, superbly exposed at Cardinal and Split Mountains, in the eastern escarpment of the central Sierra Nevada, California. Below we first consider what 'process zones' should look like for different end-member models of pluton emplacement that have been proposed in the literature. We then focus on the example of the Red Mountain Creek pluton and describe characteristics of its roof and roof–wall transition at different scales, three-dimensional pluton geometry, outcrop-scale roof structures and internal magmatic fabrics of the pluton. Finally, we use our field observations to test the main proposed emplacement models of Sierran plutons and then discuss more general implications of our study for pluton emplacement in magmatic arcs and orogenic belts.

2. Characteristics of 'process zones' during pluton emplacement

To emphasize the testable characteristics of a few end-member emplacement models we briefly consider what 'process zones' should look like for incrementally constructed (1) vertical dike complexes; (2) subhorizontal sill complexes or laccoliths; (3) fault-assisted plutonic complexes; (4) 'hot Stokes' diapirs; and (5) nested, visco-elastic diapirs.

Roofs of plutons constructed via diking mechanism (i.e. by accumulation of multiple dikes that cool below their solidi between injections; Coleman et al., 2004; Glazner et al., 2004) should consist of sheeted dike complexes (at least near the pluton walls and roof) with many preserved dike tips. Compositions and/or microstructures may vary from dike to dike and no chamber-wide pattern of zoning would be expected. We might also expect a very irregular roof–dike complex margin since there is no reason all dikes should stop at the exact same vertical position in the crust.

Tabular sill complexes emplaced by roof lifting (laccoliths) or floor down dropping (lopoliths) during folding or faulting should also preserve evidence for multiple, subhorizontal sills with many sill tips or fingers (e.g. Corry, 1988) extending out from the walls. Wall contacts might be highly irregular since sills of different composition or thickness should extend laterally different distances. Horizontal internal zoning may be possible within sills (fractionation, flow sorting) or throughout the chamber if thick sill layers are folded and cut by a subhorizontal erosional surface. Otherwise compositions and microstructures should vary vertically in the chamber but maintain some consistency from wall to wall. If roofs are preserved, they should preserve faults or shear zones and show upward deflection of host rock units defining an antiformal, roof-parallel geometry.

Fault-assisted plutonic complexes, such as emplacement into normal faults during regional extension (e.g. Hutton et al., 1990; Koukovelas and Pe-Piper, 1991), into shear-zone terminations (Hutton, 1988) or into dilatational domains within large strike-slip systems (e.g. Guineberteau et al., 1987; Morand, 1992; Tikoff and Teyssier, 1992), should produce roofs (and/or floors) detached from their walls along a pluton-scale, syn-emplacement fault or shear zone (Paterson and Fowler, 1993). The main regional fault(s) should extend away from the pluton in the roof or near the walls and growth of the plutonic complex should be closely linked to the slip rate of the fault (Yoshinobu et al., 1998). There is no a priori reason to expect compositional zoning in these bodies, but it also cannot be ruled out, particularly if chamber growth rates are fast enough to form a steady state chamber (Yoshinobu et al., 1998).

Two main types of diapiric complexes have been proposed in the literature: 'hot Stokes' diapirs (e.g. Marsh, 1982) and visco-elastic diapiric complexes (e.g. Miller and Paterson, 1999). Roofs of the former should show large strains formed by margin parallel ductile flow of host rocks in both roofs and walls with these strains following well known strain paths (e.g. Schmeling et al., 1988). Large ductile flattening strains should be recorded in the pluton aureole with the maximum shortening direction (Z axis of the finite strain ellipsoid) oriented roof- and wall-perpendicular (i.e. vertical in roof and horizontal in wall). Internal and host rock characteristics of hot Stokes diapirs have been discussed in detail by Clemens (1998). Pluton shapes can be 'tear-dropped' or cylindrical (Marsh, 1982), and chamber-wide zoning can easily form with the zoning showing at least a weak relationship to the pluton margins.

Miller and Paterson (1999) have argued that visco-elastic diapirs are expected to have both complex internal and host rock behavior that temporally evolves. These diapirs may consist of a few to many internal pulses, have variable shapes (but are typically piston-shaped), and have host rock displaced by a range of ductile to brittle processes. Compositional zoning is common in these bodies either due to nesting of magma pulses or crystal fractionation (Paterson and Vernon, 1995). Paterson et al. (1996) and Miller and Paterson (1999) note that host rock displacement is often downwards during rise of these diapirs (stratigraphic markers roll inwards and down structural aureoles) and that roof characteristics vary from ductile concordant examples to brittle, highly discordant examples. One common process during the rise of visco-elastic diapirs is magmatic stoping (Miller and Paterson, 1999; Pinotti et al., 2002; Žák et al., in press). Stoping results in highly discordant, stepped, intrusive contacts (Mahood and Cornejo, 1992; Pinotti et al., 2002) that cut off host rock markers along opening-mode (mode I) fractures and that abruptly pass into steep walls with little or no evidence for syn-emplacement ductile strain or offset by faulting.

Ambiguities in interpreting pluton emplacement processes are greatly exemplified in the Sierra Nevada Batholith, where several rather contradictory models were applied to explain emplacement of plutons in the batholith. For example, Cruden et al. (1999) and Bartley et al. (2000) argued for regional laccolith/lopolith-type emplacement. Other workers explained emplacement of Sierran plutons as a result of ballooning and lateral expansion of host rocks (e.g. Bateman and Chappell, 1979). Tikoff and Teyssier (1992) suggested that Sierran plutons were emplaced into dilatational domains between P-bridges associated with crustal-scale strike-slip systems resulting from oblique plate convergence. Paterson and Vernon (1995) suggested diapir-like emplacement of nested magma pulses with laterally and vertically variable MTPs. Glazner et al. (2003, 2004) and Bartley et al. (2002) proposed that some of the Sierran plutons were emplaced by amalgamation of innumerable dikes that solidify between injections, or were injected along gently dipping brittle fractures to form laccoliths or lopoliths (Bartley et al., 2000). All these models are readily testable by careful examination of structures in the crestal portions of plutons and their roof–wall transitions.

3. The Red Mountain Creek pluton

The Jurassic Red Mountain Creek pluton of the Palisade Crest Intrusive Suite (Bateman, 1992) crops out in the eastern escarpment of the central Sierra Nevada, California, USA (within Mount Pinchot and Split Mountain USGS 15 minute map quadrangles; Fig. 1). In map view, the pluton is ~4× 5 km, its lower part is covered by Quaternary sediments and talus to the east (~2000 meters above sea level), whereas its roof is superbly exposed at ~4000 m on the east face of Split Mountain and the northeast and southwest faces of Cardinal Mountain. The pluton consists of a nested pair of intrusions of the outer leucogranite of Red Mountain Creek and the inner leucogranite of Taboose Creek (Bateman, 1992). Both leucogranites typically contain less than 1% biotite; the former is medium-grained whereas the latter is fine-grained. The leucogranite of Taboose Creek has a mottled texture that may reflect loss of volatiles during crystallization and was interpreted as a residual core magma of the outer leucogranite of Red Mountain Creek (Bateman, 1992).

