Construction of mid-crustal sheeted plutons: Examples from the North Cascades, Washington

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ABSTRACT

Large parts of many orogenic belts consist of highly elongate plutons constructed by the injection of multiple sheets of magma. We describe in detail two such intrusions, the deep (~20–25 km), mid-crustal Cardinal Peak and Entiat plutons, and emphasize the dynamic nature of these magma chambers. These ca. 72–73 Ma plutons consist of heterogeneous mafic complexes in their margins and tips that give way inward to thicker, but still abundant, sheets of tonalite. Intrusive and petrologic relationships provide evidence for injection of early mafic (mantle?) and crustal melts, development of heated pathways utilized by larger batches of more felsic magma, and potentially a filtering mechanism in which conduits represented by the plutons fed larger, more homogenized magma bodies at shallower crustal levels.

Well-developed, gently to moderately dipping magmatic and subsolidus foliations in these plutons are commonly discordant to sheet contacts, internal layering, and pluton contacts, but are continuous with host-rock foliation. They define small to map-scale magmatic folds, which have orientations and geometries similar to those of regional host-rock folds. These magmatic structures thus primarily record regional contractional tectonism during chamber construction.

Host rocks also record complex processes during chamber evolution with narrow structural aureoles displaying remarkable lateral variability. Deflection of gently to moderately dipping host-rock markers toward parallelism with steep pluton contacts indicates vertical and largely downward ductile material transfer along sheet margins during emplacement. Several sharply discordant segments of pluton contacts imply late stoping. Regional ductile flow and folding also played a role, but regional faulting did not. Further evidence for chamber construction is provided by host-rock rafts, which are abundant along sheet contacts in the Cardinal Peak pluton and particularly between marginal sheets of the Entiat pluton, but are sparse elsewhere in the latter pluton. We interpret these relationships to indicate a temporal sequence in which magmatic sheets initially intruded host rock, then wedged aside this rock and coalesced, preserving pieces of the host along margins, and eventually formed large, relatively inclusion-free chambers as host rock was detached and transported vertically downward through the chamber.

Keywords: aureoles, Cascades, magma chambers, plutons, sheets, structures.

INTRODUCTION

It is increasingly apparent that significant parts of some orogenic belts (e.g., Caledonide, Hercynian, Lachlan) consist of markedly elongate plutons that have been constructed by the injection of multiple “dike-like” sheets of magma (e.g., Pitcher and Berger, 1972; Hutton, 1992; Ingram and Hutton, 1994). Despite the recent emphasis on sheeted plutons, relatively few such intrusions have been described in detail in comparison to the many descriptions of elliptical to spherical plutons (e.g., see review in Pitcher [1993]). This deficiency is particularly true for mid- to deep-crustal (~20 km) plutons, which commonly have been overprinted by regional deformation. Controversial questions remain, such as, are these bodies constructed from dikes or elongate diapirs (e.g., Miller and Paterson, 1999), and do the highly elongate shapes reflect the regional stress field, structural anisotropy, or control by fault zones? (e.g., compare Hutton [1992] and Paterson and Schmidt [1999]).

The construction (growth of melt-present systems) of sheeted magma chambers also involves other unresolved issues. For example, does magma wedging and dispersal of host rock lead to coalescence of sheets and formation of larger chambers (Weinberg, 1999), or are chambers constructed by incremental addition of sheets into dilatant domains in fault zones? Alternatively, Wiebe and Collins (1998) suggested that sheet-like magma batches are emplaced at the base of an active chamber and the floor gradually sinks, allowing continued emplacement of sheets. A related question is, do sheeted plutons represent frozen conduits that fed larger magma chambers at shallower depths?

One example of an orogenic belt containing numerous highly elongate plutons is the Coast Plutonic Complex (e.g., Brew and Ford, 1981; Ingram and Hutton, 1994) and its southeast extension, the crystalline core of the North Cascades (Fig. 1). In the Cascades core, this intrusive style is particularly well shown in a 20–25-km-wide zone of highly elongate plutons, with aspect ratios in map view of >7:1 (Fig. 2). In this study, we focus on two of these spectacularly sheeted, mid-crustal (20–25 km depth) intrusions, the 72–73 Ma Entiat and Cardinal Peak plutons (Fig. 2). We describe the sheets and other internal structures in these intrusions, their contact relationships, and their structural aureoles. Host-rock rafts between sheets and their implications for construction of the plutons are described in detail. We emphasize the complexity of chamber-construction processes and emplacement mechanisms, examine relationships between internal structures and regional deformation during chamber construction, and propose a general model for construction of sheeted plutons based on these Cascades plutons.

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GSA Bulletin; November 2001; v. 113; no. 11; p. 1423–1442; 14 figures.
Figure 1. Location of Cascades crystalline core relative to other Mesozoic and Cenozoic plutons (black) in the Cordillera. Inset shows major features of the Cascades core and its offset from the southern end of the Coast Plutonic Complex. Cretaceous thrust belts include CBTS—Coast Belt thrust system, ECFB—Eastern Cascades fold-thrust belt, and NWCS—Northwest Cascades thrust system. SCF—Tertiary Straight Creek fault. Perpendicular dashes—plutons, parallel dashes—metamorphic units.

Figure 2. Regional geology of part of the eastern Cascades core emphasizing the Chelan block; location shown in Figure 1. CS—Chiwaukum Schist, H—Holden unit (Triassic protolith and includes Triassic Dumbell plutons and other orthogneisses), N—Napeequa Complex (Mississippian to Jurassic protolith), SG—Skagit Gneiss, SW—Swakane Gneiss. Ages of plutons (random dashes) are indicated. Chumstick basin consists of Eocene clastic rocks. Region around scale—Miocene Columbia River basalt.

Regional Setting

The >1500-km-long Coast Plutonic Complex and Cascades core preserve the mid- to deep-crustal structural, magmatic, and metamorphic record of Cretaceous and Paleogene continental-margin tectonics in the northwestern Cordillera (e.g., Monger et al., 1982; Tabor et al., 1989). The Cascades core is bounded on the west and northeast by major high-angle Tertiary faults (e.g., Misch, 1966; Miller, 1994) and on the south by a middle Cretaceous thrust (Miller, 1985). The major internal structure is the Tertiary Entiat fault (Figs. 1, 2) (Tabor et al., 1984), which divides the Cascades core into the Wenatchee and Chelan blocks (Haugerud et al., 1991).

Tabor et al. (1987a, 1989) delineated tectonostratigraphic terranes within the core that were assembled before Late Cretaceous plutonism and metamorphism. The Swakane terrane and Chelan Mountains terrane make up the Chelan block and host the Entiat and Cardinal Peak plutons. The Swakane terrane consists of biotite gneiss (e.g., Waters, 1932) and is structurally overlain by the Napeequa Complex of the Chelan Mountains terrane along a gently dipping tectonic contact (Tabor et al., 1987a). The Napeequa Complex is quartzite (metachert), siliceous schist, and amphibolite and minor metaperidotite and marble; the complex has an oceanic protolith (e.g., Tabor et al., 1989). The other major supracrustal units in the Chelan Mountains terrane are the Cascade River unit and correlative Holden assemblage, which are part of a Triassic arc sequence (Tabor et al., 1989). The Holden assemblage consists of amphibolite, hornblende gneiss, hornblende-biotite schist, and less abundant calc-silicate rock, leucocratic gneiss, biotite schist, and marble. It is intruded by the tonalitic, strongly deformed Triassic Dumbell plutons, which are the roots of the Holden—Cascade River arc (Tabor et al., 1989; Miller et al., 1994). To the southeast, the Holden unit is injected by numerous sheets and grades into the orthogneiss-dominated Chelan Complex (Tabor et al., 1987b; Hopson and Mattinson, 1994).

