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Construction, Emplacement, and Geochemical Evolution of Deep-Crustal Intrusions: Tenpeak and Dirtyface Plutons, North Cascades, Western North America

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Construction, emplacement, and geochemical evolution of deep-crustal intrusions: Tenpeak and Dirtyface plutons, North Cascades, western North America

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ABSTRACT

Deep plutonic systems represent an important link between lower-crustal melt-generation sites and higher-level regions of magma accumulation, but models for these systems are limited by the relative scarcity of exposed weakly deformed, deep-crustal plutons. Exceptions include the ca. 92.3–89.7 Ma, dominantly tonalitic Tenpeak pluton and the smaller, nearby ca. 91 Ma Dirtyface pluton of the North Cascades (western North America), which represent deeply exposed crustal levels (~25–35 km) of a Cordilleran arc. Initial subduction-driven magmatism in the Tenpeak pluton was marked by co-magmatic hydrous mafic and felsic magmas, which formed gabbro, diorite, tonalite, and hornblendite within a heterogeneous mafic complex. High-MgO, Ni and Cr tonalitic magmas (Schaefer Lake subtype) with $(\varepsilon_{Nd})_0$ of +4.8 to +5.8 accompanied or shortly followed this magmatism, and typify the Dirtyface intrusion. This early magmatism formed moderately to steeply dipping sheets, which are best developed in the southwestern margin of the Tenpeak pluton and in an internal zone with host rock rafts. As the system evolved, a different source was tapped to produce typical calc-alkaline magmas (Indian Creek subtype) that are more isotopically evolved (initial ε_{Nd} = +3.0 to +4.0). Magmas of this subtype formed bodies that are elliptical in map view and that truncated internal magmatic contacts and more strongly deformed tonalite, compatible with removal of older solidified and magmatic materials. The Schaefer Lake subtype terminated or was overwhelmed by the Indian Creek subtype in the youngest, high-volume magmas of the Tenpeak pluton.

Both plutons have moderately to steeply dipping contacts that define the shape of an elongate asymmetric funnel to wedge. During sheet emplacement, magma wedging isolated and rotated rafts and blocks of host meta-supracrustal rock. Vertical, mostly downward transport of host rock by ductile flow and at least modest stoping were important during emplacement of the larger bodies.

Only small ephemeral magma chambers formed in the early stages of pluton construction, but larger bodies (tens of cubic kilometers) probably remained mushy during crystallization of the relatively homogeneous younger tonalites. The juxtaposition of different magma subtypes, at least local mixing at the emplacement level, and removal and/or recycling of older magmas indicates that magmas from different sources utilized the same conduit for a protracted time interval. Large volumes of magma probably ascended through the system to form the larger and relatively more homogeneous intrusions in the shallow levels of the arc. This magma was likely filtered and homogenized by processes operating at the Tenpeak level. The end result was a deep- to shallow-crustal, steep, irregularly shaped magmatic system.

INTRODUCTION

Great strides have been made over the past 25 years in understanding the mechanisms responsible for the generation of magma and the construction, emplacement, and geochemical evolution of plutons, although a number of issues remain problematic. Most studies have been conducted on upper- to mid-crustal (<15 km depth) plutons. Models for deep-crustal (lower mid-crust and lower crust; ≥25 km paleodepth) plutonism are limited by the relative scarcity of exposures of deep crust and the typically strong metamorphic and structural overprinting of plutons at these levels (e.g., Miller and Snoke, 2009).

The construction and geochemical evolution of deep-crustal intrusions and their relationships to shallower plutons are subjects of considerable conjecture, and are the focus of this paper. Exposed deep intrusions are a critical link between even deeper melt-generation sites and sites of higher-level magma accumulation and volcanic eruptions. In one widely applied model, many plutons are subhorizontal, broadly tabular bodies that are laccoliths in the shallow crust and lopoliths in the mid-crust (e.g., Hamilton and Meyers,

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1967; McCaffrey and Petford, 1997; Cruden, 1998, 2006; Brown and McClelland, 2000). Magma migrates from melt-generation sites in the lower crust via dikes (Petford, 1996) or fracture networks (Weinberg, 1999; Brown, 2004) and crystallizes in the mid- to shallow crust. In the deep crust, melts are proposed to largely accumulate as migmatites and dike-sill arrays (e.g., Collins and Sawyer, 1996; Karlstrom and Williams, 2006). Others have suggested that many plutons are sections of steep-sided, vertically extensive magma conduits (e.g., Buddington, 1959; Pitcher and Berger, 1972; Hutton, 1992; Paterson et al., 1996; Saleeby et al., 2003; Brown, 2007) that transfer magmas upward into large elliptical to irregularly shaped plutons in the upper crust. Deeper-crustal melts may accumulate in dike-sill arrays or larger melt zones, forming sizable deep-crustal plutons (e.g., Miller and Paterson, 2001a; Matzel et al., 2006; Miller et al., 2009; Klepeis et al., 2016).

A number of other processes operating during pluton assembly and emplacement in the deep crust have been documented by relatively few studies compared to shallower plutons. For example, the sizes and even existence of magma chambers in the deep crust are questioned. If melts in the deep crust accumulate in dikes and sills, as noted above, then large magma and mush zones will presumably not form, but this is less clear for more homogeneous plutons (e.g., Miller et al., 2009; Brown, 2013). A related question is: How do deeper systems evolve during the incremental construction of mid- to upper-crustal plutons (e.g., Brown, 2007; Paterson et al., 2011)? Deeper-crustal levels have been modeled as long-lived zones of relatively continuous flow of melt, whereas shallower systems are more episodic (e.g., Miller et al., 2009; Paterson et al., 2011; Karlstrom et al., 2017). It is unclear if early smaller bodies in the deeper crust typically give way to larger younger ones as mantle heat input increases, such as at shallower levels (e.g., Matzel et al., 2006; de Silva and Gosnold, 2007; Karakas et al., 2017). The material-transfer processes accommodating magma emplaced at deep-crustal levels have also received minimal study. Previous workers postulate that ductile flow of host rock should become more important with depth (e.g., Buddington, 1959; Paterson et al., 1996).

Processes that control the geochemical evolution of magmas in the deep crust are also poorly documented. Conclusions from previous studies suggest that a variety of processes are active, including lower-crustal melting, fractional crystallization, and magma mixing (e.g., Anderson, 1976; Annen et al., 2006; Tatsumi et al., 2008; Reubi and Blundy, 2009; Jagoutz, 2010). However, these studies do not provide concrete examples of where in the crust these processes take place, nor exactly how they occur. Studies of crustal sections such as in the Talkeetna (Alaska, USA) and Kohistan (Pakistan) oceanic arcs provide some insights on these processes (e.g., Greene et al., 2006; Jagoutz et al., 2006; Jagoutz, 2010; Larocque and Canil, 2010); however, these studies concentrated on the arc as a whole and were not focused on processes active within individual plutons. Moreover, there are significant differences proposed between the evolution of magmatic systems in oceanic and continental magmatic arcs.

In the North Cascades in the Northwest Cordillera (western North America), the ca. 92.3–89.7 Ma Tenpeak pluton, nearby intrusions, and host rocks represent the deep mid-crust (~25–35 km) of a thick Cretaceous arc (Brown and Walker, 1993; Miller and Paterson, 2001b; Valley et al., 2003), and the Tenpeak pluton was emplaced at depths similar to those of many lower-crustal sections (Percival et al., 1992; Miller and Snoke, 2009; DeBari and Greene, 2011). The Tenpeak pluton is an excellent target for a case study of a deep-crustal pluton. Much of the intrusion lacks a strong metamorphic or structural overprint, it is well dated, and it is part of a crustal section that includes coeval large plutons at shallow (<12 km) levels (Paterson et al., 1994; Miller et al., 2009). Furthermore, metamorphosed supracrustal host rocks are widely exposed near the Tenpeak pluton, in contrast to some other deep-crustal plutons where host rock is dominated by plutonic material (e.g., Talkeetna arc, southern Sierra Nevada batholith [California, USA], Famatinian arc [western South America]) (see review by Miller and Snoke, 2009). Finally, evaluation of the three-dimensional shape of both individual increments and the composite intrusive complex is facilitated by the ~1.5 km of topographic relief of the pluton.

In this paper, we integrate a variety of structural, petrological, and geochemical data sets with previously published geochronologic data to analyze the processes that operated during construction and emplacement of the Tenpeak pluton and to a lesser extent the nearby, smaller Dirtyface pluton. Our work builds on mapping by the U.S. Geological Survey (Crowder et al., 1966; Cater and Crowder, 1967; Tabor et al., 1987), descriptive studies of Cater (1982), petrogenetic analysis of Dawes (1993) and Chan et al. (2017), and the geochronological work of Matzel et al. (2006). In particular, we address magma sources, shapes and orientations of magmatic increments, sizes of magma chambers, changes in magma compositions, construction processes and host rock displacement mechanisms with time, and potential relationships of the Tenpeak and Dirtyface plutons to coeval shallower-level intrusions.

GEOLOGICAL SETTING AND OVERVIEW OF TENPEAK AND DIRTYFACE PLUTONS

The Tenpeak and Dirtyface plutons are part of the Cretaceous and Paleogene continental magmatic arc of the North Cascades, the southernmost segment of the >1200-km-long Coast Mountains batholith of the northwestern North American Cordillera (Fig. 1). Arc plutons were intruded into previously assembled oceanic, island-arc, and clastic terranes (e.g., Tabor et al., 1989; Monger and Brown, 2016), and accompanied major ductile contractional deformation and amphibolite-facies metamorphism (e.g., Paterson and Miller, 1998b; Miller et al., 2006). Crustal thickening by contraction (e.g., Evans and Berti, 1986; Whitney et al., 1999), arguably aided by magmatic additions (Brown and Walker, 1993), resulted in an arc crust that was ≥55 km thick in the Cretaceous (Miller and Paterson, 2001b; Miller et al., 2009).

The dominantly tonalitic Tenpeak pluton is part of a belt of mid-Cretaceous (96–88 Ma) intrusions that crystallized at ~700 MPa–1.0 GPa (Walker and Brown, 1991; Dawes, 1993; Miller et al., 2009) and contain magmatic epidote (Cater, 1982; Zen and Hammarstrom, 1984). This places the pluton at ~25–35 km