The pluton roof is exposed to the north and west of the Red Mountain Creek pluton (i.e. structurally above). The roof is made up of thin discontinuous segments of a metamorphosed sedimentary unit that was intruded along a subhorizontal contact by the Jurassic (~164 Ma U–Pb age; Chen and Moore, 1982) Tinemaha pluton making up the uppermost part of the exposed section to the north and northwest of the underlying Red Mountain Creek pluton. The metasedimentary unit consists of interlayered metapelites, metasiltstones, metapsammites, metaquartzites, and marbles. Based on the lithological characteristics, this unit may correlate with the Precambrian–Lower Cambrian Campito and Poleta formations of the Inyo Mountains (Bartley et al., 2000; see Stevens and Greene (1999) for an overview of stratigraphy of the roof pendants of the eastern Sierra Nevada). The Tinemaha pluton in the study area is composed of medium-grained monzogranite to granodiorite (Tinemaha Granodiorite) that is weakly porphyritic with phenocrysts of K-feldspar, large euhedral hornblends and abundant microgranular enclaves. All of these units are crosscut by numerous ~NW–SE basaltic dikes of the Late Jurassic and Cretaceous Independence dike swarm (Chen and Moore, 1979; Glazner et al., 1999; Coleman et al., 2000) and were intruded by the ~92 Ma Lamarck granodiorite (Coleman et al., 1995) to the east and other younger Cretaceous plutons to south.

4. Geometry of the exposed part of the pluton

4.1. Overall shape of the exposed part of the pluton

Cardinal and Split Mountains and the adjacent area in the eastern escarpment of the Sierra Nevada exposes a ~2 km vertical section through the roof and roof–wall transition of the Red Mountain Creek pluton (Figs. 2–5) allowing us to establish the three-dimensional shape of the exposed part of the pluton. In the map-view the pluton has a sub-circular outline. On Cardinal and Split Mountains, the pluton roof has a nearly sub-horizontal or gently dipping orientation and abruptly changes to a steeply dipping or sub-vertical pluton wall at the wall–roof transition. Hence, the overall shape of the exposed part of the pluton is a vertically oriented, piston-like cylinder with steep walls and flat roof. No floor is exposed, leaving the total thickness of the pluton uncertain.

4.2. Pluton roof

The generally cylinder-like geometry of the pluton roof and walls revealed from examination of photographs of steep cliffs is more complex in detail. On the southwest and northeast faces of the Cardinal Mountain ridge the roof is made up of metamorphosed clastic and calc-silicate sedimentary rocks of the Precambrian and Lower Cambrian Campito and overlaying Poleta Formations (Bartley et al., 2000). Here, the roof has large straight subhorizontal or gently SW dipping segments (Figs. 3 and 5). In places, however, the intrusive contact takes large steps. In other segments the roof is intruded by contact-parallel (subhorizontal) granite sheets. Several host rock blocks are preserved in the granite below the roof.

On the east face of Split Mountain (Fig. 4), the pluton roof, made up of the metasedimentary rocks of the Campito

Formation and the overlying Tinemaha Granodiorite, becomes more complex. The Campito Formation forms several irregular discontinuous segments in the roof that are intruded by the Tinemaha Granodiorite (Figs. 1 and 2). The Campito–Tinemaha contact is complex, often strongly sheeted consisting of thin subhorizontal sheets of the granodiorite separated by thin metasedimentary septa. The underlying Red Mountain Creek leucogranite intrudes the metasedimentary host rock along a highly irregular intrusive contact with many steps. In places, the leucogranite is juxtaposed against the Tinemaha Granodiorite and the sediments of the Campito Formation are entirely missing. In other places, where metasedimentary rocks are preserved, roof-parallel sheets of leucogranite intrude the roof suggesting they break up and spall off the metasedimentary rocks. Only rare, steeply to moderately dipping dikes from the Red Mountain Creek leucogranite intrude the roof. Abundant host rock blocks are seen all over the vertical face (Fig. 4) in the leucogranite below the roof.

4.3. Roof–wall transition and pluton wall

The flat-lying roof abruptly changes its orientation and passes continuously into a steep pluton wall making a sharp corner (Fig. 2a and b). No offsets of contacts between the Red Mountain Creek leucogranite and overlying metasedimentary rocks of the Campito Formation, nor offsetting of