Crystallization ages (U-Pb zircon) of subduction-related plutons that intrude the terranes within the Chelan block range from ca. 91 to 45 Ma; the Cardinal Peak and Entiat plutons are part of a belt of 72–78 Ma plutons that lies on the southwest side of the block (Fig. 2) (Miller et al., 1989). Plutonism was accompanied by ductile deformation that was initiated before 91 Ma and was active in some domains until ca. 45 Ma (e.g., Tabor et al., 1989). Amphibolite-facies metamorphism of host rocks reached peak conditions of ~600–700 °C at 6–11 kbar (e.g., Whitney et al., 1999; Valley et al., 2000).

CARDINAL PEAK AND ENTIAT PLUTONS

The Cardinal Peak (Figs. 3, 4) and Entiat plutons (Figs. 5, 6) were chosen for study be-
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Individual inclusions—note dominance of Figure 4, and locations of mapped inclusions showing geology, lines of cross sections in Figure 3. Map of Cardinal Peak pluton.

Figure 3. Map of Cardinal Peak pluton showing geology, lines of cross sections in Figure 4, and locations of mapped inclusions (those shown represent many more individual inclusions—note dominance of amphibolite). BR—Bearcat Ridge Orthogneiss (89 Ma), EP—Emerald Park, H—Holden unit; RP—pre—latest Cretaceous Riddle Peaks Gabbro; SG—Skagit Gneiss; T—Tertiary plutons.

cause excellent earlier mapping at 1:62 500 and 1:100 000 (Cater and Crowder, 1967; Cater and Wright, 1967; Tabor et al., 1987b) indicated that they are highly elongate (length/width > 10:1) and extensively sheeted. They are also well exposed and have a total relief of >2 km.

These approximately coeval plutons (Mattington, 1972; Tabor et al., 1987b; Haugerud et al., 1991; Hurlow, 1992) consist of similar rock types (Figs. 3, 5) and have similar structural histories. Entiat tonalites crystallized at 6.0–7.2 kbar (Dawes, 1993) and Cardinal Peak tonalites yield pressures of 6–8 kbar (Parent, 1999), indicating crystallization depths of ~20–25 km, which are compatible with the metamorphic pressures revealed by the host rocks. In the following, we emphasize the similarities and differences of these plutons through a step-by-step comparison of the main features.

General Geology

The Cardinal Peak pluton is ~35 km by 3 km in map view (Fig. 3) and is narrower in the northwest, where it has a tip-like termination. The southwest and northeast sides dip steeply (>60°) along most of their lengths. The Holden assemblage hosts most of the pluton, and the 89 Ma Bearcat Ridge Orthogneiss and pre—latest Cretaceous Riddle Peaks Gabbro are locally in contact with the pluton on the northeast (Cater and Crowder, 1967; Cater and Wright, 1967).

The Cardinal Peak pluton displays major compositional variations both along strike and, in the northwest half of the pluton, from the margins inward (Figs. 3, 4). In the northwest, extensively sheeted mafic to granodioritic rocks, which we refer to as the mafic complex, form 50–500-m-wide marginal zones. The mafic complex is wider on the southwest side of the pluton and gives way inward and to the southeast to less extensively sheeted, hornblende-biotite tonalite, which along strike farther to the southeast grades into biotite tonalite and local granodiorite. The dominant tonalite consists of biotite + hornblende + plagioclase (An_{0–45}) + quartz + epidote + K-feldspar (Cater, 1982; Parent, 1999).

The Entiat pluton is ~80 by 8 km in map view (Fig. 5) (Cater and Crowder, 1967; Tabor et al., 1987b). It is buried by Miocene Columbia River basalt on the southeast (Fig. 2), narrows to the northwest where steep sheets are very abundant, and ends in several narrow, steep, overlapping bodies (Fig. 2). On the southwest, the pluton intrudes the Napeequa Complex along a moderate to steep, northeast-dipping contact; undated felsic orthogneiss of the Leroy Creek pluton hosts part of the northwestern tip (Figs. 5, 6). Along its steep northeast contact, the Entiat pluton intrudes the Chelan Complex at the southeast end and the Holden assemblage and Dumbell plutons to the northwest.

The largely tonalitic pluton resembles the Cardinal Peak pluton in the Entiat’s general trend from mafic to felsic from the margins toward the interior and from the northwest to southeast (Fig. 5) (Cater, 1982; Tabor et al., 1987b; Dawes, 1993). Mafic rocks are particularly abundant in the intensely sheeted northwestern part of the pluton, where they are not restricted to the pluton margins (Fig. 5). Most of the pluton interior is tonalite, consisting of hornblende + biotite + plagioclase (An_{0–45}) + quartz + epidote + K-feldspar (Cater, 1982). A >20 km² body of heterogeneous, sheeted leucocratic biotite granodiorite containing muscovite and local garnet intrudes tonalite in the interior of the pluton. Compositionally similar, gneissic granodiorite forms a 0.5–1.5-km-wide sheeted body that is separated from the southwest contact of the main mass of the pluton by a narrow screen of Napeequa Complex (Tabor et al., 1987b). Thinner sheets of similar age and petrography as the Entiat pluton are also common in the Napeequa Complex (Fig. 5, inset) (Tabor et al., 1987b; Hurlow, 1992).

Mafic Complex and Interior Tonalite

Heterogeneity characterizes the mafic complexes in both plutons (Fig. 7). Textures are highly variable, and rocks range from fine grained to pegmatitic (Cater, 1982; Dawes, 1993). Hornblende gabbro and diorite are the most abundant rock types; also present are hornblende-diorite, quartz diorite, tonalite, trondhjemite, granodiorite, muscovite- and garnet-bearing leucogranodiorite, pegmatite, aplite, and widespread host-rock inclusions. The mafic complex contains abundant, compositionally and texturally defined sheets (typically 10 cm to 2 m thick, but locally attaining thicknesses of tens of meters), layers (Fig. 7), and irregularly shaped bodies with short dimensions reaching more than 25 m. An 18 km² body of two-pyroxene gabbro and diorite along part of the northeast margin of the Entiat pluton (Fig. 5) is finer grained and less sheeted than the rest of the mafic complex; it grades into tonalite of the pluton interior (Tabor et al., 1987b).

The general emplacement sequence in both plutons is from mafic to felsic, and the tonalitic “core” rocks intrude the mafic complexes (Cater, 1982). Hornblende is the earliest
rock type and forms irregularly shaped to subspherical inclusions, 5 cm to 1.5 m long, which lie in planar zones. They are commonly enclosed by gabbro and diorite, but in places are cut by a network of tonalite veins. The hornblende inclusions probably represent early solidified cumulates that were incipiently disaggregated during stoping. Sheets and irregularly shaped bodies of tonalite intrude gabbro and diorite and, in turn, are cut by more leucocratic sheets. In local intrusive breccias, blocks up to 1 m in length of hornblende, gabbro, diorite, and tonalite of variable grain size and texture, as well as some amphibolite blocks, are enclosed in a trondhjemitic matrix (Fig. 7G). In contrast, diffuse, swirled, and locally crenulate contacts suggest mingling of mafic and tonalitic magmas, and mafic rocks locally intrude felsic ones.

The interior tonalite of both plutons is more homogeneous than the mafic complex. Sheets are still widespread, but are thicker. Most are >50 m thick, although <1-m-wide felsic sheets intrude the tonalite, and some display diffuse, mingled contacts. Microgranoid enclaves and mafic clots are widespread in the Entiat pluton (Dawes, 1993) and are found in places in the Cardinal Peak pluton.