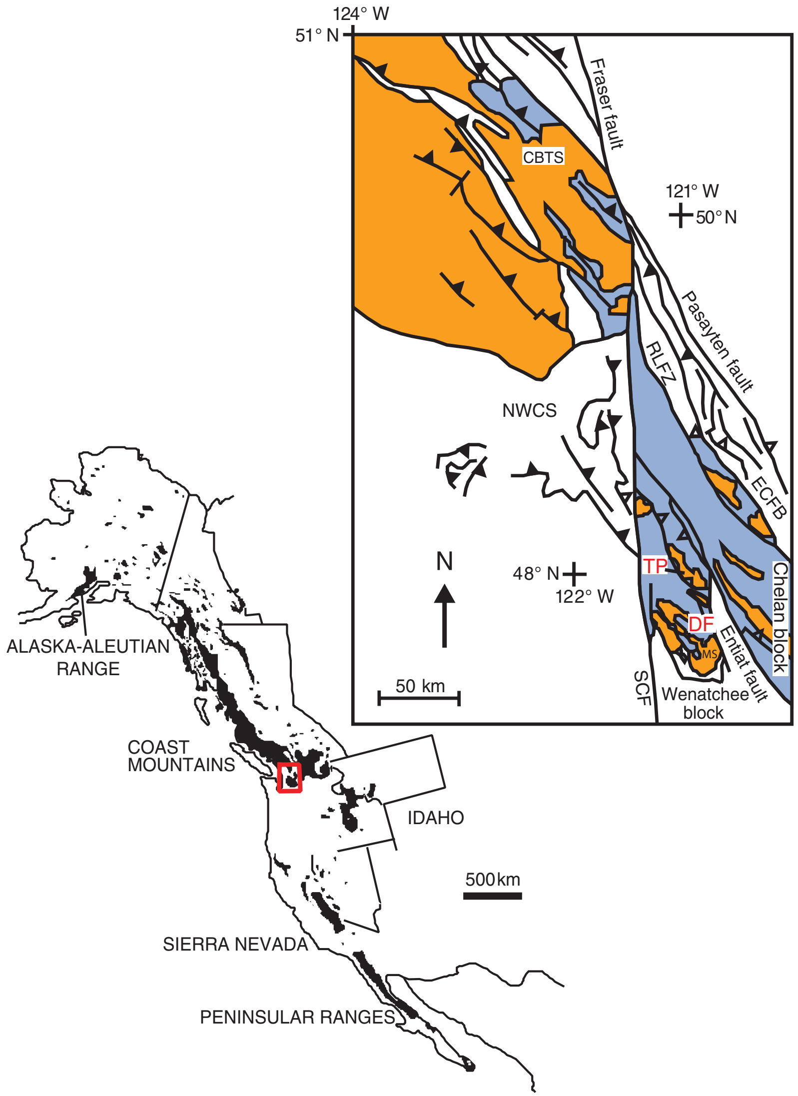


Figure 1. Generalized map of Mesozoic and Paleogene western North American Cordilleran arc plutons (black). Red box highlights the area of the inset, which emphasizes the distribution of metamorphic rocks and plutons in the Cascade Range core and southern Coast belt. The Coast belt thrust system (CBTS), Eastern Cascades fold belt (ECFB), Northwest Cascades thrust system (NWCS), and reverse shear zones in the Cascades core are also shown. The dextral Fraser–Straight Creek fault (SCF) displaces the Cascades core from the main part of the Coast belt. The Entiat fault, Pasayten fault, and Ross Lake fault zone (RLFZ) are also major high-angle faults; the Cascades core is divided by the Entiat fault into the Chelan and Wenatchee blocks, which have different thermal histories. Dirtyface (DF) pluton and Tenpeak (TP) pluton are highlighted with red labels.

depth in the thick arc. The pluton is an elongate body in map view with an aspect ratio of ~5:1, and has a northeastern protrusion referred to as the White Mountain lobe (Fig. 2). We have subdivided the Tenpeak pluton into a number of units, most of which have been precisely dated (isotope dilution–thermal ionization mass spectrometry [ID-TIMS] on zircon; Matzel et al., 2006). These include: (1) the ca. 92.2 Ma *mafic complex*; (2) the ca. 92.3–91.8 Ma *Schaefer Lake tonalite*, which includes the ca. 91.8 Ma *sheeted complex*; (3) the ca. 91.3 Ma *tonalitic gneiss*; (4) the undated *interlayered unit*; (5) the ca. 90.6 Ma *northern mafic tonalite*; and (6) the ca. 89.7 Ma *Indian Creek tonalite* (Fig. 2).

We have also examined the ca. 91 Ma Dirtyface pluton (Hurlow, 1992), which is located just south of the Tenpeak pluton (Fig. 1). The Dirtyface intrusion is an internally sheeted body that has an aspect ratio of 3:1 in map view and, assuming an overall elliptical shape, was probably ~5:1 before truncation and removal of one end by the Eocene Leavenworth fault (Fig. 3). Examination of this tonalitic to locally dioritic body provides additional information on how parts of the Tenpeak pluton formed and evolved petrologically.

The Tenpeak pluton intrudes the Napeequa complex (Napeequa Schist of Cater and Crowder [1967]) on the east and north (Figs. 2, 4). This unit is dominated by amphibolite and quartzite (metachert), some biotite schist, and minor metaperidotite and calc-silicate rock (e.g., Cater and Crowder, 1967; Tabor et al., 1989). Concordant undated tonalitic sheets, ranging from 10 cm to 1 km in thickness, probably make up >30% of the Napeequa outcrop belt (Miller et al., 2009) and commonly record greater solid-state deformation than Tenpeak rocks. On the southwest, the Tenpeak pluton intrudes the dominantly metapelitic and metapsammitic Chiwaukum Schist, which also includes amphibolite, metaperidotite, and rare marble (Plummer, 1980; Tabor et al., 1989). The Dirtyface pluton intrudes the Chiwaukum Schist (Fig. 3).

These plutons were emplaced during the major mid-Cretaceous dynamothermal metamorphic event of the North Cascades, and yield pressures similar to those recorded by nearby metamorphic rocks. Thermobarometric determinations, utilizing the garnet-plagioclase-aluminosilicate-quartz and garnet-hornblende methods, from the Chiwaukum Schist and Napeequa unit near the Tenpeak and Dirtyface plutons, are ~650–680 °C and 750–900 MPa and ~565 °C and 860–980 MPa, respectively (Brown and Walker, 1993; Magloughlin, 1993; Whitney et al., 1999; Stowell et al., 2007). A xenolith of kyanite-bearing schist in the Dirtyface pluton records values of ~650 °C and 900 MPa (Miller et al., 2000). Results using the Al-in-hornblende barometer (Schmidt, 1992) from this study and Dawes (1993) yield average pressures of 700–900 MPa for the Tenpeak pluton and ~700 MPa for one sample of the Dirtyface pluton. These data suggest emplacement at ~25–30 km depths.

The regional structure of the host rocks is described in detail by Paterson et al. (1994) and Miller et al. (2006). The Chiwaukum Schist is structurally overlain by the Napeequa unit across the NE-dipping, reverse-slip White River shear zone (Figs. 2, 4) (e.g., Van Diver, 1967; Magloughlin, 1993). The map-scale structure of the Napeequa unit is dominated by an asymmetric, gently SE-plunging synform with a steeply NE-dipping axial plane and a minimum wavelength of 7 km. The Dirtyface pluton occupies the NE-dipping limb of a subhorizontal

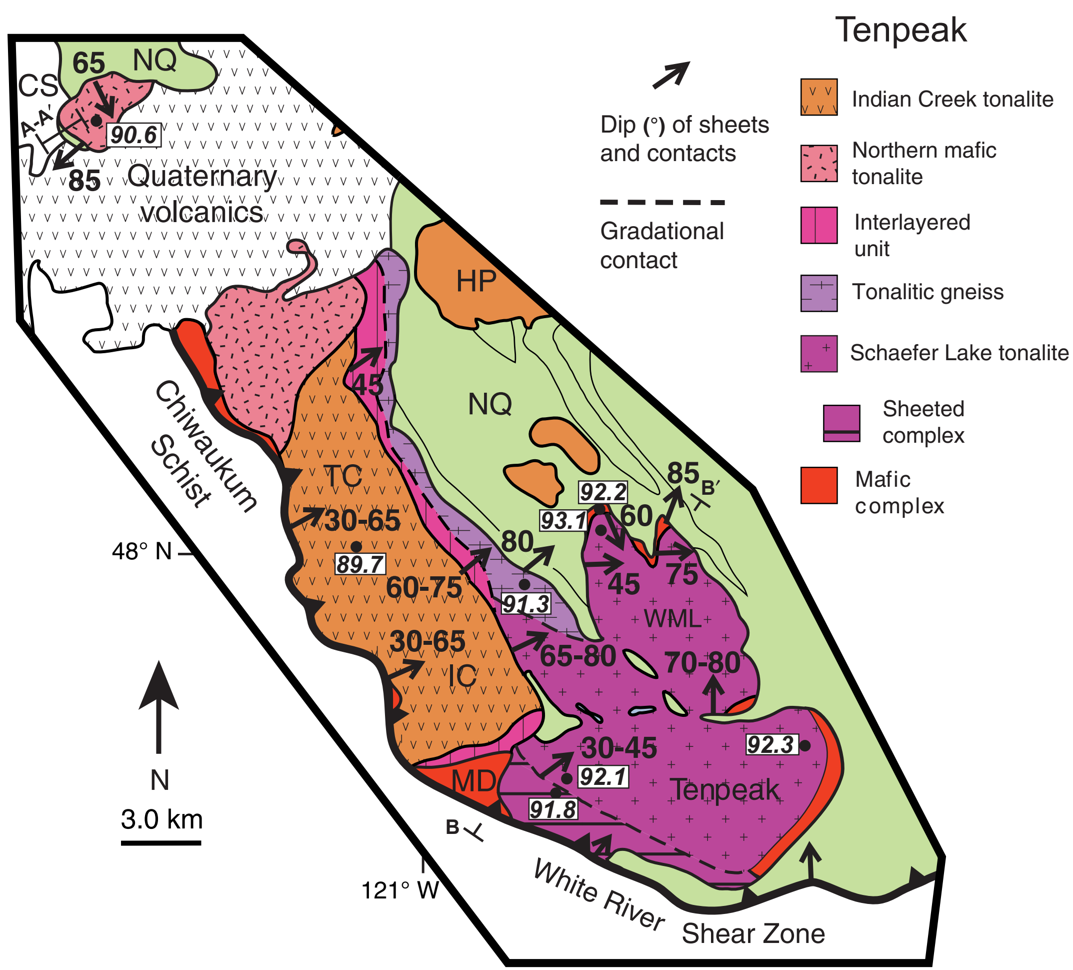
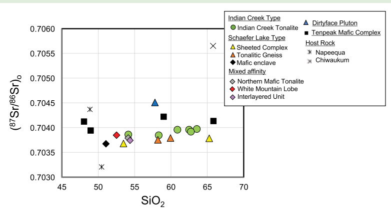


Figure 2. Simplified map of the Tenpeak pluton and adjacent rocks, emphasizing units, dips of contacts, U-Pb (zircon) crystallization ages, and specific localities in the pluton. CS—Chiwaukum Schist; HP—High Pass pluton; IC—Indian Creek; MD—Mount David; NQ—Napeequa unit; TC—Thunder Creek; WML—White Mountain lobe. Lines in the Napeequa unit represent contacts between subunits of quartzite, amphibolite, and biotite schist. A-A′ and B-B′ are lines for the cross sections shown in Figure 4. Ages are from Matzel et al. (2006). Subdivisions of the Tenpeak pluton include those based on our mapping and others modified from Cater and Crowder (1967), Crowder et al. (1966), and Tabor et al. (1987).



[1]Supplemental Material. Figure S1: Plot of initial Sr versus SiO_2. Table S1: Supplementary descriptions of units and structures of the Tenpeak pluton and Dirtyface pluton. Table S2: Whole rock geochemical data (major and trace elements) for the Tenpeak and Dirtyface plutons. Table S3: Sr, Nd, and Pb isotope composition for rocks of the Tenpeak pluton, Dirtyface pluton, and host rock. Supplementary File 1: Analytical methods. Please visit http://doi.org/10.1130/GES01490.S1 or the full-text article on www.gsapubs.org to view the Supplemental Material.

to gently WNW-plunging, upright regional antiform in the Chiwaukum Schist. On the outcrop scale, multiple cycles of folding of foliation dominate in both the Chiwaukum and Napeequa rocks (Paterson et al., 1994; Miller et al., 2006). Axial planes are on average close to the regional orientation of the dominant folded, WNW- to NW-striking foliation, and hinge lines are broadly subparallel to the gently to moderately NW- or SE- to E-plunging mineral lineation.

There is no geobarometric or thermochronologic evidence for major tilting of either pluton. Ar/Ar and K-Ar biotite and muscovite cooling ages ($n = 5$) for the Tenpeak pluton range from ca. 77 to 67 Ma (Engels et al., 1976; Matzel, 2004) and show no consistent spatial pattern. On a regional scale, metamorphic pressures increase and cooling ages decrease from southwest to northeast (e.g., Brown and Walker, 1993).