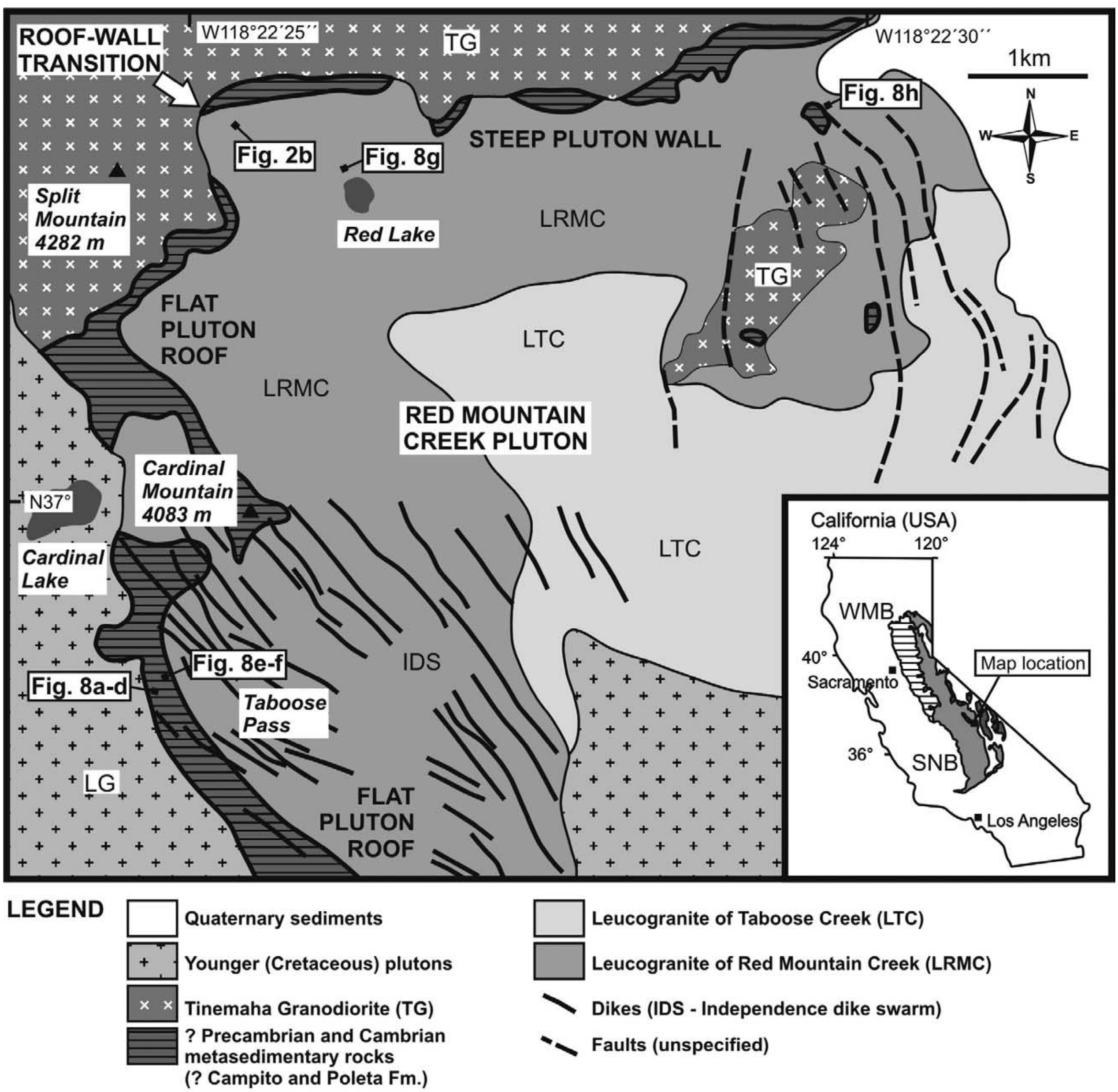


Fig. 1. Simplified geologic map of the exposed part of the Red Mountain Creek pluton (Quaternary is largely omitted). The pluton is made up of two nested intrusive units; the outer leucogranite of Red Mountain Creek and the inner leucogranite of Taboose Creek. The pluton roof, represented by the metasedimentary rocks Campito and Poleta Formations, passes continuously into a steep pluton wall. Inset map shows location of the pluton within the Sierra Nevada Batholith (California, USA). Small boxes indicate locations of field photographs. LG—Lamarck Granodiorite, SNB—Sierra Nevada Batholith, WMB—Western Metamorphic Belt.

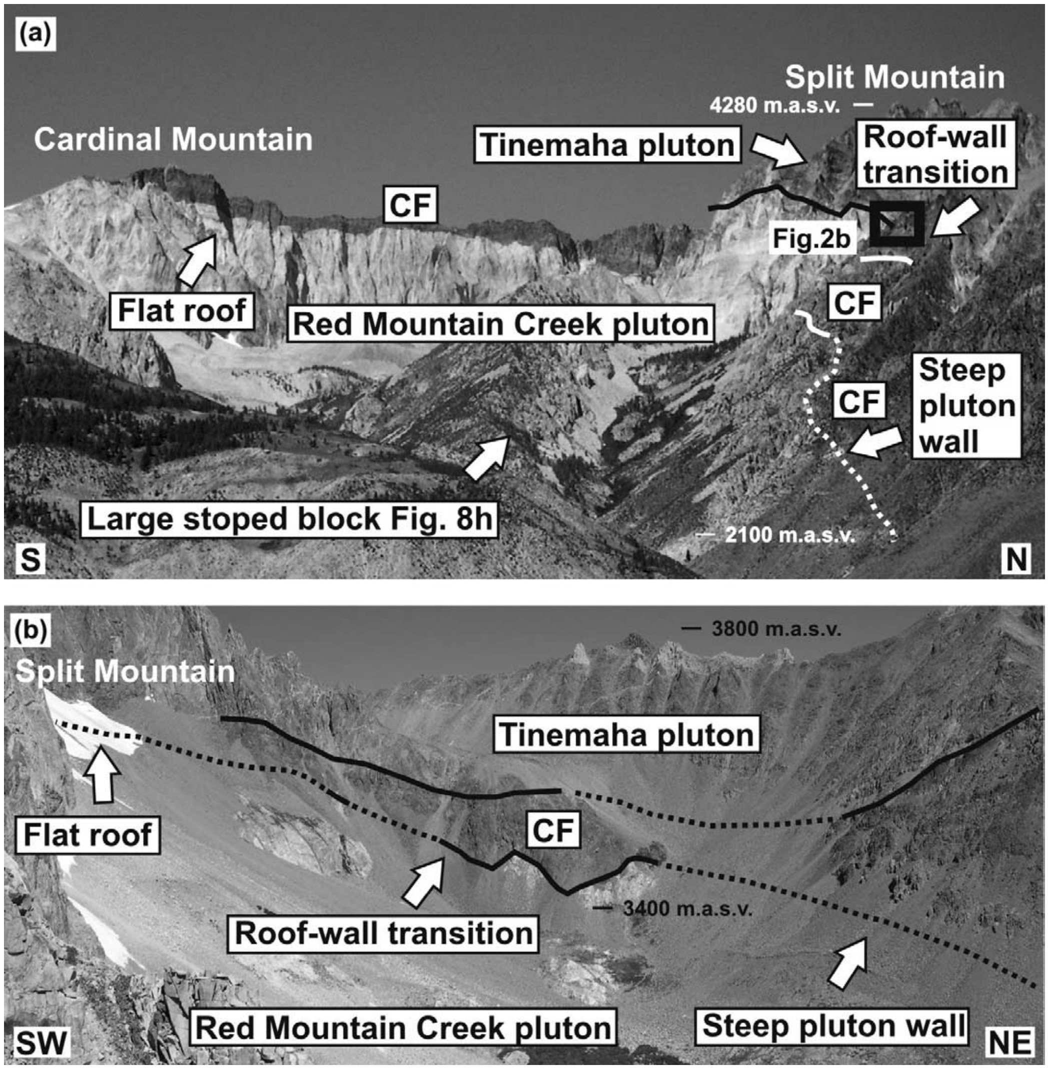


Fig. 2. (a) Photograph of the Split and Cardinal Mountains area showing exposed flat-lying roof, roof–wall transition and steep wall of the Red Mountain Creek pluton. View is looking west; the vertical relief of the exposure is more than 2 km. (b) Detail of roof–wall transition exposed to the NW of Red Lake. The flat-lying roof continuously passes into the steep pluton wall with no off-sets or deflection. Note large rectangular steps at the roof-wall transition.

the contact between the metasedimentary rocks and the uppermost Tinemaha Granodiorite are observed at the roof–wall transition (Fig. 2a and b). Instead, the contact is smoothly curviplanar and continuous on all exposed outcrops. In some places the contact forms several large steps forming rectangular corners of host rock intruded by the pluton. Further to the east (structurally downward), the steeply oriented pluton wall is made up by discontinuous thin slices of the metasedimentary rocks of the Campito Formation; in some places the metasedimentary rocks are entirely omitted where the leucogranite is in contact with the Tinemaha Granodiorite.

5. Structural pattern

In this study, we mapped only limited accessible parts of the Red Mountain Creek pluton and its roof in the Red Lake and Taboose Pass areas because large parts of the pluton are exposed on steep mountain faces or are covered by talus and moraines.