Sheets are a more important component of the main-stage tonalite than is easily recognized. In the Cardinal Peak pluton, inclusions of Holden assemblage and earlier plutonic rocks (Fig. 3) mark internal contacts between bodies with slightly different composition and texture. These contacts are difficult to trace where inclusions are absent. Inclusions may also delineate otherwise cryptic contacts between nearly identical sheets (cf. Pitcher and Berger, 1972), as abundant, fine-grained leucocratic sheets intrude inclusions and adjacent Cardinal Peak tonalite, but are less common away from inclusions. Compositional layering is also more common near inclusions, including diffuse biotite-defined banding that may record mingling of different sheets. Furthermore, the existence of sheets with diffuse boundaries in both plutons is suggested by widespread zones of schlieren, narrow (<5 m wide) diffuse zones of finer-grained tonalite, and subtle changes in orientation of magmatic foliation across planar boundaries. Possibly the most convincing evidence for sheets within tonalites is where individual sheets are separated by host rocks, but coalesce along strike into larger masses.

**Petrogenesis**

Petrologic studies by Dawes (1993), DeBari et al. (1998), Parent (1999), and Miller et al. (2000) demonstrate that mafic rocks in the plutons have compositions typical of high-Al basalts in arcs and probably represent mantle-derived magmas. These magmas were relatively hydrous, as indicated by the presence of hornblende as the dominant mafic phase in the Entiat pluton, cumulus hornblendites, comb layering, and hornblende-plagioclase pegmatites.

The dominant tonalitic magmas are variably homogenized mixtures of the mafic magmas and more silicic melts formed by lower-crustal melting of a garnet-amphibolite source (Dawes, 1993; DeBari et al., 1998; Parent, 1999; Miller et al., 2000). Geochemical modeling by Parent (1999) indicates that the Cardinal Peak pluton contains a higher percentage of crustal melt than the Entiat pluton.

**Inclusions**

Widespread rafts (nonrotated host rock) and xenoliths (rotated host rock) make up a few percent of the Cardinal Peak pluton (Fig. 3) and occur locally in the Entiat pluton. They are particularly common in the mafic complex. The Cardinal Peak inclusions comprise two groups: metamorphic rocks of the Holden assemblage and variably metamorphosed plutonic rocks that are more mafic than the host tonalite and are probably earlier phases of the pluton. These groups are in places intimately mixed, and pieces of Holden assemblage are locally enclosed by plutonic inclusions. Most of the inclusions are highly elongate (Fig. 7C).
Thickneses range from <5 cm to >30 m, but are commonly <2 m. The largest inclusions extend for >100 m.

The plutonic inclusions in the Cardinal Peak pluton are complexly sheeted and more heterogeneous than the host tonalite. They also show greater subsolidus deformation and recrystallization to amphibolite-facies assemblages and better-developed layering (on the scale of 1–10 cm). Furthermore, the hornblende tonalite of the inclusions contrasts with the biotite tonalite host in the southeastern part of the pluton. The main rock types in the inclusions are hornblende-biotite tonalitic gneiss and tonalite; biotite tonalite sheets similar to the host Cardinal Peak are also common. Local mafic inclusions, including mafic gneiss, lie more than 1 km inward from the marginal mafic complexes, and some are in the southeastern part of the pluton where the marginal complexes are absent. Rock types in Holden inclusions in the margins of the Cardinal Peak pluton match up well with those in the adjacent host rock, but in the interior, the abundant inclusions do not define recognizable raft trains (cf. Pitcher and Berger, 1972) or “ghost stratigraphy” (Fig. 3).

The long axes of inclusions are commonly subparallel to foliation in the host tonalite, particularly in the margin of the Cardinal Peak pluton. In the interior, some inclusions, including several large ones, are elongated north to northeast and thus are discordant to the northwest-trending contacts of the pluton. Most inclusions dip moderately to steeply, but several of the thickest (tonalite gneiss) dip <30°.

The inclusions contain structures that predate the host tonalite and thus serve as markers to evaluate rotation of inclusions. Foliation in inclusions and host tonalite is commonly parallel to inclusion contacts, including in localities where a range in raft sizes suggests that smaller rafts were wedged apart from larger ones. Rotation is indicated, however, in several places where foliation orientation differs markedly between closely spaced, weakly elongate xenoliths. In other localities, there are both concordant and discordant (to host foliation) inclusion contacts. In a zone of abundant amphibolite inclusions, foliation in the largest raft is parallel to that in the host, but is discordant in smaller xenoliths; this circumstance suggests ripping off and rotation of smaller xenoliths from larger rafts.

These relationships fit a model whereby rafts mark internal contacts between coalescing sheets of tonalitic magma. In many places, sheets wedged aside without rotating foliation in the rafts. Elsewhere, sheets coalesced sufficiently so that inclusions became detached and rotated and, in some cases, became widely dispersed, as implied by the absence of ghost stratigraphy. Repeated sheeting in the same zone is indicated by the plutonic inclusions that contain Holden xenoliths.

The local rafts and xenoliths in the Entiat pluton consist of rock types similar to those in the Napeequa Complex, and a few pieces of hornblendite and mafic rock are enclosed in the leucocratic granodiorite phase. Most inclusions are <1 m in length, although an ~500-m-long raft lies near the southwest margin. The long axes of inclusions are parallel to adjacent sheet margins.

Relationships between the tonalitic, Entiat-type intrusive sheets (10 cm to 500 m wide) and the Napeequa Complex next to the southwest margin of the main body of the Entiat pluton (RC in Fig. 5) include a complete spectrum from continuous Napeequa lenses between sheets (Fig. 5, inset), to discontinuous lenses that are meters to tens of meters long, to smaller rafts completely surrounded by intrusive rock. Rafts invariably lie along boundaries between sheets, and their long axes are parallel to sheet margins.

We speculate that the range of inclusion-pluton relationships—from those near the individual sheets in the Napeequa Complex (Fig. 5, inset), to the numerous rafts along coalesced sheet margins in the Cardinal Peak...
Figure 6. Cross sections through the Entiat pluton. Short, heavy dashes—locations of measured foliations, thin lines within units—interpreted foliation patterns, thick lines—contacts between lithologic units, shaded plus light vertical lines—Entiat pluton with extensive sheets, shaded plus random dashes pattern—Tertiary plutons that postdate Entiat pluton and thus do not serve as host rock, mc—mafic complex.

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pluton, and to the coalesced sheets with little to no rafts in the Entiat pluton—represents a temporal sequence in which magmatic sheets initially intruded host rock, coalesced but preserved pieces of host rock along margins, and eventually formed large, relatively inclusion-free magma chambers. If correct, then a process must have occurred by which 50% of the host rock was removed along sheet margins during construction of large plutons like the Cardinal Peak and Entiat (discussed subsequently).

Internal Structures

The Cardinal Peak and Entiat plutons display a complex array of internal structures (Figs. 7–11). Sheets (discussed previously) and layers are the earliest structures, and lay-
ers are best developed near sheet contacts. Layered zones are typically a few meters wide in the Cardinal Peak pluton; individual layers are mostly 1–15 cm thick and pinch out within a few meters. In the Entiat pluton, layered zones range up to hundreds of meters wide, and individual layers can be followed for tens to hundreds of meters, particularly in the southwest margin of the pluton.

Layering is best defined by variations in the ratios of felsic and mafic minerals. Grain-size differences and local hornblende-defined comb layering (in mafic complexes) accompany modal differences in places and are solely responsible for layering locally. Three main types of layering have been recognized (Fig. 7). (1) Widespread, laterally continuous, relatively planar layers are interpreted to represent injections of thin, discordant sheets with diffuse boundaries resulting from minor mingling with their hosts (Fig. 7, A, F, and H). (2) More diffuse layers that grade into schlieren probably result from flow sorting and fractionation within sheets and, less commonly, from intimate magma mingling or rare partial digestion of inclusions (Fig. 7, B, E, and G). (3) Layers in zones of intense magmatic and/or subsolidus foliation formed by transposition of compositional heterogeneities and attenuation of microgranitoid enclaves during magmatic and subsolidus deformation (Fig. 7B).