MAP-SCALE UNITS OF THE TENPEAK PLUTON

In the following, we describe each of the main units of the Tenpeak pluton (Fig. 2) in inferred chronological order, starting with the oldest rocks. In general, the older units are in the southeast. Additional descriptions are given in Supplemental Table S1[1].

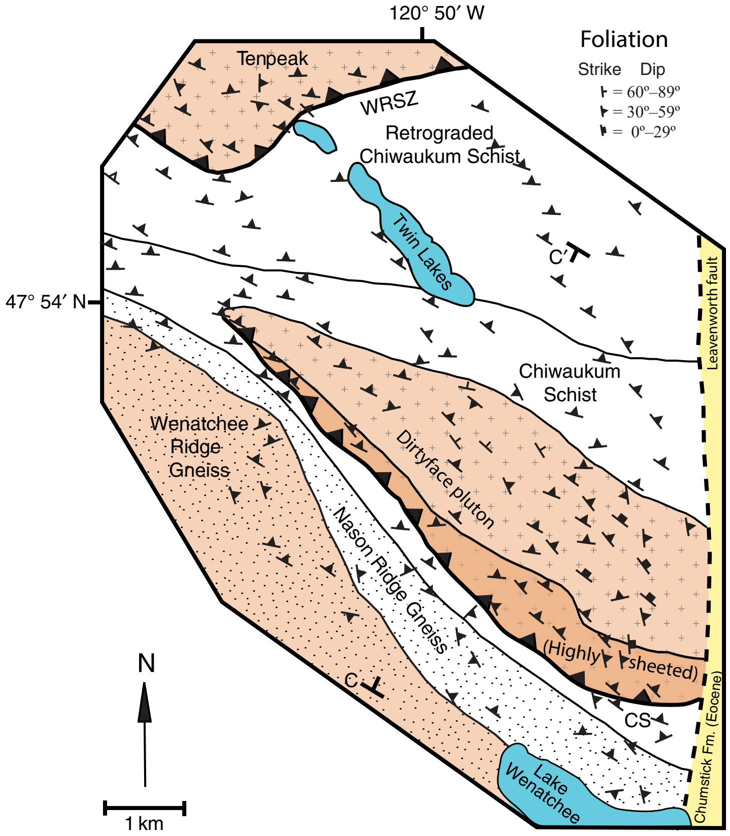


Figure 3. Simplified map of the Dirtyface pluton, adjacent units, and foliation orientations. Note that most foliation dips are 30°–60°. C-C′ is the line of the cross section shown in Figure 4. CS—Chiwaukum Schist; WRSZ—White River shear zone.

Mafic Complex

The margin of the Tenpeak pluton contains a discontinuous, narrow (<25 m to 1.2 km wide) and heterogeneous zone of gabbro, diorite, tonalite, and hornblendite that we refer to as the mafic complex ("contact complex" of Cater [1982]) (Fig. 2). These rocks enclose abundant rafts and xenoliths of the Napeequa unit and locally the Chiwaukum Schist. Rocks of the mafic complex are intermixed on the centimeter to meter scale and display intricate mingling textures. Abundant sheets are typically 10 cm to 2 m wide and have sharp to diffuse contacts.

Hornblendite is a distinctive component of the complex. It commonly occurs as meter-scale lenses and irregularly shaped masses. Foliation and schlieren in enclosing mingled gabbro, diorite, and tonalite typically wrap the hornblendite bodies. Hornblendite xenoliths are also disaggregated by trondhjemitic veinlets; angular boundaries suggest fracturing during injection.

The mafic complex is in contact with tonalitic units of different ages. In places, mafic rocks are cut by tonalites, and in other places there are mutually intrusive relationships and mingling textures. Field relationships do not conclusively demonstrate that these co-magmatic felsic rocks are the same age as the adjacent interior tonalitic unit, but such a relationship is supported by geochronologic data. A diorite in the northern margin of the White Mountain lobe is 92.22 ± 0.17 Ma, which overlaps with the crystallization age of adjacent Schaefer Lake tonalite (Matzel et al., 2006). If the co-magmatic tonalites are synchronous elsewhere with their adjacent interior tonalities (e.g., Indian Creek tonalite), then this implies that the mafic complex formed over a wide range of ages.

Schaefer Lake Tonalite

The 92.27 ± 0.09 to 91.83 ± 0.12 Ma (Matzel et al., 2006) Schaefer Lake tonalite forms much of the southeastern part of the pluton (Fig. 2). The Schaefer Lake rocks in the White Mountain lobe are separated from the rest of the unit by map-scale, NW-trending Napeequa inclusions and a tongue of Napeequa unit on the east. The southern part of the tonalite, adjacent to the White River shear zone, is mapped separately as the sheeted complex (Miller and Paterson, 1999; Miller et al., 2009; Chan et al., 2017) (Fig. 2).

Outside of the sheeted complex, the Schaefer Lake unit is dominantly medium-grained tonalite, which has more biotite than hornblende, contains widespread mafic magmatic enclaves, and is composed of many bodies that differ slightly to substantially in color index and grain size. Sheeting is common, and individual sheets are typically 25 cm to tens of meters in width. Contacts are sharp to gradational, and some are marked by zones of schlieren and abundant mafic magmatic enclaves that can be traced for at least 30 m along strike.

Enclaves locally are so highly elongated (aspect ratios of >10:1) that they form banding, and there is apparent hybridization of tonalite and mafic material. Diffuse schlieren and well-developed compositional and grain-size layers (most 1–12 cm thick) are commonly associated with enclave concentrations. The largest mapped enclave swarm is weakly elongate (~300 m long) in map view and may represent a pipe-like conduit (Fig. 5A).

The *sheeted complex* is a more extensively sheeted subdivision of the Schaefer Lake tonalite (Miller et al., 2009), and part of it has been studied recently in detail (Chan et al., 2017). It consists mainly of tonalite and less-common diorite sheets that form a ≤1.5-km-wide zone along part of the southwestern margin of the pluton (Fig. 2). Eight dated sheets range from 91.929 ± 0.023 Ma to 91.835 ± 0.027 Ma, only slightly younger than the main part of the Schaefer Lake tonalite (Matzel et al., 2006; Chan et al., 2017). Color index and the ratio of biotite to hornblende vary between sheets. Many of the tonalites broadly resemble those in the rest of the Schaefer Lake unit.

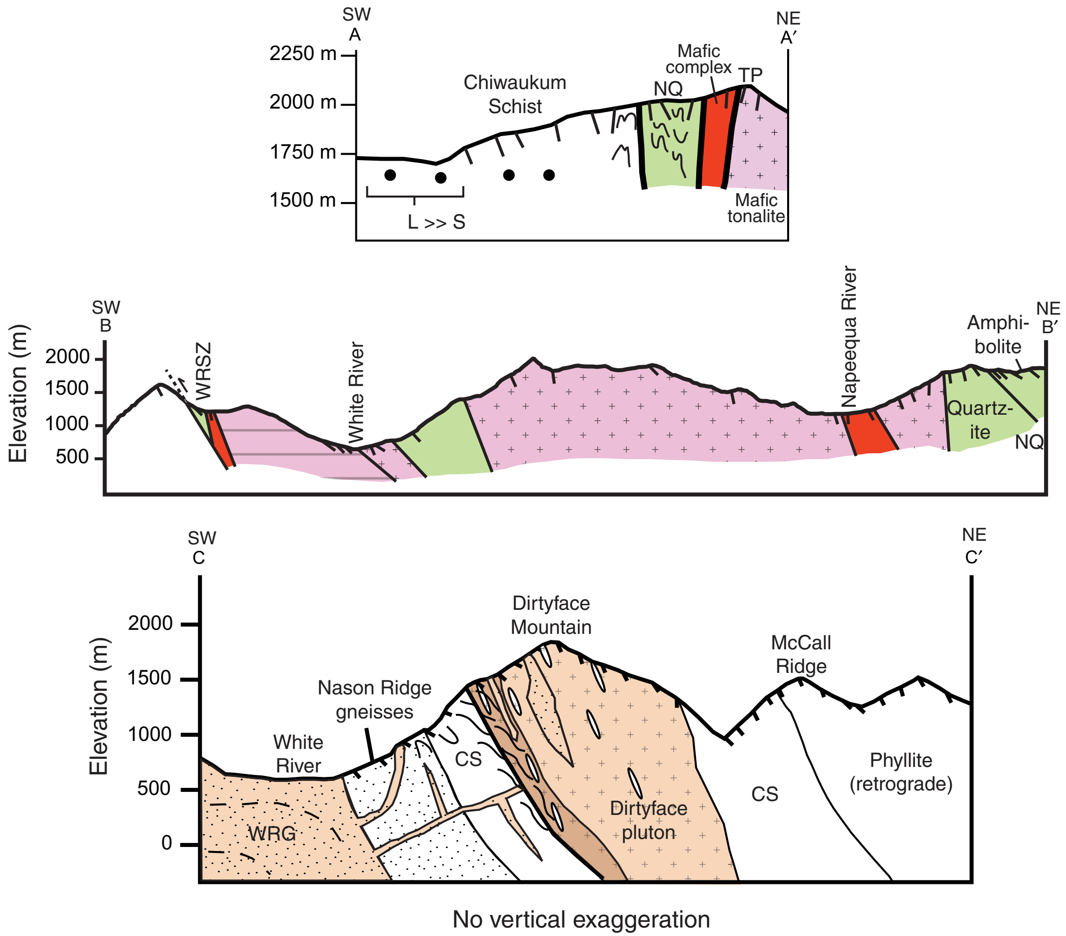


Figure 4. Cross sections through the Tenpeak and Dirtyface plutons. Lines of cross sections A-A′ and B-B′ are shown on Figure 2, and C-C′ on Figure 3. Bold tick marks on the topographic profiles show measured dips of foliation, and dashed lines approximate foliation traces projected into sections. Filled circles in A-A′ indicate strong gently plunging lineation. CS—Chiwaukum Schist; L—lineation; NQ—Napeequa unit; S—foliation; TP—Tenpeak pluton; WRG—Wenatchee Ridge Gneiss; WRSZ—White River shear zone. Colors and patterns are the same as in Figures 2 and 3.

In our most detailed traverses through nearly 100% exposure (>250 m thick), individual sheets and compositional layers are mostly 5 cm to 2 m in thickness and thicken inward (northeastward) (Fig. 5B) (also see Chan et al., 2017). Contacts range from sharp to “blurred”, and in places, there is so much interaction between injections of felsic and mafic magmas that compositional layering formed at the centimeter scale. Mingling textures, such as incorporation of coarse plagioclase grains from felsic sheets within finer-grained mafic sheets, and gradational color variations attest to the interplay between these magma types (Fig. 5C). Dikes (10 cm to 1 m thick) of porphyritic tonalite, pegmatitic trondhjemite, and muscovite-bearing felsic rock cut the complex.