Structural pattern of the roof metasedimentary rocks is defined by a widespread metamorphic foliation (schistosity and compositional banding) bearing a stretching lineation (Figs. 6, 7 and 8a and b). The foliation is homogeneously oriented in the pluton roof, strikes ∼NE–SW, and dips steeply to moderately to the SW or NE. The stretching lineation plunges steeply to the SW or NE (Figs. 6 and 7). Variations in fabric ellipsoid symmetry are observed in the pluton roof with domains of plane-strain LS (foliations and lineations are equally developed) alternating with domains of flattening fabric (pinch-and-swell and chocolate-table structures are present, lineation absent; Fig. 8a and c). Locally the metamorphic foliation is complexly folded into tight to isoclinal folds.

In the Tinemaha Granodiorite, the magmatic fabric is defined by the alignment of large euhedral hornblends and micrograniotoid enclaves and is typically sub-parallel to the bottom contact of the granodiorite, i.e. is subhorizontal or gently to moderately dipping (∼20–40°) with variable strikes (Figs. 6 and 7). However, along contacts with metasedimentary rocks of the Campito Formation the structures (fabrics, enclave alignment, intrusive relationships) in the Tinemaha Granodiorite are more complex (Fig. 8d).

The contact between the Red Mountain Creek pluton and the overlying roof, made up of the metasedimentary rocks of the Campito Formation, is typically sharp, truncating structures in the roof at the centimeter-scale. Locally, leucocratic aplitic to pegmatitic dikes intrude the roof and discordantly cut across the roof host rock foliation and folds, or leucocratic dikes pervasively intrude and break up the strongly foliated host rock (Fig. 8e and f).

The structures in the leucogranites of Red Mountain Creek and Taboose Creek are characterized by very weak or no mesoscopically discernible magmatic fabric. The magmatic fabric, where present, is defined as weak planar preferred shape orientation of platy biotite crystals (magmatic foliation) and has variable orientations. No magmatic lineations or biotite zone axes were observed. In the Red Lake area, the steeply dipping magmatic biotite foliations strike ∼NW–SE. Thus the foliations are at a high angle to the pluton/roof contact, or are gently (∼20°) to moderately dipping to the NW (Figs. 6 and 7), and typically are subparallel to the gently dipping pluton roof but are at a high angle to the pluton wall. Aside from the mineral fabrics, other magmatic structures (e.g. schlieren, enclaves) are very rare or absent. No field evidence for internal sheeting or diking is preserved throughout the pluton, the leucogranites of Red Mountain Creek and Taboose Creek are typically compositionally and texturally very homogeneous.

Several meter to tens of meters scale stoped blocks of both metasedimentary rocks and granodiorites very similar to Tinemaha Granodiorite occur within the Red Mountain Creek leucogranite (Fig. 8g and h). These blocks are entirely engulfed by the leucogranite and are presently exposed in positions up to several hundred meters below the pluton roof. As an example, a stoped block of Tinemaha-like granodiorite (20 m in diameter) occurs NW of Red Lake (Fig. 8g) and is entirely enclosed and intruded by the leucogranite and is preserved several hundred meters below the roof. The stoped block shows in its present-day position sub-vertical internal igneous layering striking N40°W that is overprinted by a sub-vertical magmatic foliation striking S50°W, orientations that are not observed elsewhere in the Tinemaha Granodiorite where exposed in the pluton roof. No dikes or lithological contacts were observed near or at block margins; the leucogranite around the block is compositionally and texturally homogeneous. The position within the leucogranite several hundred meters below the roof, the orientation of internal fabrics of these blocks, and the homogeneity of the leucogranite around the block indicate that they were stoped from the pluton roof, were rotated and sunk into the chamber and do not represent in situ rafts along former sill margins.

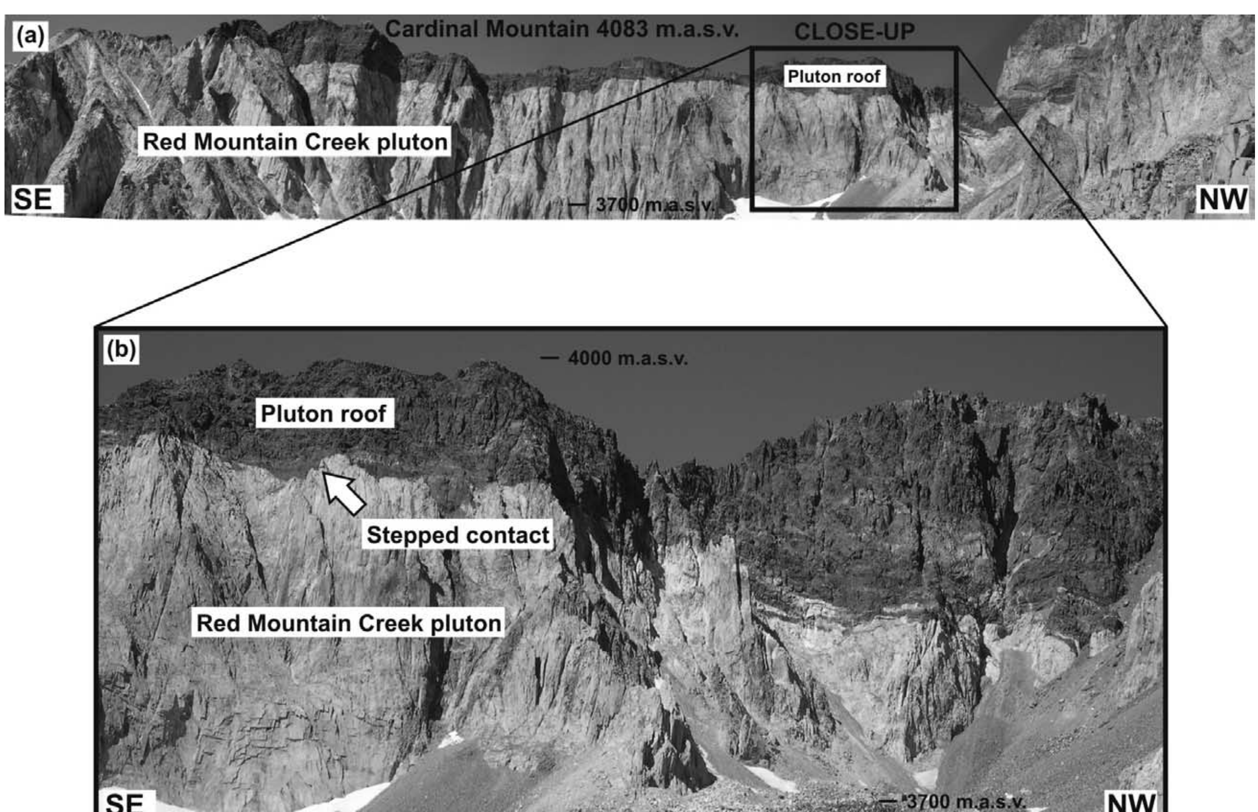


Fig. 3. Photomosaic (a) and close-up (b) of the northeastern face of Cardinal Mountain (looking southwest). The pluton roof is sub-horizontal or gently dipping and has straight segments but also several large rectangular steps. Note the absence of dikes in the pluton roof. The height of the face is approximately 300 m.