On a local scale, layers range widely in orientation, but on a larger scale, more consistent patterns emerge. Sheets and layers in the Cardinal Peak pluton are steep in the northwestern tip and are commonly moderately dipping in the mafic complex (Fig. 4). Further southeast, the thicker, less well-defined tonalitic sheets are difficult to measure, but are less consistently oriented. In the Entiat pluton, sheets and layers dip steeply in the northwestern tip, moderately northeast in the southeast margin, and steeply northeast in the northeast margin (Fig. 6). Layers and presumably sheets typically dip gently southward in the wider southeast part of the pluton.

In both plutons, the best-developed structures are magmatic; they are subparallel to moderate- to high-temperature subsolidus foliation and/or mineral lineation (Figs. 8–11). At the outcrop scale, foliation in some places is parallel to layers and sheet contacts, but in many other places, foliation cuts these structures at small to moderate, and locally high, angles. Similarly, magmatic foliation is commonly discordant to contacts between major units in the plutons (Figs. 8, 9).

Foliation in the Cardinal Peak pluton strikes approximately due north, discordant to the northwest-trending contacts of the pluton (Fig. 8). Dips in the southeast and central part of the pluton are gentle to moderate, whereas in the northwest, they are on average somewhat steeper. Lineation is more consistently oriented, plunging gently due north (average plunge of 11° and bearing of 169°) (Fig. 10). In the southeastern part of the pluton, lineation was not measured because of the flattening-type fabric and overall weaker intensity of the fabric.

Fabrics in the plutons were categorized in the field as magmatic (M), subsolidus (S), or both (MS or SM; the first letter denotes the stronger fabric) and ranked in intensity from 0 to 5 (see Fig. 8 caption for more detail). These rankings are complemented in the Cardinal Peak pluton by field and laboratory measurements of aspect ratios of quartz grains and aggregates (Fig. 8C), which in weakly deformed tonalite are roughly spherical; ratios thus give relative values of subsolidus strain.

The relative intensity of magmatic versus subsolidus deformation differs on various scales in the Cardinal Peak pluton. In the southeastern half of the pluton, foliation is mainly magmatic and moderate to weak (most commonly M2); most quartz aspect ratios there are <1.5 (Fig. 8C). Subsolidus fabrics are better developed in the northwest half of the pluton (fabrics of SM3 or SM4 type are common); most quartz aspect ratios are >3:1, and in places magmatic foliation has been obliterated. Subsolidus deformation is particularly intense next to a 5.5-km-long, east-trending segment of the northeast contact near Emerald Park (Fig. 3). Fabric intensity increases slightly toward the pluton margins in other transects, and no change was noted in several transects. Fabric shapes also vary widely, as S-, L-S, and L-fibrils are all present. Complicating the fabric pattern are zones, 1 m to tens of meters wide, of strong, medium- to high-temperature subsolidus deformation (SM3–4) (not shown in Fig. 8C) that locally are protomylonitic to mylonitic. These zones are scattered throughout the pluton, including in domains otherwise dominated by magmatic fabrics. Particularly distinctive in the northern part of the pluton are constrictional strain shadows characterized by rodded quartz ribbons and rod-shaped sheets and inclusions.

We did not identify kinematic indicators associated with the magmatic fabrics. Shear-sense indicators in the medium- to high-temperature subsolidus fabric are prominent in the east-trending zone near Emerald Park (see subsequent discussion), but are sparse elsewhere. Stations (26 total) recording dextral or sinistral strike slip on variably dipping surfaces occur in subequal amounts. In most of the Entiat pluton, magmatic foliation is stronger than subsolidus foliation. Lineation is weaker than foliation except in local constrictional zones. Analogous to the Cardinal Peak pluton, foliation dips are shallower in the wider southeast end and are moderately to steeply northeast in the northwest end and along the southwest margin (Fig. 9). Local magmatic to high-temperature subsolidus shear zones include steeply dipping dextral and sinistral structures and gently dipping, top-to-the-north zones.

Magmatic and subsolidus mineral lineations generally plunge gently and trend north-northeast at a moderate angle to the long axis of the Entiat pluton (Fig. 11). In the southern part of the southwest margin, however, weak lineation approaches the dip of strong foliation (Hurlock, 1992), and near sheet tips it ranges from horizontal to vertical (Paterson and Miller, 1998).

The highest fabric intensities (>MS3) in the Entiat pluton are in a 1-km-wide belt along the southeast margin, which gives way inward to weaker (MS3 to M2), but still strong, dominantly magmatic fabrics (Fig. 9C). M2 to MS3 fabrics also dominate much of the southwest extent of the pluton. The weakest, but still well-developed, magmatic fabrics (<M2) form a significant part of the interior of the pluton.

Narrow (1 cm to 10 m) greenschist- and lower-amphibolite-facies shear zones are the latest-formed ductile structures in these plutons. They are moderately to steeply dipping and north to north-northwest striking; both sinistral and dextral strike-slip zones are common. Miller and Paterson (2000) interpreted these structures as conjugate Eocene shear zones reflecting late, orogen-parallel stretching.

The most intriguing structures in the plutons are magmatic folds of foliation, layers, and sheets, which are best developed in the Entiat pluton (Figs. 6, 7, F and H, 9A). Folds range in style from gently to isoclinal, and tight and isoclinal mesoscopic folds are locally refolded by open structures. An axial-planar magmatic foliation also formed locally (Fig. 7, F and H). Wavelengths are typically 5 cm to 3 m, but map-scale folds are well displayed in the Entiat pluton (Figs. 6, 9), particularly in the southeast end where magmatic foliation at the scale of the pluton defines a broad, asymmetric, southwest-vergent antiform (Fig. 6D). Smaller macroscopic folds with local mesoscopic folds in their hinge regions lie on the limbs of the large antiform (Fig. 9A, inset). Foliation in the southeast part of the Cardinal Peak pluton also defines a broad, symmetric folds (Fig. 4, C and D).

Fold axes plunge gently to moderately (<30°). Map-scale folds in the Entiat pluton
have northwest-trending axial traces that are subparallel to the length of the pluton and to outcrop-scale folds, in agreement with the axis defined by poles to foliation (Fig. 9). In the Cardinal Peak pluton, the poles to foliation define a girdle with an axis plunging 5° toward 353°, an orientation close to the mineral-lineation maximum (Fig. 10). Axial planes dip moderately to steeply in both plutons.

At least seven relationships indicate that upright folding occurred during emplacement. (1) Folds deform magmatic foliation in domains with only minor subsolidus deformation. (2) In a few mesoscopic folds in the Entiat pluton, magmatic foliation defined by aligned igneous hornblende and plagioclase is folded and overgrown by igneous hornblende oriented parallel to the axial plane of the fold (Fig. 7 in Paterson et al. [1998]). This geometry implies folding of a crystal-rich mush with late growth of igneous minerals parallel to the axial plane. (3) Some sheets in the structural aureoles are folded, and others cut these folds (Hurlow, 1992). (4) In the northwestern tip of the Cardinal Peak pluton, several tonalite sheets intrude along axial planes of folds of subsolidus foliation in gabbro, others cut folds, and still others that are at high angles to foliation are pytgmatically folded, but not as tightly as the gabbro. (5) Fold axes are subparallel to magmatic lineation. (6) Folds in the plutons have similar styles and orientations to host-rock folds, and folded host-rock foliation is continuous with magmatic foliation. (7) Folds and locally refolded folds of magmatic and subsolidus foliation are
more common and tighter in plutonic inclu-
sions, and are truncated by the host Cardinal
Peak tonalite.