Tonalitic Gneiss

A ~1-km-wide belt of tonalitic gneiss (flaser gneiss of Crowder et al. [1966] and Cater and Crowder [1967]), which in places is protomylonitic, forms the northeastern boundary of the northern half of the Tenpeak pluton (Fig. 2). The tonalitic gneiss–Schaefer Lake tonalite contact was arbitrarily drawn on the basis of the amount of solid-state deformation. This gradational relationship suggests that the units are broadly equivalent, which is supported by our geochemical data; however, the 91.28 ± 0.09 Ma tonalitic gneiss is younger than the ca. 92.3 to 91.8 ± 0.12 Ma Schaefer Lake tonalite (Matzel et al., 2006). The greater solid-state deformation in the younger rocks probably reflects its

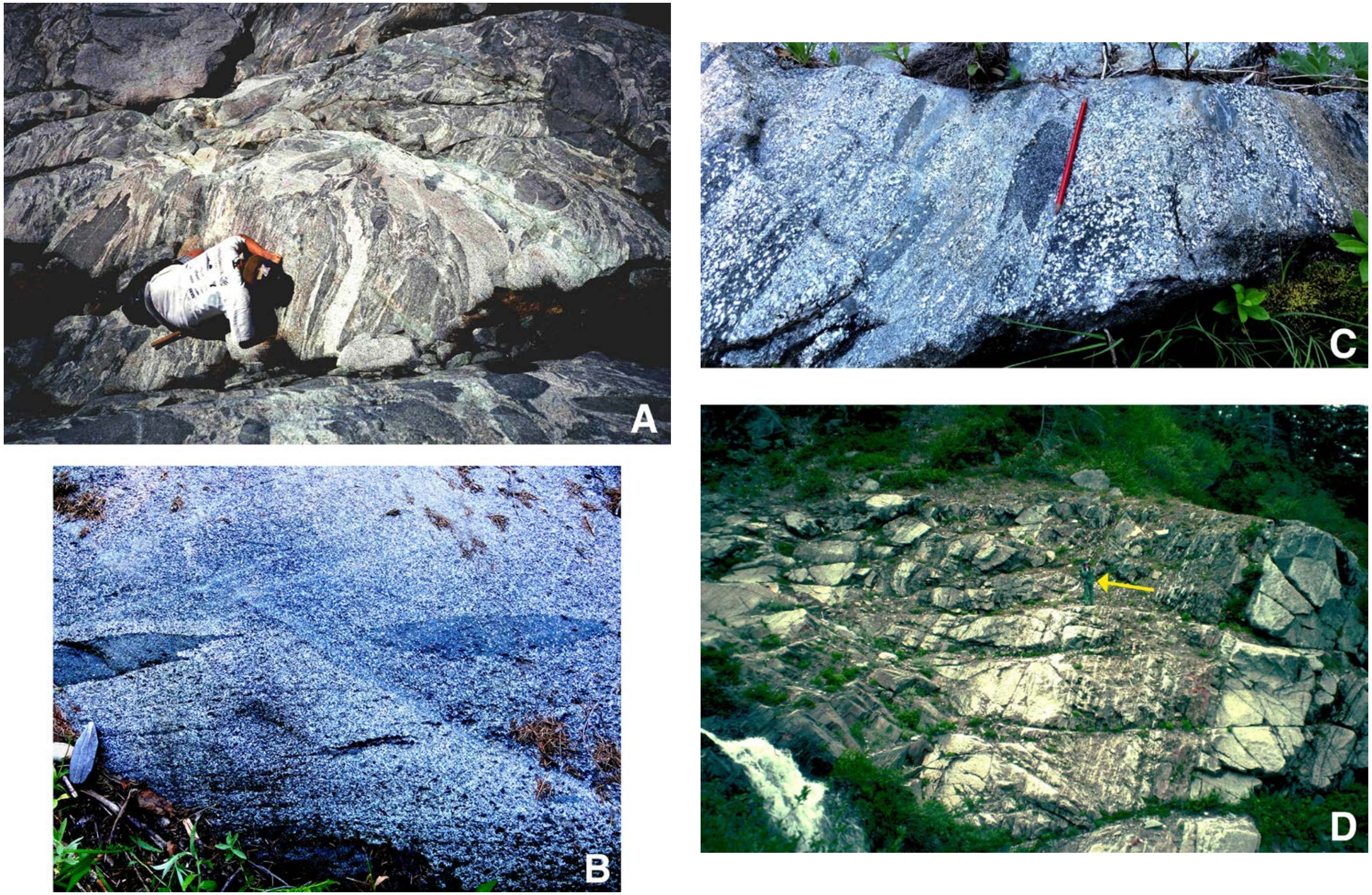


Figure 5. Field relationships in the Tenpeak pluton. (A) Mingled domain in the Schaefer Lake unit of the White Mountain lobe. This zone of mingling of hornblende-rich gabbro and tonalite defines an elliptical (in map view), steeply SE-plunging zone parallel to a steeply plunging magmatic lineation. Various blocks of layered plutonic material, some likely cognate inclusions, also occur within the mingling zone. (B) Contact between mafic and felsic tonalite sheets in the sheeted complex. Note the discordance of magmatic foliation (parallel to elongation of enclaves) to the contact. (C) "Hybridized zone" in the sheeted complex. A variety of enclaves of mafic and felsic tonalite, and local hornblendite, occur within a fine-grained matrix containing large plagioclase crystals inferred to have been mechanically mixed from coarser-grained tonalite. (D) Alternating tonalite (light color) and amphibolite in the interlayered unit. Note the 1.9-m-tall person (yellow arrow) for scale.

position in the pluton margin. The lack of consistent kinematic indicators implies that the gneiss does not represent a significant shear zone, although we cannot rule out early non-coaxial shear followed by flattening.

Interlayered Unit

The interlayered unit crops out in a 500-m- to 1-km-wide, NNW-trending zone of tonalite and rafts (~3 cm to 2 m thick) of amphibolite and other rocks of the Napeequa unit that extends for ~12 km in the northern half of the pluton (Cater and Crowder, 1967; Tabor et al., 1987), and in a smaller area in the southwestern part of the pluton (Fig. 2). It, in part, separates the Indian Creek tonalite on the southwest from the Tonalitic gneiss unit on the northeast. Tenpeak sheets are generally thicker than the rafts (Fig. 5D), and the gradational northeastern contact of the unit is marked by increasingly thick sheets. Contacts are concordant to locally mildly discordant (~10°) to foliation. The granitoid sheets resemble tonalite of the Schaefer Lake and tonalitic gneiss units. We retain this as a separate unit because of its abundant host rock rafts, spatial position, unknown age, and geochemical traits described below.

Northern Mafic Tonalite

The northernmost part of the Tenpeak pluton is medium- to coarse-grained mafic tonalite, and minor diorite and quartz diorite. Rocks resembling the Schaefer Lake tonalite are most common, but Indian Creek–like rocks (described below) are also present. One sample of tonalite crystallized at 90.6 ± 0.1 Ma (Matzel et al., 2006).

Indian Creek Tonalite

The 89.7 ± 0.1 Ma Indian Creek tonalite (Matzel et al., 2006) makes up much of the western part of the Tenpeak pluton. It is the youngest unit in the intrusion and truncates internal features of the Schaefer Lake tonalite (Miller and Paterson, 1999; Matzel et al., 2006) (Fig. 2). Indian Creek rocks form the most homogeneous unit in the pluton and have the weakest solid-state deformation. The unit is dominantly coarse-grained tonalite; hornblende is more abundant than biotite, or the two occur in subequal amounts, in contrast to the commonly more biotite-rich Schaefer Lake tonalite. Mafic magmatic enclaves are common, and generally have much lower aspect ratios than those in the Schaefer Lake tonalite.

DIRTYFACE PLUTON

The Dirtyface pluton consists of a southwestern and larger northeastern unit (Fig. 3). Both are elongate northwest-southeast, parallel to the long axis of the pluton. Additional descriptions of the pluton are given in Table S1 (footnote 1).

The southwestern unit is intensely sheeted and more compositionally variable than the northeastern unit (Fig. 3). Northwest-striking, NE-dipping (25°–55°) sheets range from <0.5 m to 5 m in thickness. Sheets vary from diorites to the dominant tonalites to leucotonalites, and are commonly internally layered. Color index and the ratio of biotite to hornblende vary between sheets. Some sheets are separated by rafts of Chiwaukum Schist and locally include blocks of rotated schist (Fig. 4C).

In the northeastern unit, sheets of tonalite and minor diorite dip more steeply to the northeast. Layering is common, and host rock rafts and blocks are rare. Magmatic microgranitoid enclaves are found locally in sheets and display mingling textures with the host tonalite.

MINERALOGY, WHOLE ROCK GEOCHEMISTRY, AND ISOTOPE COMPOSITIONS OF THE TENPEAK AND DIRTYFACE PLUTONS

The Tenpeak pluton contains hornblende-rich rocks, inferred to be either cumulate or non-cumulate in origin depending on bulk-rock chemistry and texture as described below. We describe the textural and geochemical characteristics of each below.

The dominant tonalite of the Tenpeak pluton consists of plagioclase, hornblende, biotite, quartz, and magmatic epidote (± minor magmatic sphene, apatite, and garnet) in differing proportions that define a continuous variation from mafic to felsic tonalite. The Schaefer Lake tonalite has a higher ratio of biotite to hornblende than the Indian Creek tonalite, but otherwise the tonalites are modally similar. Plagioclase is the most abundant mineral (>40%), but more mafic tonalites have higher proportions of hornblende to biotite and lesser quartz and plagioclase than the felsic tonalite. Hornblende locally contains cores of pyroxene. Magmatic epidote occurs as coarse subhedral to euhedral grains intimately associated with biotite, quartz, and hornblende (Cater, 1982; Zen and Hammarstrom, 1984). Euhedral, 1–2 mm grains of garnet (<5% by mode), which contain few inclusions and are interpreted as magmatic, are found locally in the tonalitic gneiss, northern mafic tonalite, and Indian Creek tonalite. Potassium feldspar is rare to absent.

Mafic and ultramafic rocks displaying cumulate textures consist dominantly of euhedral cumulate hornblende (50%–95% by mode) and intercumulate plagioclase (5%–30%), ± apatite, epidote, and zoisite. In a few ultramafic samples, hornblende is a pseudomorph after pyroxene, and only rare pyroxene cores are left.

Mafic rocks lacking obvious cumulate textures occur as sheets and enclaves within all phases. They display hypidiomorphic granular texture and consist of variable proportions of hornblende and plagioclase, ± sphene, apatite, and epidote.

In the Dirtyface pluton, samples showing little solid-state deformation are marked by well-aligned, euhedral to subhedral hornblende, biotite, and zoned plagioclase that is commonly saussuritized. Unequivocal magmatic epidote has not been recognized.

Rocks of the Tenpeak and Dirtyface plutons span a wide geochemical compositional range (Fig. 6; Table S2 [footnote 1]; see description of analytical methods in Supplementary File 1 [footnote 1]). Rocks with >55% presumed cumulus hornblende uniformly have ≤51 wt% SiO_2. They are distinct in their rare-earth-element (REE) patterns from rocks lacking cumulus textures, in that they have the typical concave-down pattern of hornblende and a small negative Eu anomaly (Fig. 7). We interpret these rocks to be hornblende cumulates. In contrast, we interpret rocks with >51 wt% SiO_2, much flatter REE patterns, and no Eu anomalies in the most mafic samples to represent liquid compositions (Fig. 7).

Hornblende cumulates in the mafic complex contain 48–51 wt% SiO_2, and intermixed silicic tonalites contain up to 68 wt% SiO_2 (Fig. 6). The cumulates contain 7–14 wt% MgO and 7–12 wt% FeO. Some of the hornblende grains are pseudomorphs after pyroxene; thus, those cumulate samples with moderate amounts of Ni (20–50 ppm) and high Cr (100–350 ppm) could be a result of accumulation of pyroxene, which was later replaced by peritectic reaction to hornblende.

Rocks without obvious cumulus textures (and without cumulate REE patterns) in the Tenpeak pluton range from 51 to 66 wt% SiO_2 and 2–8 wt% MgO.