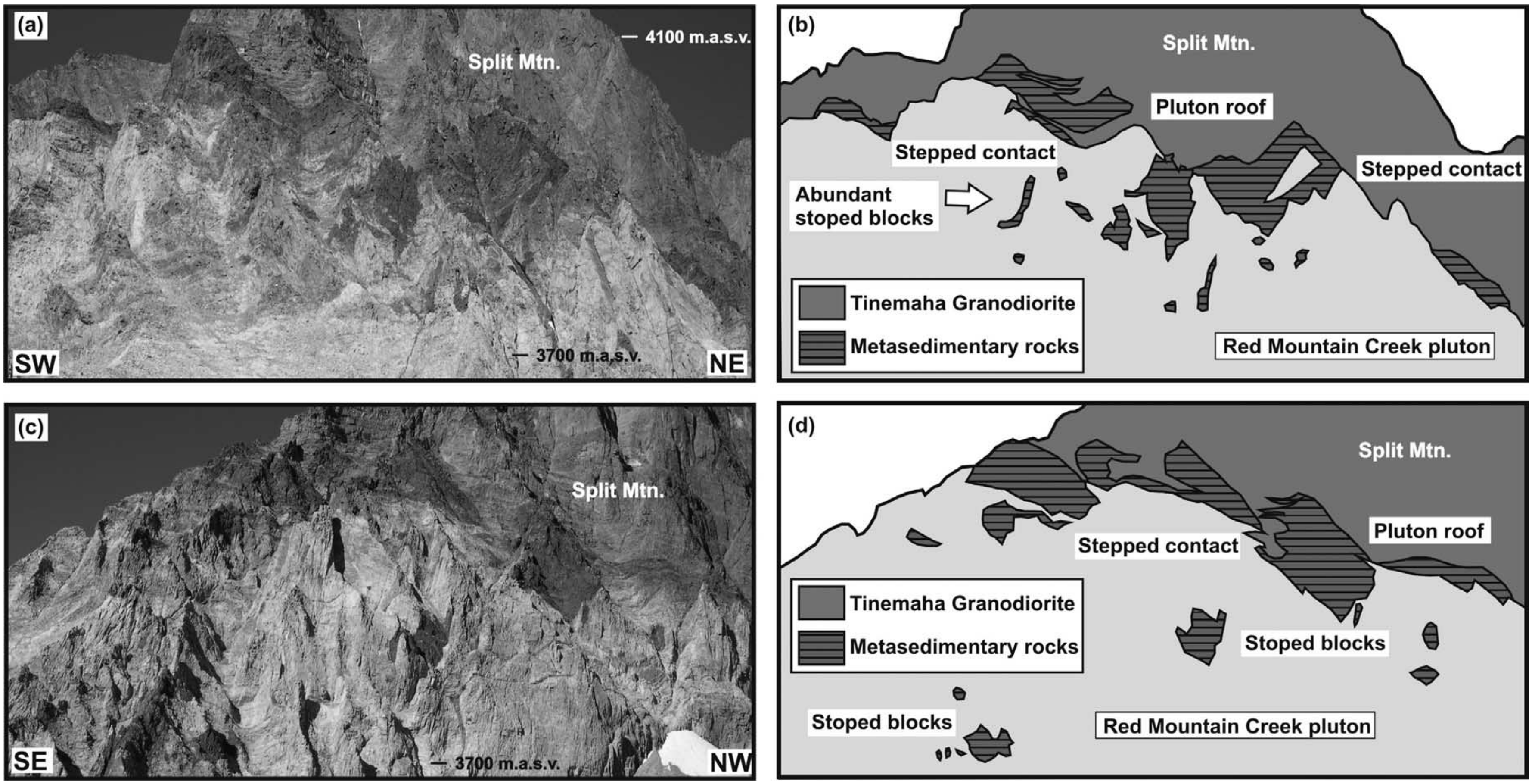


Fig. 4. Photos and line drawings of the southeast ((a) and (b)) and northeast ((c) and (d)) faces of Split Mountain, looking northwest and southwest, respectively. The pluton roof here is highly irregular in detail with many rectangular steps and abundant large stoped blocks of metasedimentary rocks of the Campito Formation that were apparently detached and transported downward from the roof. Note the absence of dikes in the pluton roof. The height of the cliffs is 400 m.

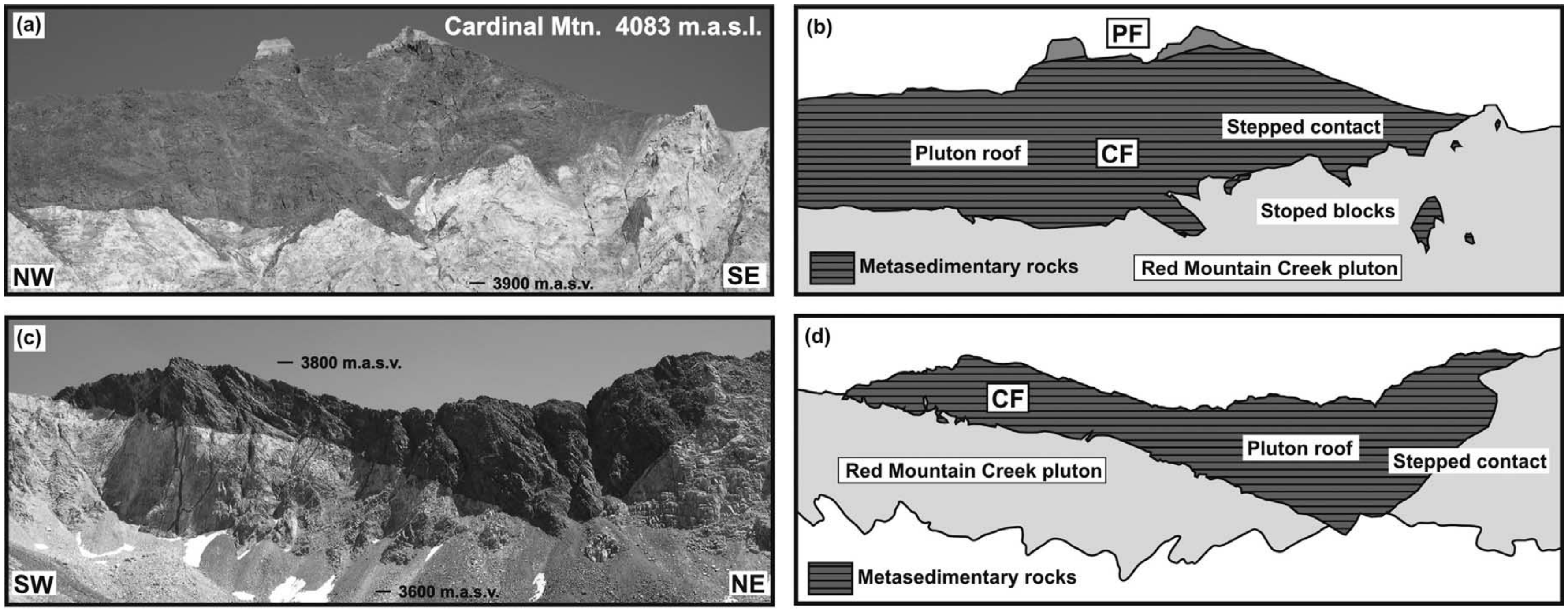


Fig. 5. Photos and line drawings of the southwest ((a) and (b)) and north ((c) and (d)) faces of Cardinal Mountain, looking northeast and south, respectively. The pluton roof is irregular in detail with several rectangular steps and stoped blocks that were apparently detached and transported downward from the roof. The height of the cliffs is 100–200 m. CP—Campito Formation, PF—Poleta Formation.