Relationships 4 and 7 indicate that subsol-
idus deformation affected early-crystallized
phases while tonalite sheets continued to in-
trude into the chamber. This interpretation is
further supported by plagioclase-phyric ton-
alite sheets that cut subsolidus fabrics in main-
stage tonalite, but themselves have a strong
subsolidus fabric. A U-Pb zircon date suggests
that one of the sheets is about the same age
as the main-stage tonalite (S.A. Bowring,
1997, personal communication).

In summary, deformation of the plutons be-
gan while melt was present. Internal structures
related to chamber construction (sheets) and
to flow of magma (layers) were overprinted
late in the crystallization history by magmatic
foliation and lineation, which in turn were
folded while melt was still present. Weak and
moderately strong subsolidus (amphibolite-fa-
cies) deformation and narrower high-strain
zones probably formed shortly after the plu-
tons solidified.

Microstructures

Magmatic foliation and lineation in Cardi-
nal Peak and Entiat tonalites are marked by
biotite, hornblende, and plagioclase. In rocks
with the weakest subsolidus overprint, quartz
forms coarse-grained aggregates or isolated
large crystals displaying minor subgrains and
recrystallization. With greater subsolidus de-
formation, the tonalites develop an anasto-
mosing fabric. Elongate quartz grains and ag-
gregates, which in more strongly overprinted
rocks become ribbons, and foliae of recrystal-
lized biotite, quartz, plagioclase, and locally
hornblende wrap plagioclase and epidote por-
phyroclasts. Quartz contains subgrains, and
plagioclase is variably recrystallized (grain-
boundary migration) into fine- to medium-
grained mosaics. Evidence of an earlier mag-
natic fabric survives in tonalites with a
moderately strong overprint, as shown by
aligned large plagioclase grains retaining os-
cillatory zoning, biotite, and hornblende that
are not separated by continuous bands of re-
crystallized mosaic. These microstructures
and assemblages are compatible with a con-
tinuum from magmatic to subsolidus defor-
mation under amphibolite-facies conditions.

Regional Host-Rock Structures

Regional host-rock structures and their
modification in structural aureoles of plutons
are important for understanding emplacement
mechanisms, the relative timing of develop-
ment of internal and host-rock structures, and
the strain and stress fields at the time of em-
placement (e.g., Paterson et al., 1996, 1998).
All units that host the Cardinal Peak and En-
tiat plutons have strong amphibolite-facies
Figure 8. Structural map of Cardinal Peak pluton showing (A) foliations, (B) stereonet plots of foliation, and (C) foliation intensities and quartz aspect ratios. BR—Bearcat Ridge Orthogneiss (89 Ma), EP—Emerald Park, H—Holden unit, RP—Riddle Peaks Gabbro; SG—Skagit Gneiss, T—Tertiary plutons. Patterns for units in Cardinal Peak pluton in A and B are same as those in Figure 3. In B, domains are outlined by gray lines (CP—Cardinal Peak). In C, M—magmatic, S—solid-state. For intensities, 0—no visible fabric; 1—weak, very difficult to measure; 2—moderate crystal alignment, easy to measure; 3—strong crystal alignment, some layering may be visible; 4—very strong mineral alignment, throughgoing layering, mylonite if subsolidus; 5—intense alignment and layering, mylonite to ultramylonite if subsolidus. Quartz aspect ratios—average $x:z$ ratios of grain axes; data are sparse in northwest because of greater percentage of mafic rocks and strong subsolidus deformation that in places led to coalescence of quartz aggregates into throughgoing ribbons.

Foliation mostly dips $<50^\circ$ (Figs. 4, 6, 8, 9) outside of structural aureoles and is deformed by overturned to recumbent, tight to isoclinal mesoscopic folds. Mineral lineation regionally plunges gently north-northwest or south-southeast. These structures were deformed by gentle to tight upright folds with wavelengths of a few centimeters to several kilometers; the axes are oriented close to the mineral lineation. Finally, top-to-the-north shear is recorded pervasively in the Swakane Gneiss and sporadically in the overlying Napequa unit (e.g., Alsleben et al., 1999).

The ages of these structures are moderately well known. On a larger scale, the Cascades core records ductile top-to-the-southwest-dominated, northeast-southwest shortening.
that was initiated before 96 Ma (e.g., Miller and Paterson, 1992), continued at least episodically for >30 m.y. in the Chelan block, and in part overlapped intrusion of the Cardinal Peak and Entiat plutons, as shown by the upright magmatic folds (Hurlow, 1992; Paterson and Miller, 1998). The top-to-the-north shear ended by 48 Ma (Miller et al., 1996; Alsleben et al., 1999). For our purposes here, the most important conclusions are that at the time of pluton emplacement, host rocks had gently to moderately dipping foliation and a parallel anisotropy imposed by contacts between units and compositional layering, and these structures were being folded.

**Structural Aureole of the Cardinal Peak Pluton**

A narrow (<300-m-wide) structural aureole that changes markedly along its length lies adjacent to much of the Cardinal Peak pluton (Fig. 12), but a thermal aureole is absent. The aureole is best defined by changes in orientation of regional foliation and deflection of preemplacement regional markers (unit contacts, compositional layers in Holden assemblage).

The sides of the pluton are generally discordant to regional structures except in the structural aureole, as best displayed along the steep (>60°) southwest contact, which dips southwest beneath the Holden assemblage (Fig. 12, cross-sections A-A′, C-C′, D-D′). This margin is much steeper than regional foliation (Fig. 4), and, particularly along the southeast part of the margin, the foliation has a trend more to the northwest (by up to 50°) than the foliation (Fig. 8A). At several localities, upright folds with gently dipping limbs persist up to this contact; thus here the margin is discordant on even a local scale (Fig. 12, cross sections C-C′ and D-D′). More commonly, both foliation in the Holden assemblage and the contact separating interlayered leucogneiss and amphibolite from a calc-silicate–rich unit (Figs. 4C, 12, cross section C-C′) change in <300 m from gentle to steep dips as the pluton is approached. The sense of deflection indicates downward transport of host rock. Folds tighten in some transects, and in places open recumbent folds and later steeply plunging folds have been developed in the aureole, but are absent outside of it.

Widespread Cardinal Peak sheets in the southwest structural aureole have both concordant and discordant contacts relative to foliation, which is continuous from the sheets into the host rocks. These sheets were deformed into upright and younger localized folds in the aureole, which in turn were cut by younger sheets. Leucocratic bodies locally occupy a saddle–reef position in open, gently to moderately inclined host-rock folds, suggesting intrusion into actively forming structures.

The structural aureole next to the northeast margin is more difficult to interpret. Regional foliation dips 20°–60° southwest (except at the northwestern tip of pluton), generally less steeply than the southwest-dipping pluton contact (Figs. 4, 8, 12, cross section D′-D′′). Foliation and compositional layers steepen by ~20°–40° within a zone <1 km in width next to the pluton, implying downward flow in the aureole.

Markedly different relationships characterize the east-trending segment of the northeast margin near Emerald Park (Figs. 3, 4, 12). The contact lies within a 25°–50°S-dipping shear zone and is discordant to foliation in the pluton, the underlying <200-m-thick belt of intensely deformed Holden assemblage, and still lower Bearcat Ridge Orthogneiss. Lineation plunges south to south-southeast and lies in a downdip orientation. Protomylonites form an ~200-m-thick zone in the Cardinal Peak pluton and extend downward for >200 m in the Bearcat Ridge Orthogneiss. Kinematic indicators (S-C fabric, extensional crenulation cleavage, plagioclase porphyroclast systems) defined by amphibolite-facies assemblages record north-directed reverse shear (pluton side up) in all units. Despite its width, this shear zone was probably the site of only modest displacement; the zone has a short strike length (5.5 km) and sheets of Cardinal Peak tonalite intrude the adjacent Holden assemblage.