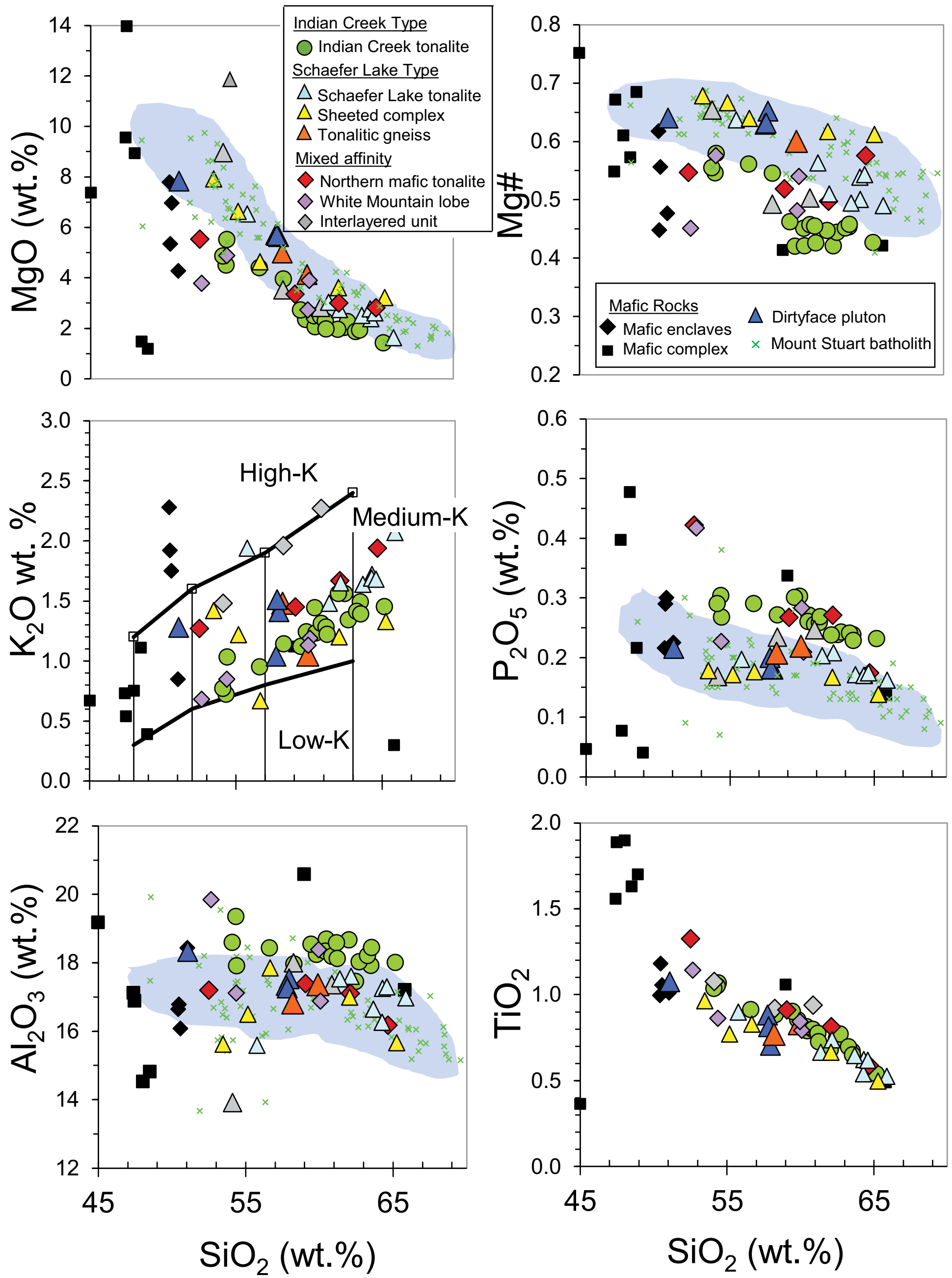
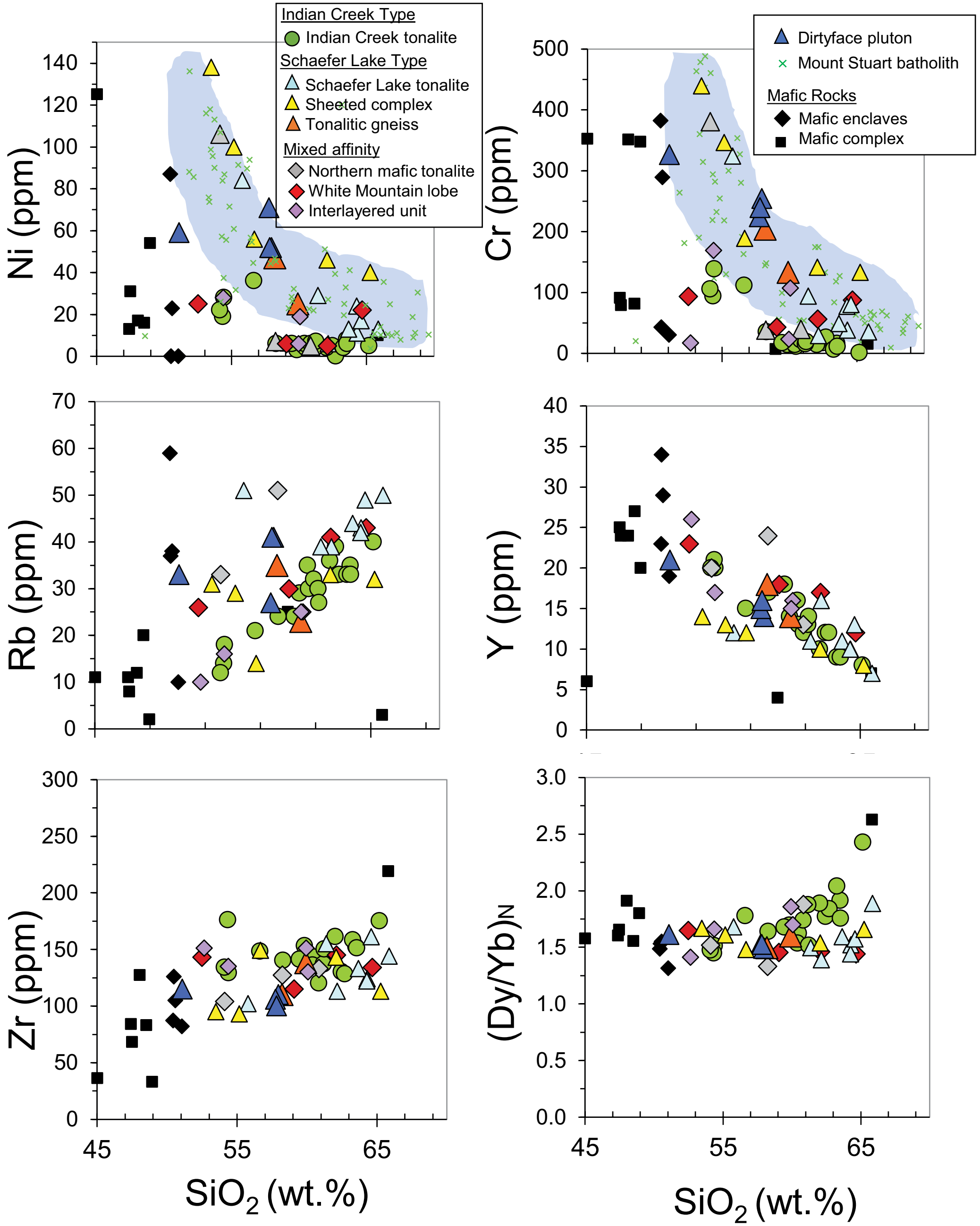


Figure 6 ***(continued on following page)*****. Plots of various oxides and trace elements against SiO_2 for units of the Tenpeak and Dirtyface plutons. Triangular symbols of varying color represent units that are made up of Schaefer Lake subtype magmas. Circular symbols represent units that are made up of Indian Creek subtype magmas. Diamond-shaped symbols represent units with samples of both magma types. Samples from the Mount Stuart batholith (data from Paterson et al., 1994) are shown for comparison in panels where there is a clear distinction between Schaefer Lake and Indian Creek subtype magmas (the Mount Stuart data field is also shaded in light blue). Mafic complex constituents (both mafic and felsic) are solid black squares. Mafic enclaves and sheets are solid black diamonds N—chondrite-normalized value. Mg# is 100 × Mg / (Mg + Fe_T).**



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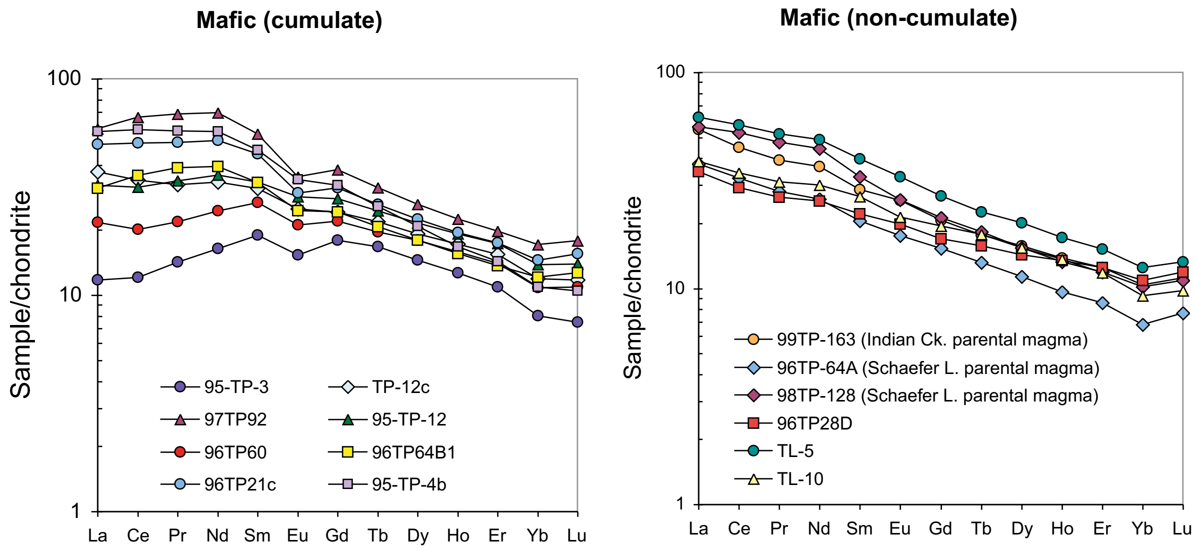

Figure 7. Rare-earth-element patterns of mafic sheets and enclaves (<55% SiO_2) from the mafic complex and larger bodies of tonalite (Schaefer Lake and Indian Creek). (A). Samples from mafic sheets that have characteristics of hornblende cumulates. (B). Samples from mafic sheets and enclaves that may represent liquid compositions. Three of these samples are chosen as potential parental magmas for the suites (53.5%–54.5% SiO_2, 5.5–9.0 wt% MgO). See text for details. Normalization factors are from Sun and McDonough (1989).

The most mafic compositions occur in sheets in the mafic complex and mafic enclaves (Fig. 6; Table S2 [footnote 1]). The Dirtyface pluton is overall more mafic and has compositions of 51–58 wt% SiO_2. Rocks in both plutons with >55 wt% SiO_2 plot in the tonalite field on normative anorthite-albite-orthoclase (An-Ab-Or) diagrams and display a medium-K calc-alkaline trend. They have 3.5–4.5 wt% Na_2O and average 16–19 wt% Al_2O_3. The compositions are typical of arc magmas worldwide. All rocks have characteristic arc trace element signatures with enrichments in large-ion-lithophile elements (LILE) and depletions in high-field-strength elements (HFSE) (Fig. 8). Notably, the presumed non-cumulate plutonic rocks are high in Sr (500–1000 ppm) and low in Y (7–26 ppm), producing high Sr/Y ratios (Fig. 9), which increase strongly with weight percent SiO_2 (not shown). The tonalites also have steep REE patterns (average La/Yb = 25) (Fig. 10).