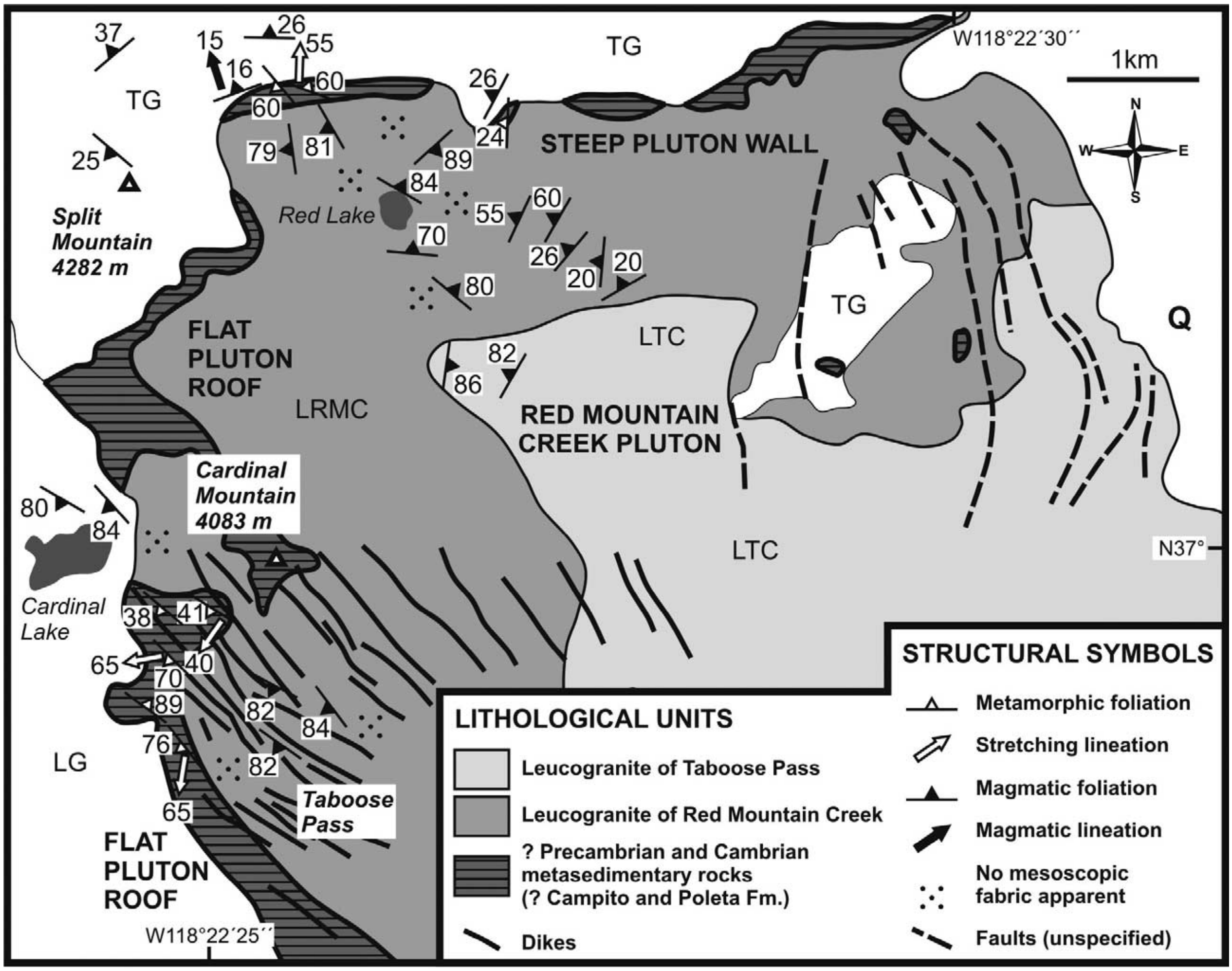


Fig. 6. Structural map of the accessible part of the Red Mountain Creek pluton and its roof. LG—Lamarck Granodiorite, TG—Tinemaha Granodiorite.