It is difficult to evaluate the aureole at the ends of the pluton. The northwestern tip consists of sheets that are mostly <5 m wide and finger out into the Holden assemblage. Steep foliation in the sheets and host rocks strikes north-northwest, and lineation plunges gently north-northwest; both are oblique to the tip contacts (Fig. 8). The poorly exposed southwestern end of the pluton is blunted in map view (Fig. 3, 8), but along strike to the southeast, foliation steepens in host rocks, which are intruded by concordant sheets that may mark the feathering out of the Cardinal Peak. These sheets, however, are more heterogeneous and more strongly foliated than the southeastern part of the pluton.

**Structural Aureole of the Entiat Pluton**

No thermal aureole and a narrow, discontinuous structural aureole also characterize the Entiat pluton. Adjacent to the southern part of the southwest margin, both regional markers (Swakane-Napeequa contact, compositional layers) and foliation in the Swakane and Napeequa units steepen and bend downward into subparallelism with the moderately northeast-dipping pluton margin in an ~500-m-wide aureole (Fig. 13, D–D′). This deflection indicates significant downward displacement of host rock during ductile flow. Foliation intensifies in the aureole and mineral lineation steepens, producing strong flattening-type fabrics. Lineations are variably oriented, but steepen overall and have moderate to steep pitches in the foliation (Fig. 13) (Hurlow, 1992). Small open to isoclinal folds that refold the regional foliation are also preferentially developed in the structural aureole.

Along strike to the northwest, foliation and markers in the Napeequa are regionally steeper, most dipping 50°–70° (Fig. 9), and lie at a relatively small angle (~20°) on average) to the steep, northeast-dipping pluton contact, making it difficult to distinguish regional from aureole structures. Lineations and fold axes plunge gently (0–30°) even next to the pluton. Fabrics are more intense close to the pluton, suggesting some emplacement-related ductile deformation.

The northwest end of the pluton is marked by many sheet tips that intrude other sheets or host rock (Fig. 13, A–A′). Paterson and Miller (1998) described four of these tips, which intruded parallel to the axial planes of upright, northwest-trending, gently plunging folds; the sheets thus cut the folded anisotropy in the host rock. Magmatic foliation is either steep and subparallel to sheet contacts and axial planes of host-rock folds, or is openly to tightly folded about upright, mesoscopic and macroscopic folds that mimic those in the host rocks. Magmatic lineations are subhorizontal and parallel to the trend of sheets with the largest length/width ratio, but plunge steeply in sheets with smaller ratios (Paterson and Miller, 1998). No faults were found along sheet margins or extending from sheet tips.

The structural aureole next to the steep northeast margin of the Entiat pluton also changes along strike. In the north, the pluton contact ranges from discordant to markedly discordant to the folded foliation in the host rocks (Fig. 13, B–B′). Locally, gently dipping foliation steepens within ~250 m of the pluton, folds increase in number and tightness, and there are examples of both downward and upward deflection of host-rock markers into subparallelism with the contact. Lineation in the host rocks and pluton is subhorizontal and subparallel to the contact. Along strike to the southeast, foliation steepens and is subparallel to the pluton contact between the Entiat and 46 Ma Duncan Hill.
pluton (Fig. 13, C–C'); the cause of the steep fabrics is uncertain. In this part of the aureole, several local steep, medium-temperature ductile shear zones with variable kinematics cut host-rock structures and the margin of the pluton. These structures are probably part of a regional set of Eocene conjugate shear zones (Miller and Paterson, 2000). Farther southeast, an aureole has not been recognized in the Chelan Complex.

DISCUSSION

At mid-crustal depths, ambient temperatures can be high enough that batches of magma may remain molten for hundreds of thousands to millions of years (e.g., Yoshinobu et al., 1998). Ascent and emplacement of individual magmatic pulses and their petrologic evolution can differ dramatically despite being part of the same pluton-forming event, because of changing tectonic processes and progressive feedback between the growing pluton and its tectono-metamorphic environment. Geochemical studies, the complex structural aureoles, and the varied properties of sheets in the Cardinal Peak and Entiat plutons support this contention. At this crustal level, a single structure (e.g., magmatic foliation, lineation) may form over a lengthy time span and by several processes (e.g., regional strain plus magmatic flow). In addition, in these plutons, early, thin, dominantly mafic sheets can solidify rapidly with larger interior magma batches cooling much more slowly, thus leading to time-transgressive foliation patterns. Inferring processes from the final composite structure is thus difficult. Next, we evaluate these issues with the goal of determining the tectonic setting and origin of the magmatic structures as well as the host-rock processes operating during chamber construction and emplacement; we conclude with a general growth model for sheeted plutons.
Tectonic Setting During Chamber Construction

Regional studies and local crosscutting relationships indicate that emplacement of the Cardinal Peak and Entiat plutons occurred after initial thrust juxtaposition of the Swakane, Napeequa, and Holden units (Tabor et al., 1987a) and during the late stages of generation of recumbent, tight to isoclinal folds. The latter conclusion is supported by rare isoclinal folds of sheets in the Entiat pluton and adjacent Napeequa Complex (Hurlow, 1992), which are deformed by upright, north-northwest-trending folds, and the gentle dips of foliation in the southern parts of both plutons. We have already summarized much evidence that the upright folding, which records west-southwest–east-northeast, subhorizontal shortening, accompanied emplacement of the plutons. Finally, several observations hint that top-to-the-north shear occurred during final crystallization of these plutons: rare near-solidus shear zones in the Entiat pluton record top-to-the-north shear, melt-present top-to-the-north shear is associated with magmatic sheets in the Napeequa Complex (Miller et al., 2000), and north-directed shear is recorded along part of the northeast margin of the Cardinal Peak pluton.

The interpretation that the plutons were emplaced during shortening nearly perpendicular to their sides and late, top-to-the-north, subhorizontal shear oblique to their margins raises several questions, including how to interpret the magmatic fabric patterns. Previously, we have emphasized the importance of the degree of continuity of fabric patterns between plutons and host rocks for...
determining the degree of mechanical coupling (Paterson et al., 1998). For the Cardinal Peak and Entiat plutons, magmatic structures (foliation, lineation, folds) are commonly parallel to equivalent regional host-rock structures; both steepen somewhat from southeast to northwest, possibly reflecting changes in the intensity of regional shortening. The magmatic structures are also discordant in many places to pluton contacts, internal sheet contacts, and layering. These relationships indicate strong mechanical coupling and a small viscosity contrast between pluton and host rock during formation of the magmatic structures; this situation is only likely when magma is near its solidus and crystal rich and host rocks are hot. The small viscosity contrast and the discordance of magmatic fabrics to contacts and layers demonstrate that the fabrics formed after chamber assembly and late in the crystallization history and suggest that they largely record regional strain rather than internal magmatic processes.

Magmatic fabrics are locally discordant, however, to regional structures and instead are parallel to nearby igneous contacts. This observation may reflect refraction of regional strain parallel to rigid margins (not compatible with small viscosity contrasts), or more likely strain caused by flow parallel to the margins. Given the lengthy time over which these fabrics may have formed, a single magmatic fabric may change in age by 1 m.y. or more from one location to the next and reflect strain dominated by regional deformation in one spot and magmatic flow during chamber construction in another. This hypothesis is supported by the lack of overprinting relationships between margin-parallel and regionally oriented fabrics.