Geochemical trends throughout the Tenpeak pluton display decreasing Y and Yb with increasing weight percent SiO_2 (Fig. 10). La/Yb increases with increasing SiO_2, and this is shown most strikingly in the sheeted complex (Fig. 11) where the most mafic (inferred non-cumulate) bulk compositions (8 wt% MgO) have the flattest REE patterns, and the patterns become progressively steeper with increasing SiO_2 content. The Dy/Yb ratio is high ($[Dy/Yb]_N$ = 1.5–2.5 [N—chondrite-normalized value]) and increases or stays constant with increasing SiO_2, depending on the subunit (Fig. 6). Samples from the Dirtyface pluton are more compositionally homogenous, but their compositions fall within the range of the Tenpeak samples.

Within this overall framework, there are noteworthy variations that separate the Tenpeak pluton into two main geochemical subtypes. Rocks composing the Schaefer Lake tonalite have geochemical characteristics that distinguish them from younger rocks of the Indian Creek tonalite. Most notably, the Schaefer Lake magma subtype contains higher MgO, Ni, and Cr and lower P_2O_5 for a given SiO_2 content than the Indian Creek subtype (Schaefer Lake subtype samples are colored triangles in Fig. 6). It is found in most of the Schaefer Lake tonalite, including the sheeted complex, and in some samples in the northern mafic tonalite and interlayered unit. The Dirtyface pluton also falls within this subtype. The Mg#s [100 × Mg / (Mg + Fe_T)] in the Schaefer Lake subtype are higher than those of typical arc magmas, and are comparable to those of high-Mg andesites from Japan (Tatsumi, 2006) and parts of the modern Cascades (Grove et al., 2002; Baggerman and DeBari, 2011). This compositional subtype is also compositionally similar to the roughly coeval, shallower Mount Stuart batholith (Paterson et al., 1994) (Fig. 6).

In contrast, rocks of the Indian Creek tonalite are poorer in MgO, Ni, and Cr for a given SiO_2 content, but richer in Al_2O_3 and P_2O_5, than those of the Schaefer Lake magma subtype (Indian Creek subtype samples are colored circles in Fig. 6). The Indian Creek subtype is also found in lesser amounts within the

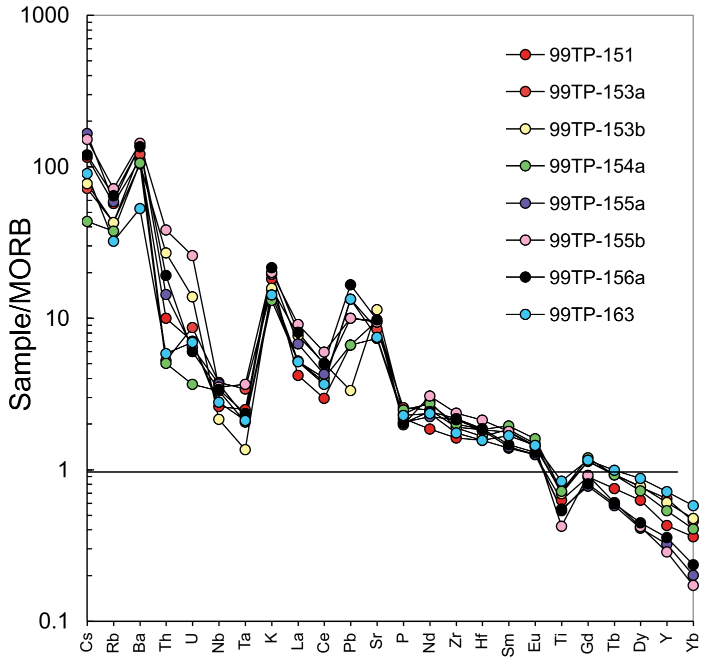

Figure 8. Mid-ocean ridge basalt (MORB)–normalized trace element diagram for representative samples of the Tenpeak pluton (54–65 wt% SiO_2). Note pattern of enrichments and depletions, especially in Nb and Ta, that are characteristic of arc magmas. Also note strong depletions in trace elements that are compatible in garnet (Gd to Yb).

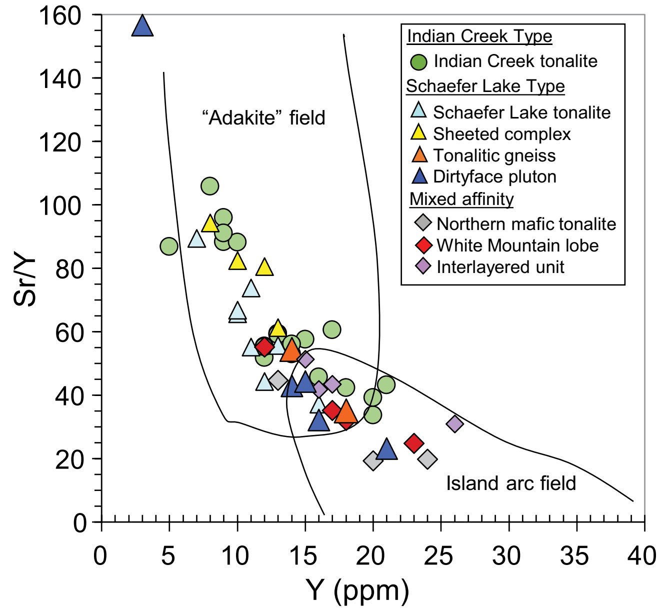

Figure 9. Plot of Sr/Y against Y for Tenpeak and Dirtyface diorites and tonalites. More mafic compositions (<55% SiO_2) plot in the island arc field. More felsic compositions (>55% SiO_2) plot in the "adakite" field of Defant and Drummond (1993). Note that the high Sr/Y and the high Dy/Yb ratios seen in Figure 6 support involvement of garnet in the source of these magmas. See text for details.

Schaefer Lake tonalite in the White Mountain lobe, and in some samples in the northern mafic tonalite and interlayered unit. In the Indian Creek area (Fig. 2), the Indian Creek subtype is compositionally restricted; the rocks contain 59–63.5 wt% SiO_2 and 2.0–2.5 wt% MgO (Fig. 6). Farther north (Thunder Creek basin; Fig. 2), there is a wider compositional range, from 54 to 65 wt% SiO_2 (1.4–5.5 wt% MgO) (Fig. 6).

The mix of textural types in the northern mafic tonalite (described above in the Map-Scale Units section) is matched by geochemical attributes. Some mafic tonalites have geochemical affinity to the Schaefer Lake magma subtype, and some to the Indian Creek magma subtype.

The limited number of analyses of the Dirtyface pluton suggest that it is compositionally more restricted than the Tenpeak pluton. Tonalites have ~58 wt% SiO_2 and diorites have ~51 wt% SiO_2. The tonalites have the relatively high MgO (~5.7 wt%) and Ni (50–70 ppm) characteristic of the Schaefer Lake subtype (Fig. 6). REE patterns of the tonalites are similar to those of Tenpeak samples with similar SiO_2 contents.

All units of the Tenpeak and Dirtyface plutons contain mafic magmatic enclaves that have clear mingling textures (Fig. 5C), which supports the interpretation that mafic magmas were inputs into the magma system throughout pluton growth. The enclave geochemistry indicates that some are cumulates (concave-down REE patterns), whereas others more likely represent liquid compositions (flat REE patterns) (Fig. 7). The latter have 51–52 wt% SiO_2, 4–9 wt% MgO, 1.2–1.4 wt% TiO_2, and 14–19 wt% Al_2O_3 (Table S2 [footnote 1]). Their compositions are equivalent to those of high-Al basalts typical of magmatic arcs worldwide (Perfit et al., 1980). They have moderate Ni (35–65 ppm) and Cr (60–225 ppm) contents (Fig. 6) and high Ba/Nb (~85). The REE patterns are flatter than those of the tonalites, with $(La/Yb)_N$ of ~3–8 (Figs. 7, 10).

Lead (Pb), Nd, and Sr isotopes of the plutons and host rocks were measured at the University of North Carolina (see Supplemental File 1 [footnote 1]). The Tenpeak pluton spans a range of isotopic values that lie between end members defined by its host rock of the Napeequa unit and Chiwaukum Schist (Fig. 12). Two Napeequa samples were analyzed: an amphibolite that is isotopically similar to primitive mantle (initial ε_{Nd} = +7), and a biotite-quartz–bearing amphibolite that is more isotopically evolved (initial ε_{Nd} = +2.8).

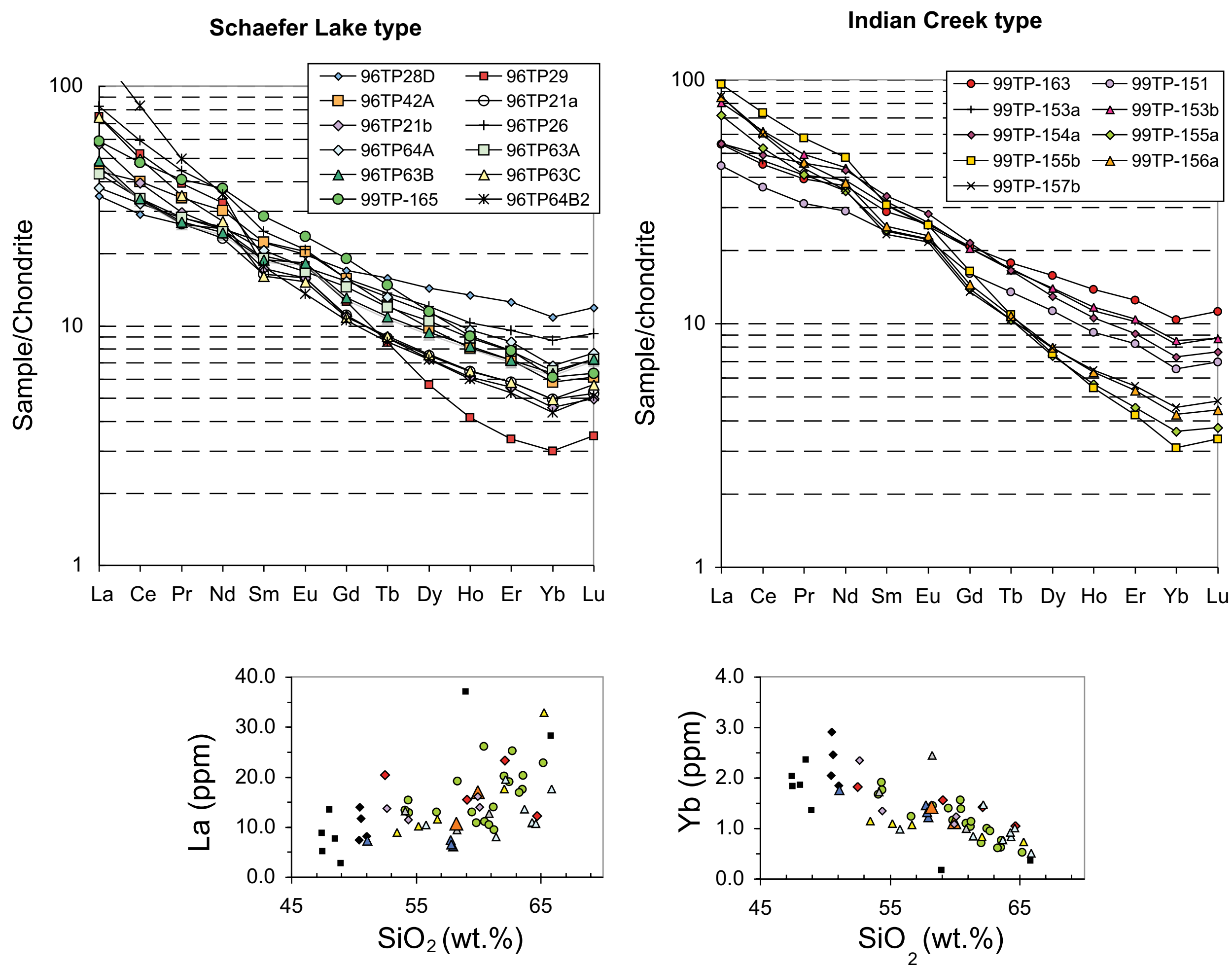

Figure 10. Rare-earth-element (REE) patterns of Schaefer Lake and Indian Creek subtype magma samples. Lower panels show how La (light REE) and Yb (heavy REE) vary with SiO_2. These variations indicate an increase in La and decrease in Yb with differentiation; i.e., patterns progressively steepen with increasing SiO_2. Symbols in the plots of La versus SiO_2 and Yb versus SiO_2 are the same as in Figure 6.