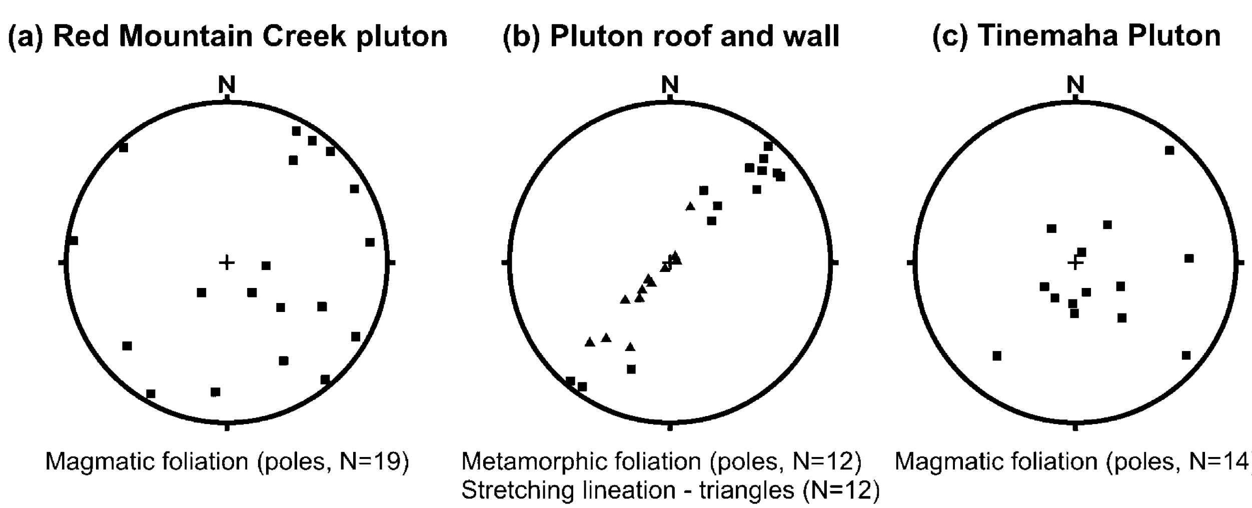
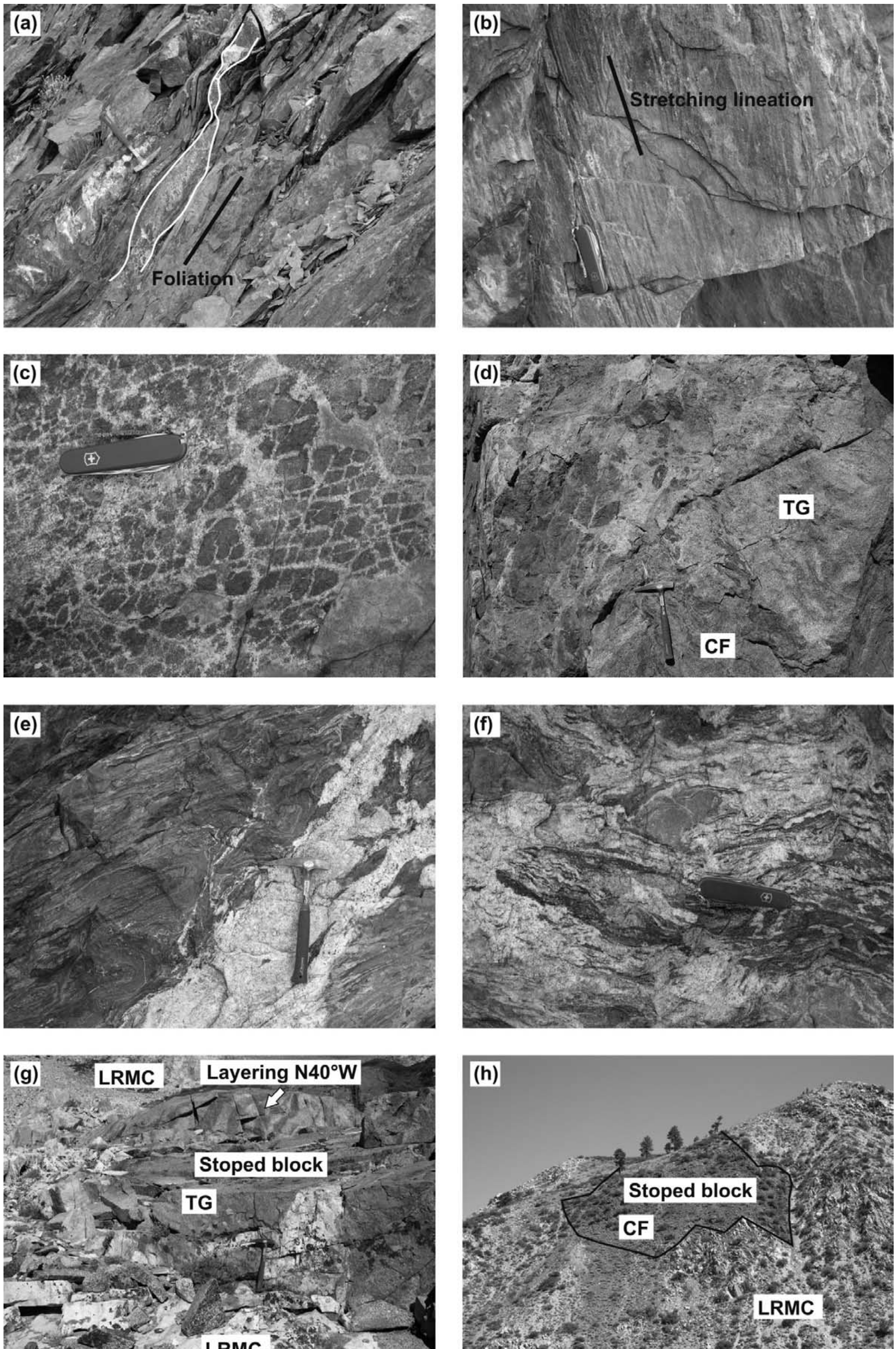


Fig. 7. Equal area stereonets showing orientation of main structural elements (a) in the leucogranites of the Red Mountain Creek pluton, (b) in the pluton roof metasedimentary rocks, and (c) in the Tinemaha pluton.


(a)
Foliation
(b)
Stretching lineation
(c)
(d)
TG
CF
(e)
(f)
(g)
LRMC
Layering N40°W
Stoped block
TG
LRMC
(h)
Stoped block
CF
LRMC

6. Discussion

6.1. Interpretation of emplacement of the Red Mountain Creek pluton

Bartley et al. (2000) interpreted emplacement of the Red Mountain Creek pluton and the overlying Tinemaha pluton as a result of injection of magma along gently dipping brittle fractures to form laccoliths and/or lopoliths. They suggested that the plutons began as injection of dikes and that the interpluton screen at Cardinal and Split Mountains formed by opening of subparallel fractures that admit magma (Bartley et al., 2000). Thus, in their model, sharp fractured contacts record intrusion of dikes rather than stoping of blocks from the roof of a large magma body. Based on presumed lack of stoped blocks in the leucogranite they also stated that stoping was unimportant during emplacement of the Red Mountain Creek pluton (Bartley et al., 2000).

In the present paper, we have shown that the exposed part of the Red Mountain Creek pluton has a sub-circular outline in horizontal map section and a generally flat roof and steep walls. Hence, the three-dimensional shape of the upper part of the pluton resembles a vertically-oriented piston-shaped cylinder the bottom and vertical extent of which is unknown. Our examination of the roof–wall transition revealed that the pluton roof continuously passes into its steep wall, is not off-set by any fault and shows no evidence for extensive diking or syn-emplacement ductile strain. Although generally flat, the pluton roof is discordant, sharply truncates host rock markers and has a highly irregular geometry in detail with common rectangular steps. Rectangular stoped blocks, typically bounded by knife-sharp margins, are preserved in the leucogranite below the roof and their internal fabrics are not parallel to fabrics observed elsewhere, indicating that they were detached from roofs, rotated and sank into the chamber.

Based on the above, we argue that the field data presented in this paper place severe constraints on emplacement processes of the exposed upper part of the Red Mountain Creek pluton and place significant doubt on the model proposed by Bartley et al. (2000). For example, continuous transition from flat pluton roof to sub-vertical wall rules out faulting and laccolith-like roof uplift during emplacement, since both of these processes require detachment (off-set) or deflection of the roof with respect to the pluton wall; no syn-emplacement faults nor deflections of host rock markers were observed in the overlying Campito Formation nor in the Tinemaha Granodiorite above the Red Mountain Creek leucogranite. No emplacement-related ductile deformation related to pluton emplacement was observed in the host rocks above the pluton or in the pluton wall. Instead, host rock markers are typically sharply truncated by pluton contacts. Thus the preserved segments of pluton roof and wall remained fixed relative to one another and were not extensively deformed during emplacement of the leucogranite. The vertical extent of the Red Mountain Creek pluton is unknown and its floor unexposed; thus there is also no field evidence for floor subsidence to form a lopolith-like intrusion although this mechanism is permissive.