Another intriguing issue is the significance of the gently dipping, broadly folded, magmatic foliation in the southeastern halves of both plutons. Such foliations are not widely reported in sheeted plutons. Subhorizontal tectonic foliations typically form in gently dipping shear zones or by vertical shortening and extensional collapse. Although collapse may occur during or shortly following regional shortening, it is a less plausible explanation for the gentle dips given that west-southwest–east-northeast subhorizontal shortening generated upright folds after formation of the foliation. We thus suggest that the gentle foliation formed during regional, subhorizontal, southwest-directed thrust shear and was folded during continued shortening. The discordance between the foliation and steep contacts also implies that subhorizontal shear caused greater rotation of individual crystals than chamber margins because of the potential for rapid rotation of crystals in a melt.

Gently dipping foliations may also form in the upper parts of diapirs (e.g., Dixon, 1975; Cruden, 1990), and it is possible that as large sheets coalesced in the southeast parts of these plutons, the chambers rose as viscoelastic diapirs (Miller and Paterson, 1999). Diapiric flow, however, does not explain the discordance between contacts and foliation. A more likely scenario is that fabrics formed by diapiric flow were modified by southwest-direct-

Figure 10. Lineations in Cardinal Peak pluton. (A) Map of mineral lineations. (B) Stereonet plots of lineation. Note subparallelism of lineation and fold axes (defined by girdles of foliation in Fig. 8B). Abbreviations same as for Figure 8.
CONSTRUCTION OF MID-CRUSTAL SHEETED PLUTONS

Host-Rock Processes During Chamber Construction

The magmatic fabrics largely provide information about regional tectonism, and we therefore use other evidence to decipher how host rock was displaced during emplacement. Critical observations include (1) the discordance of steep pluton contacts to regional host-rock structures, which implies that host-rock displacement took place largely within the narrow and highly variable structural aureoles or in the regions now occupied by the plutons (Paterson et al., 1996); (2) the transition from sheets separated by host rock, to rafts along sheet margins, to relatively inclusion-free chambers; and (3) the evidence of late stoping along some chamber margins, which indicates that parts of the inner ductile aureoles were removed and thus information on emplacement has been lost.

Ductile flow of host rock in structural aureoles clearly occurred during emplacement of both plutons. The lack of deflection of regional markers outside aureoles necessitates that any host-rock shortening caused by lateral expansion of the chambers was compensated for by vertical material transfer within aureoles (cf. Paterson and Vernon, 1995). Lateral ductile flow in the Cardinal Peak aureole is indicated by the tightening of upright folds and development of a younger generation of folds, as previously described herein. An interpretation of vertical ductile material transfer around this pluton is supported by the downward deflection of host-rock markers into parallelism with parts of the southwest margin (Figs. 4, 12) and, to a less certain extent, along the northeast margin. Host rocks adjacent to the northeast margin of the Entiat pluton recorded limited vertical flow, which changed from downward to upward along strike, and only minor horizontal displacement. In the southern part of the more strongly deformed southwest aureole downdip to oblique lineation, local pluton-side-up kinematic indicators and downward deflection of host-rock markers imply a larger magnitude of downward material transfer (Fig. 13, D–D').

Estimating the amount of space formed by the ductile flow is difficult at best. The narrowness, lack of complete transposition of older structures, and absence of unusually highly strained rocks in the aureoles all suggest modest emplacement-related strain. Lineation also generally retains its regional subhorizontal orientation, suggesting that regional strains dominated and/or outlasted the pluton-induced vertical flow. Tempering these conclusions is the observation that parts of inner aureoles were removed by stoping.

The transition from sheets separated by host rock (Roaring Creek), to rafts along sheet margins (Cardinal Peak), to relatively inclusion-free chambers (Entiat) suggests to us the following emplacement scenario, also dominated by vertical ductile flow. As each sheet was intruded, host rock was displaced by lateral shortening and horizontal and/or vertical extension in narrow aureoles along the sheet margins. This process caused local folding, variable transposition of older structures parallel to sheet margins, and upward or downward deflection of regional markers. As more sheets intruded, the process continued. The gradual removal of host rock required this rock to be transported vertically downward along sheet margins. We envision that this

Figure 11. Lineations in Entiat pluton. (A) Map of mineral lineations. (B) Stereonet plots of lineation with domains outlined in gray lines. N—Napoequa Complex, SW—Swakane Gneiss.
Figure 12. Summary of Cardinal Peak structural aureole, delineated by dashed lines, with insets documenting details of cross sections and changes along strike in the aureole. Solid circles—gently plunging mineral lineations trending at high angles to cross sections. Arrows—moderately to steeply plunging mineral lineations. Abbreviations and patterns are the same as in Figures 3 and 8.
CONSTRUCTION OF MID-CRUSTAL SHEETED PLUTONS

Figure 13. Summary of Entiat aureole, delineated by dashed lines, with insets showing cross sections through aureole and variations of structures along strike. Patterns are the same as in Figure 5. CC—Chelan Complex, H—Holden unit, N—Napeequa Complex, SW—Swakane Gneiss. Cross sections: Dashed lines—magmatic foliation. Thin solid lines—host-rock foliation. Solid circles—gently plunging mineral lineations trending at high angles to cross sections. Arrows—moderately to steeply plunging mineral lineations.

transport happened by ductile flow, which resulted in boudinage of units, and by detachment of host-rock rafts that sank through the chamber. This model is akin to the magmatic wedging of Weinberg (1999), but also has features of crack-seal mechanisms to form rafts between sheets.

Regional folding may have also transferred material during emplacement if regional vertical and/or northwest-southeast horizontal extension was greater than was needed to compensate for regional northeast-southwest horizontal shortening. The lack of quantitative strain data precludes evaluation of this scenario with confidence, but the association of emplacement with regional folding suggests that this process may have been important. A few sheets in the Cardinal Peak aureole do occupy saddle-reef positions, and steep Entiat sheets in tip regions lie along axial planes of upright folds of host rock.

Other processes made little or no space for the plutons. Emplacement of magmas into diachronous zones along faults (e.g., Hutton, 1988, 1992) is commonly proposed, but we find no evidence for faults extending from the ends of the plutons, as best shown by the Entiat sheet tips (Paterson and Miller, 1998), and the sides of the plutons are for most of their extents not faulted. The Emerald Park shear zone is localized along a short segment of the northeast margin of the Cardinal Peak pluton and thus was not a major factor in emplacement. High strains do occur on the southwest side of the Entiat pluton, but they are discontinuous along strike, regional markers are not offset by shear zones, and gently plunging folds are continuous from outside the aureole to the pluton contact; thus, a regional fault does not exist along this margin. Roofs are not preserved, but roof uplift shortly above the present exposure levels is unlikely given the absence of steep faults along pluton sides, the only-local upward deflection of host-rock markers, and the relatively deep crustal levels. Emplacement by depression of the floors of initially subhorizontal tabular plutons (Cruden, 1998; Wiebe and Collins, 1998) is compatible with the downward deflection of host-rock markers; however, the discordance of the steep pluton contacts to the gentle regional structures and the lack of syneformal patterns of layering in the plutons imply that this mechanism is unlikely. Significant volume loss from metamorphic reactions during emplacement (e.g., Yoshinobu and Girty, 1999) is also unlikely as the host rocks were metamorphosed to amphibolite facies in the middle Cretaceous (Miller et al., 1993) and should have undergone significant dewatering more than 15 m.y. before emplacement. Incorporation of host rock by melting was unimportant at the emplacement level; migmatites are rare next to the plutons and host-rock compositions (amphibolite, hornblende-biotite schist, quartzite) require higher melting temperatures than expected to be achieved in medium-grade rocks intruded by narrow bodies of tonalite.