A Chiwaukum pelitic schist is the most isotopically evolved sample in this study (initial ε_{Nd} = +0.5). Matzel et al. (2008) reported similar values for these metamorphic units elsewhere. Three Napeequa amphibolites range from +5.1 to +8.5, and a biotite schist is more evolved at +3.4 (Matzel et al., 2008). An amphibolite in the Chiwaukum Schist has initial ε_{Nd} of +7.7, whereas two samples of biotite schist yield initial ε_{Nd} of –1.8 and +2.7 (Matzel et al., 2008). Nd and Sr isotopic values for Tenpeak plutonic rocks range from initial ε_{Nd} of +3.0 to +5.8 and initial $^{87}Sr/^{86}Sr$ ($^{87}Sr/^{86}Sr_0$) of 0.7037 to 0.7043 (Fig. 12). Values for one sample of the Dirtyface pluton (initial ε_{Nd} = +2, $^{87}Sr/^{86}Sr_o$ = 0.7045) show it to be more evolved than all of the Tenpeak samples. Pb isotopes of the plutonic rocks trend from more primitive (close to Northern Hemisphere Reference Line) toward the more ^{207}Pb-enriched character of the Chiwaukum Schist, indicating that the Pb-isotope signature of these rocks has been strongly affected by crustal Pb signatures.

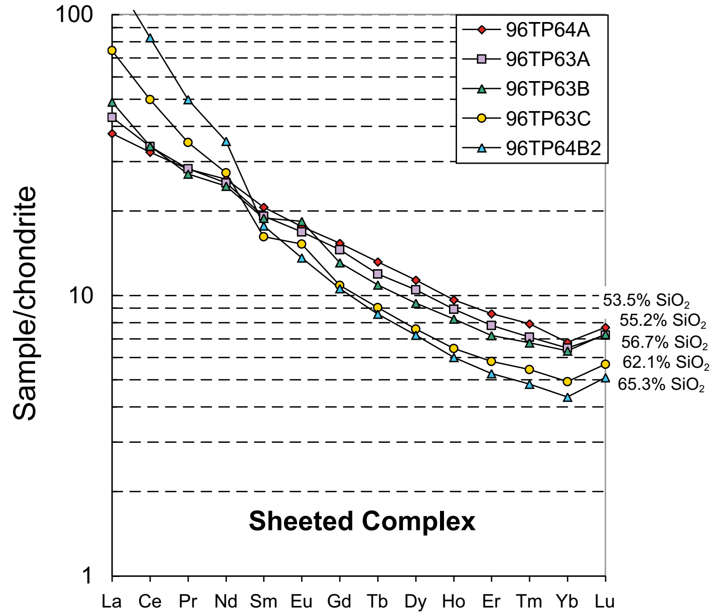

Figure 11. Rare-earth-element (REE) patterns for samples of adjacent compositional sheets within the sheeted complex. Within one large outcrop, sheets range from 53.5% SiO_2 and 7.9% MgO (flattest REE pattern) to 65.3% SiO_2 and 3.2% MgO (steepest REE pattern). This compositional range within one outcrop is representative of almost the entire compositional range of the Tenpeak pluton, as is the pivoting of the REE patterns from flat to steep.

In keeping with their Mg-rich character, samples of the Schaefer Lake magma subtype have the most isotopically primitive compositions (Fig. 12). This subtype has initial ε_{Nd} ranging from +4.8 to +5.8, and $^{87}Sr/^{86}Sr_o$ = 0.7037–0.7038. Matzel et al. (2008) also reported an initial ε_{Nd} value of +5.1 for a dated (ca. 92.3 Ma) sample of the Schaefer Lake tonalite.

The Indian Creek tonalite is more evolved isotopically than the older Schaefer Lake tonalite (Fig. 12). Indian Creek initial ε_{Nd} is +3 to +4, similar to that from a single analysis of +3.9 by Matzel et al. (2008; dated sample, ca. 89.7 Ma), and initial $^{87}Sr/^{86}Sr$ is restricted to ~0.7040. This pattern of more evolved isotopic ratios with time (younger age) mimics the overall trend for 96–45 Ma Cascade plutons described by Matzel et al. (2008).

Mafic and felsic compositional end members from specific regions within the mafic complex are isotopically indistinguishable. For example, a hornblendite and a felsic tonalite from the complex at the northern tip of the White Mountain lobe (adjacent to the Napeequa complex) both have initial ε_{Nd} = +3.5. These values are among the more isotopically evolved in the pluton (Fig. 12) and suggest that local small-scale assimilation near pluton margins may overwhelm the source-controlled isotopic variation within the pluton (see discussion below).

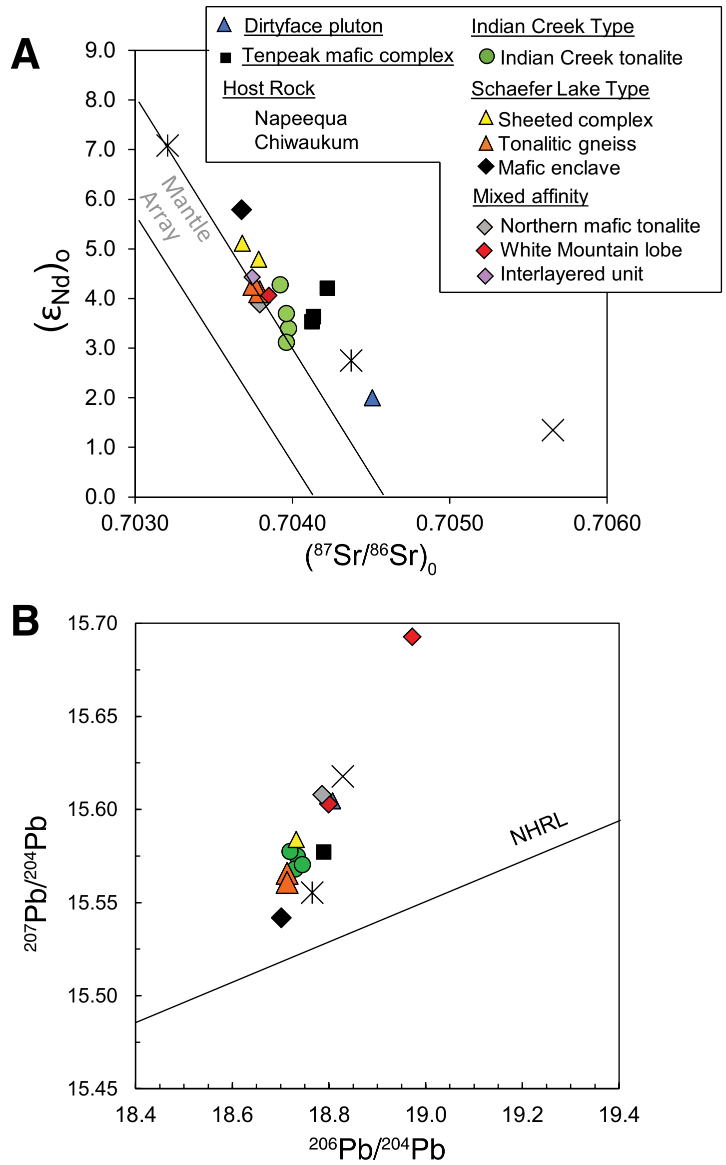

Figure 12. Isotope plots for various units of the Tenpeak and Dirtyface plutons, and the Napeequa and Chiwaukum host rocks. (A). Initial ε_{Nd} ($[\varepsilon_{Nd}]_o$) versus initial $^{87}Sr/^{86}Sr$ ($[^{87}Sr/^{86}Sr]_o$) corrected back to crystallization age (ca. 92 Ma). (B) $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ (also corrected back to crystallization age). Symbols and descriptions are as in Figure 6. NHRL—Northern Hemisphere Reference Line from Hart (1988). 2σ errors are smaller than the symbol size.

Individual sheets within the sheeted complex have only a small range in isotopic composition between the most mafic sheet (53.5 wt% SiO_2, initial ε_{Nd} = +5.1, $^{87}Sr/^{86}Sr_o$ = 0.70368) and the most felsic sheet (65 wt% SiO_2, initial ε_{Nd} = +4.8, $^{87}Sr/^{86}Sr_o$ = 0.70379) (Fig. 12; Fig. S1 [footnote 1]). Thus, the specific unit within the pluton appears to be the more important driver of isotopic composition than is the degree of differentiation.

STRUCTURE OF THE TENPEAK AND DIRTYFACE PLUTONS

The Tenpeak and Dirtyface plutons contain a range of well-preserved magmatic structures, which bear on internal magmatic processes and the construction of the plutons. These structures are variably overprinted by solid-state deformation, which is relatively weak in much of the interiors of the plutons.

Magmatic foliation and lineation in the Tenpeak pluton are defined by variably aligned hornblende, biotite, plagioclase, and epidote. Magmatic and solid-state fabrics in much of the pluton are marked by roughly subequal foliation and lineation. Magmatic shear zones and faults are recognized locally where they deflect or offset sheet contacts and layers. These structures are interpreted as magmatic because of the weak grain-size reduction and lack of other evidence for dynamic recrystallization.