Moreover, no granitic dikes were observed in the pluton and only little granitic dikes intrude the host rock making up the roof or walls. The Red Mountain Creek pluton is compositionally very homogeneous in general and shows no field evidence for internal diking or sheeting as should occur when constructed via injection of multiple dikes. Instead, the pluton consists of two nested cylinder-shaped intrusions with steep walls (Bateman, 1992; this study), a geometry which is unlikely to have formed by amalgamation of subhorizontal multiple dikes (sills). The host rock blocks found within the leucogranite several hundred meters below the roof were clearly rotated and have no dikes or internal contacts at their margins. Instead, they are entirely engulfed in homogenous leucogranite; thus there is no field evidence that they are in situ rafts isolated between separate sheet-like intrusions.

Therefore, we propose an alternative model for emplacement of the upper part of the Red Mountain Creek pluton. We have shown that large sections of the roof/pluton contact are sharp, discordant, commonly have stepped geometry, and that large blocks of the overlying host rocks are seen up to several hundred meters below the roof. All the above can be interpreted as a result of magmatic stoping, i.e. thermal cracking and downward transport of host rock blocks into a magma chamber where ascending magma replaces the blocks (Daly, 1903; Marsh, 1982; Furlong and Myers, 1985; Pignotta, 1999; Pignotta and Paterson, 2001; Pignotta et al., 2001a,b). A continuous stepped roof–wall transition, not off-set by faults, also provides direct evidence for magmatic stoping as has been shown by Yoshinobu et al. (2003) and Paterson and Miller (1998). Hence, we may assume that the exposed section through the Red Mountain Creek pluton may represent the crestal portion of vertically extensive piston-shaped plutonic system the upper part of which was largely emplaced by stoping. We suggest that other material transfer processes may have operated earlier during emplacement of the pluton; however, the evidence for these processes are not preserved due to removal of large sections of host rock by later stoping.

Fig. 8. Photos of outcrop-scale structures in the Red Mountain Creek pluton and its roof (see Fig. 1 for locations). (a) Foliation (? bedding) in the metasedimentary rocks of the Campito Formation, moderately dipping to the southwest. Pinch-and-swell structures indicate foliation-perpendicular shortening. (b) Stretching lineation plunging to the southwest, metasedimentary rocks of the Campito Formation. (c) 'Chocolate table' structure (looking at foliation plane) filled by a melt indicating oblate strain in the pluton roof, metasedimentary rocks of the Campito Formation. (d) Irregular intrusive contact between the Tinemaha Granodiorite (TG) and metasedimentary rocks of the Campito Formation (CF). (e) Irregular leucocratic sheet intruding discordantly to the complexly folded metasedimentary rocks of the Campito Formation, several meters above the pluton/roof contact. (f) Foliated metasedimentary rocks of the Campito Formation that are pervasively intruded and disrupted by leucocratic melts, several meters above the pluton/roof contact. (g) Block of the Tinemaha-like granodiorite (TG) entirely enclosed within the leucogranite of Red Mountain Creek (LRMC). The block (20 m across) is exposed several hundreds meters below the roof and its internal layering indicates that it has been stoped from the roof, transported downward and rotated. (h) Large stoped block of metasedimentary rocks of the Campito Formation (CF) bounded by rectangular stepped fractures and entirely engulfed within the leucogranite of Red Mountain Creek (LRMC).

The above characteristics of the pluton thus fit well that proposed for upper parts of visco-elastic diapirs with vertically variable material transfer processes (see Miller and Paterson (1999) for definition).

6.2. Implications for general problems of pluton emplacement

We believe that our study has several broader implications for studies of pluton emplacement in magmatic arcs and orogenic belts. By comparing our present work with other studies of roofs of upper-crustal plutons in arcs (e.g. Buddington, 1959; Myers, 1975; Mahood and Cornejo, 1992; Paterson and Miller, 1998; Yoshinobu et al., 2003; Žák et al., in press) we can summarize some of the most important common characteristics of their roofs and roof–wall transitions. In all the above mentioned cases, the pluton roofs are flat and discordant with abundant steps across which large sections of host rock are missing. The sharp pluton/roof contacts truncate pre-existing host rock markers and are not associated with syn-emplacement ductile strain or large-scale faulting, thus they represent opening-mode (mode I) fractures. During emplacement, pre-emplacement host rock markers in roof rocks indicate that these roofs were not detached or extended by faults or significantly displaced upwards or laterally with respect to other parts of the roof. If dikes are preserved in the roofs, they are commonly composed of highly-evolved volatile-rich residual melts (e.g. aplites, pegmatites) emanating from the magma chamber below and thus provide no record of initial chamber construction. Where roof–wall transitions are exposed, roof rocks above plutons are continuously attached to their walls; in every case these transitions are abrupt with flat-lying roof contacts rapidly changing into steep-sided wall contacts. Typically, no faults or fault zones crosscut or off-set the roof–wall transition.

We emphasize that ambiguities which may arise by interpreting pluton emplacement processes from two-dimensional horizontal map sections and/or discontinuous outcrops are largely eliminated when a roof and roof–wall transition is exposed. Characteristics of the pluton roof examined in this paper as well as other studies on pluton roofs directly rule out some emplacement models commonly applied to plutons in the Sierra Nevada and elsewhere (lateral or vertical translation by faulting, significant roof uplift, diking) and place severe constraints on others (ballooning, hot Stokes diapirism). All of the above indicates, however, that by whatever means host rock was displaced, the overall direction was downwards in the region now occupied by the pluton and its aureole. In the upper-crustal plutons examined, the most widespread process of downward transport of host rock now preserved in the rock record is magmatic stoping.

7. Conclusions

The exposed part of the Red Mountain Creek pluton has a sub-circular outline in horizontal map section, generally flat roof and steep walls; thus the three-dimensional shape of the upper part of the pluton resembles a vertically-oriented piston-shaped cylinder the bottom and vertical extent of which are unknown. The pluton roof sharply truncates host rock markers, has highly irregular geometry in detail with common rectangular steps, and continuously passes into its wall. The roof–wall transition is not off-set by faulting and shows no evidence for extensive diking, deflection or syn-emplacement ductile strain, indicating that the preserved segments of pluton roof and wall likely remained fixed and were not extensively deformed during emplacement of the leucogranite, which rules out faulting and laccolith-like roof uplift during emplacement.

We propose that the exposed section through the Red Mountain Creek pluton may represent the crestal portion of a vertically extensive piston-shaped plutonic system, the upper part of which was largely emplaced by voluminous magmatic stoping. Other material transfer processes may have operated earlier during emplacement, but are not preserved due to removal of large sections of host rock by later stoping.

We point out that ambiguities which may arise by interpreting pluton emplacement processes from two-dimensional horizontal map sections and/or discontinuous outcrops are largely eliminated when a roof and roof–wall transition is exposed. Characteristics of the many well-exposed pluton roofs directly rule out or place severe constraints on some models proposed to explain the emplacement of plutons in the Sierra Nevada and in magmatic arcs elsewhere. Instead, they fit well the characteristics of visco-elastic diapirs with vertically variable material transfer processes. Our present study indicates that by whatever means host rock was displaced, the overall direction was downwards in the region now occupied by pluton and its aureole. Magmatic stoping was the dominant process of downward transport of host rock in the upper-crustal plutons.

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