Along-Strike Changes in the Plutons

The Cardinal Peak and Entiat plutons change systematically from northwest to southeast. Both are narrower, more mafic, and more heterogeneous in their northwest ends, and foliation is stronger and steeper there than in the southeast. Most of these differences are also mirrored by the younger (46 Ma) Duncan Hill pluton, which lies between the Cardinal Peak and Entiat plutons. In the Duncan Hill pluton, Hopson and Dehlinger (1989) ascribed these changes to tilting of a vertically zoned body; hornblende barometry suggests north-side-up tilting (~10°–13°) (Dehlinger, 1996), although many of the pressure determinations are below 2.5 kbar, the lower limit of experimental calibration for this barometer (Schmidt, 1992).

In contrast, the Entiat and Cardinal Peak plutons do not appear to have been appreciably tilted. Dawes’s (1993) samples used for hornblende barometry in the Entiat pluton were spaced along the length and across the
strike of the pluton. His calculated pressures overlap for all samples when analytical errors are considered, but the highest values are in the southeast end (rather than northwest) and are at elevations 2 km lower than those from localities in the northwest. Metamorphic pressures in the Napeequa and Swakane host rocks to the Entiat pluton are similar along strike (insufficient data exist for Cardinal Peak host rocks), and the marked variability in the structural aureoles is not consistent with along-strike changes in depth. The apparently contradictory relationships between the Duncan Hill and the older plutons may reflect a pre-Duncan Hill phase of northwest-side-down tilting (C.A. Hopson, personal communication, 1993), but in any case we conclude that the along-strike differences in the Entiat and Cardinal Peak plutons do not reflect appreciable vertical changes in these magma chambers. In the next section, we propose that these variations largely record changes in the amount of partial melting of lower crust in the source regions (cf. Parent, 1999), with greater melt production to the southeast.

Synthesis of Chamber Construction and General Implications

The abundant steeply dipping sheets of the Cardinal Peak and Entiat plutons imply vertical ascent of magma in numerous meter- to kilometer-scale, sheet-like batches. We visualize a scenario whereby initial, predominantly mantle-derived, mafic sheets rose from deep-seated magma ridges to an emplacement site in part controlled by active deformation (Fig. 14). We speculate that the shape of the magma ridges was controlled by the geometry of the melt-generation site and note that in many arcs, such as the Cascades core, plutons of similar age occur in linear belts (e.g., Miller et al., 1989; Bateman, 1992). We have proposed elsewhere that these magmas ascended as highly elongate, “viscoelastic diapirs” (Paterson and Miller, 1998; Miller and Paterson, 1999); alternatively, they may represent deeply emplaced “viscoelastic dikes” intruded perpendicular to the regional shortening direction. Regardless, ascent was probably facilitated by the magmas’ high water contents and thus relatively low (for mafic magmas) densities (e.g., Sisson et al., 1996). The magmas may have been modified during ascent by fractionation and/or interaction with lower-arc crust, and cumulates from the mafic magmas are represented by the hornblendites. Space for the thin mafic bodies was probably made by folding and vertical ductile flow of host rocks during magma wedging, and by local stoping, although it is difficult to determine host-rock behavior during this initial stage of magmatism.

Mantle-derived mafic magmas also provided heat that enhanced melting of the lower crust (Dawes, 1993; DeBari et al., 1998).
Lower-crustal and mantle magmas mixed to form tonalite either in the lower crust or during ascent, and tonalitic and mafic magmas mingled at the emplacement level. Mafic magmas were progressively overwhelmed by tonalitic melts, particularly in the more felsic and homogeneous southeast halves of each pluton, which marked the locus of tonalitic magmatism.

The early tonalites also intruded as thin sheets. Evidence from both plutons suggests that these sheets wedged apart, ductily strained, and locally stopped parts of the mafic complex and host rocks (Fig. 14C). These tonalitic sheets then were detached during wedging by younger and probably wider tonalitic sheets and were dispersed by ductile flow and stopping along margins as sheets coalesced and a larger chamber formed (Fig. 14D). Sheets crystallized sufficiently so that they were not strongly disrupted during passage of later magmas (cf. Bergantz, 2000), yet retained enough melt so that magmatic foliations cut across sheet contacts. The enclaves in the younger tonalite indicate that mafic magmas continued to be intruded into the tonalite-dominated chamber. Space also continued to be made by lateral shortening, vertical flow, and stopping. Regional deformation occurred throughout emplacement of the numerous magmatic pulses (Figs. 14, B and C).

We view these plutons as frozen conduits that fed larger magma chambers at shallower levels, such as represented by larger and more equant plutons of about the same age in southwest British Columbia that form the offset continuation of the Entiat–Cardinal Peak belt (Umhoefer and Miller, 1996). In this interpretation, the magma chambers were very dynamic systems with early mafic sheets solidified along the sides, large volumes of magma that passed upward to higher chambers where it became thoroughly hybridized, early tonalite sheets that intruded mafic rocks and then were intruded by younger tonalite sheets, and finally development of a larger chamber with a greater percentage of crustal melt in the southeast part of each pluton. After solidification of the initial mafic sheets, these conduits also served as a planar anisotropy, which controlled ascent of subsequent “dike-like bodies” and acted as a preheated pathway for larger, more felsic, “diapiric-like” batches. Regional contractional deformation persisted throughout the life of the conduit system.

These systems may also have acted as “filters” between lower-crustal zones of magma generation and mixing and upper-crustal zones of large, relatively homogeneous plutons. Such “filtering” could have happened in several ways. Until heated and eventually partially molten pathways were formed, more felsic magmas could not reach shallow levels because they did not have enough heat to rise diapirically long distances through the crust (e.g., Marsh, 1982). These pathways allowed larger, and thus potentially more homogenized, batches of magma (e.g., southeast parts of the plutons) to reach shallower crustal levels. And, as subsequent batches of magma passed through these systems, they may have preferentially tapped and mixed with the more evolved magmas in the center of the chambers, but did not interact with the less evolved magmas that were already frozen in sheets along the chamber margins. This mixing and homogenization in turn erased many of the layers and sheets in the interiors of the chambers.

We speculate that our model of chamber construction can account for features of other sheeted plutons, particularly those in arcs. For example, we see overall similarities among the Cascades plutons, the Great Tonalite sill of southeast Alaska and British Columbia (e.g., Ingram and Hutton, 1994; Hutton, 1997), and the western part of the Idaho batholith (Man- duca et al., 1993), which are tonalitic, mid-crustal, sheeted complexes emplaced in broadly similar tectonic settings. We also note similarities with shallower and more felsic sheeted plutons containing abundant host-rock inclusions, such as the Main Donegal Granite (Pitcher and Berger, 1972; Hutton, 1988) and the Ox Mountains igneous complex (Mc-Caffrey, 1992) of Ireland.

CONCLUSIONS

The Cardinal Peak and Entiat plutons represent chambers constructed by numerous sheet-shaped pulses of magma. Magmatic and subsolus foliation and lineation in the plutons are commonly discordant to layers, sheet contacts, and pluton contacts. They are parallel to equivalent structures in the host rocks and define magmatic folds. These structures formed largely after chamber construction and record regional strain and tectonism during emplacement.

Pluton contacts are discordant to regional host-rock structures except in narrow structur- al aureoles, which show remarkable lateral variability. Vertical material transfer facilitated emplacement and occurred primarily during magma wedging by ductile downward flow of host rock, particularly in narrow aureoles between coalescing sheets, and by late stopping. Regional folding and ductile flow was a potentially significant material-transfer process, but regional faulting was not important. These plutons represent a very dynamic type of mid-crustal magma chamber that probably acted as a filtering mechanism, allowing larger and more felsic magma batches to become more homogenized and rise to shallower crustal levels.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grants EAR-9219536 and EAR-9614521 (to Miller) and EAR-9218741 and EAR-9614758 (to Paterson). We thank Hugh Hurlow for discussions about Chelan block geology and geochronologic data, Karen Schmidt for help with drafting figures, and Barbara John, Calvin Miller, Nick Petford, and Tom Sisson for reviews.

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