In the Tenpeak pluton, magmatic foliation, external and internal contacts (Figs. 2, 13A), and layering are typically subparallel to parallel, but in some places foliation is oblique (10°–30°) to the compositional contacts (Fig. 5B). Foliation typically strikes NW, parallel to the long axis (map view) of the pluton; exceptions are where the margin deviates from the dominant trend and in parts of the pluton interior. Foliation dips moderately to steeply (35°–90°) and mostly to the NE (Fig. 13A). Orientations of magmatic and solid-state lineations are relatively consistent in individual domains, but are more heterogeneous at the scale of the entire pluton (Fig. 13B). Most plunge moderately (30°–70°), typically to the E, SE, or N. Minor gentle to open magmatic folds of sheets, layers, enclaves, and pegmatite veins are best seen in the mafic

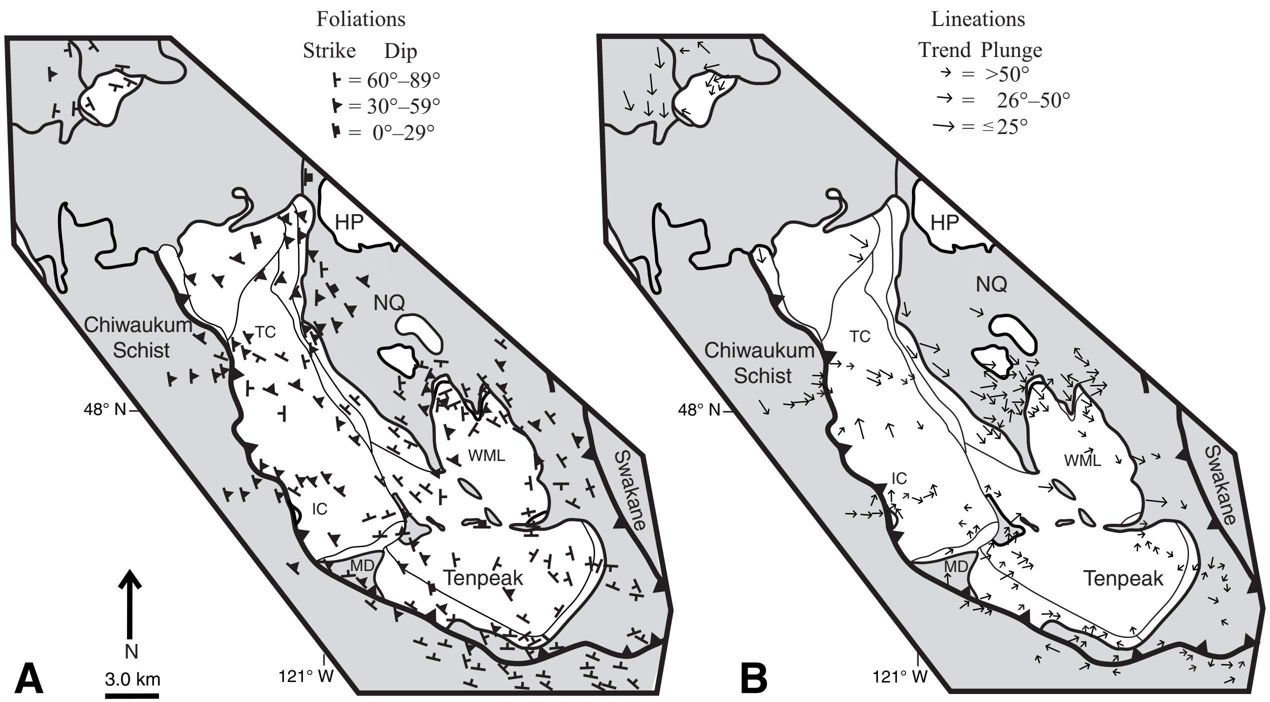

Figure 13 (*continued on following page*). (A, B) Summary of foliation orientations (A) and lineation orientations (B) in the Tenpeak pluton and adjacent rocks. HP—High Pass pluton; IC—Indian Creek; MD—Mount David; NQ—Napeequa unit; TC—Thunder Creek; WML—White Mountain lobe. (C) Summary of lineation orientations in Dirtyface pluton and adjacent units. CS—Chiwaukum Schist; WRSZ—White River shear zone. C-C′ is line of cross section shown in Figure 4. Refer to Figures 2 and 3 for units within the Tenpeak pluton and Dirtyface pluton, respectively. Our structural data are supplemented for parts of the Tenpeak pluton by data from Crowder et al. (1966), Cater and Crowder (1967), and Tabor et al. (1987).

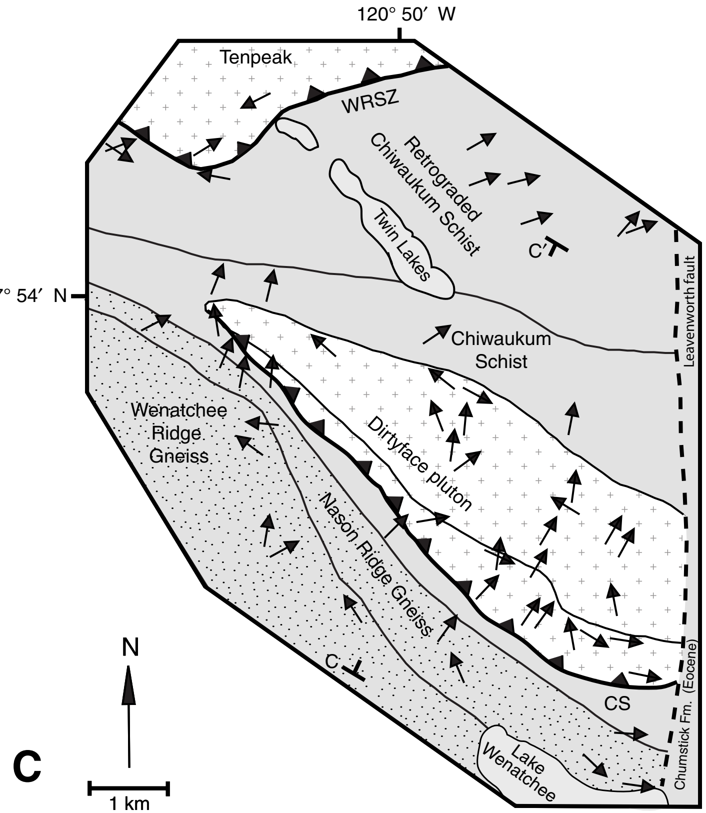

Figure 13 (*continued*).

complex and Schaefer Lake tonalite. Most have wavelengths of 10 cm to 5 m, and magmatic foliation is axial planar to some of the tighter folds.

Considerable evidence indicates that magmatic structures in some places record regional strain and in other domains record internal magmatic processes. Evidence for regional strain includes the discordance between foliation and some sheets. In sizable map-scale domains, foliation and lineation are largely subparallel to equivalent regional structures in the host rocks (Figs. 13 A, 13B), and in and near the White River shear zone, they particularly show the influence of NE-SW regional shortening. Magmatic fabrics deviate from regional patterns in the northernmost and easternmost part of the pluton and in part of the White Mountain lobe. Sparse fabric measurements from the center of the pluton are more complex, also compatible with local control by internal magmatic processes.

Solid-state deformation in the Tenpeak pluton is particularly focused in the White River shear zone and in the tonalitic gneiss and interlayered unit inward for ≥1 km from the northeastern pluton contact. Scattered zones of relatively strong, medium- to high-temperature solid-state deformation (recrystallized plagioclase mosaics and other microstructures) are mostly 1–10 m wide and moderately to steeply dipping.

In the Dirtyface pluton, the southwestern domain has strong solid-state fabrics, which overprint a sub-parallel magmatic fabric. The foliation commonly contains a steeply pitching mineral lineation (Figs. 3, 13C), although flattening fabrics dominate. Local magmatic and high-temperature solid-state kinematic indicators, including S-C fabrics, shear bands, and asymmetric porphyroclasts, record reverse, top-to-the-southwest motion near both the northeastern and southwestern contacts. Local upright to overturned folds deform the subsolidus foliation in the sheets and the main fabric in the host Chiwaukum Schist. Plunges are gentle to the NW, to moderate to the N and NE, consistent with formation and subsequent rotation in a SW-directed shear zone, and/or in the northeastern limb of a regional, flexural-flow fold. Solid-state deformation decreases in the northeastern part of the pluton.

The ages of solid-state deformation are only loosely constrained. The sub-parallelism of magmatic and medium- to high-temperature solid-state fabrics in the Tenpeak pluton is compatible with deformation shortly after these rocks cooled below their solidi. Furthermore, there is no obvious metamorphic or structural aureole around the Dirtyface pluton, and we infer that the pluton and host rocks were hot and deforming during emplacement. In contrast, the discordance of the northeastern contact, which cuts folds, indicates at least slightly older ductile host rock strain. Muscovite Ar/Ar and K-Ar cooling ages of 86.9 ± 0.4 to 80.8 ± 1.6 Ma (Tabor et al., 1987; Matzel, 2004) from three samples of Wenatchee Ridge Gneiss and Chiwaukum Schist within 3 km of the Dirtyface pluton suggest that medium- to high-temperature deformation ended within ~5 m.y. of intrusion of the pluton.

INTERNAL CONTACTS WITHIN THE TENPEAK AND DIRTYFACE PLUTONS

Contacts between units of the Tenpeak pluton range from gradational to less commonly sharp. Many of the gradational contacts are marked by sheeting, and most sheets dip moderately to steeply NE (Fig. 2; Table 1; Table S1 [footnote 1]). Co-magmatic features, such as mingling, are preserved across some contacts. The Indian Creek tonalite has relatively sharp boundaries, and contacts of this tonalite and the northern mafic tonalite, the two youngest dated units of the pluton, are in map view partly discordant to NW-trending contacts and foliations in older units (Figs. 2, 13A). These observations are compatible with geochronological data; age contrasts are <1 m.y. across some internal contacts, whereas they are ≥2 m.y. across the Indian Creek tonalite–Schaefer Lake tonalite contact (Matzel et al., 2006).

Inclusions of the Napeequa unit, ranging from ≤10 cm^2 to ~1 km^2, are concentrated along host rock and internal contacts of the Tenpeak pluton. The largest Napeequa body lies at the intersection of multiple units (Fig. 2). Else-

TABLE 1. CONTACT ORIENTATIONS AND STRUCTURAL AUREOLES OF THE TENPEAK PLUTON

Contact segment	Contact and sheet dips	Adjacent aureole
Northern end	~60°–70° S (inward)	800 m wide; downward motion of host rock
Northwestern contact (isolated body)	Subvertical	400–700 m wide; downward deflection of host rock
Southwestern contact (White River shear zone)	30°–65° NE to N (inward)	500 m to 1 km wide; downward deflection of host rock
Northeastern contact (planar)	80° NE to 90° vertical	400 m wide; foliation steepens slightly, rotates 30° counterclockwise from regional strike
White Mountain lobe	40° inward to vertical	>200–500 m wide; motion unclear
Sheeted complex	30°–80° NE	Not applicable
Schaefer Lake tonalite—internal	70°–80° N	Not applicable
Interlayered unit	40°–75° NE	Not applicable

where, the interlayered unit with its metamorphic rafts separates the Indian Creek tonalite from tonalitic gneiss and Schaefer Lake tonalite (Fig. 2). A string of map-scale and smaller inclusions separates the White Mountain lobe from the rest of the Schaefer Lake tonalite (Fig. 2), and these inclusions are intruded by steep, N- to NE-dipping tonalite sheets and mafic complex. Thus, the largest inclusions appear to mark boundaries between intrusive bodies with distinct modal and textural differences.

Contacts between sheets in the Dirtyface pluton are similar to those in the Tenpeak sheeted complex. The generally thinner sheets in the southwestern unit dip 25°–50° NE, and sheet dips steadily increase to the northeast to 55°–70° (Fig. 4C). Rafts and rotated blocks of Chiwaukum Schist range from tens of centimeters to tens of meters in width.

CONTACTS WITH HOST ROCKS AND STRUCTURAL AUREOLES

Contacts between the *Tenpeak pluton* and its host rocks range from relatively straight to highly curved in map view. They mainly dip moderately NE to vertically (Fig. 2), and are subparallel to magmatic and solid-state foliation.

The contact between the isolated *northern body* and its host rock curves from NW to approximately E-W trending at the northern end of the intrusion (Fig. 2). The map pattern (Crowder et al., 1966; Tabor et al., 2002) and foliation orientations suggest that the northern contact dips moderately to steeply southward (inward). Near this contact, foliation in the pluton and adjacent Napeequa unit strikes WNW to WSW and dips steeply (60°–70°) southward. The Napeequa foliation strikes roughly parallel to the trend of the contact and discordant to the regional NW strike for distances extending ~800 m from the contact, defining a relatively wide structural aureole (Figs. 2, 13A). Similarly, the mostly moderately (40°–50°) WSW-plunging lineation is discordant to the gently NW- and SE-plunging regional lineation in the Napeequa complex (Fig. 13B). The Napeequa unit–Chiwaukum Schist contact bends ~30° in map view from its regional trend within 600 m of the pluton contact, but appears to be truncated at high angles by the contact (Crowder et al., 1966; Tabor et al., 2002).

The western contact of the northern body dips steeply (~80°–65°), and dip directions change from inward to outward over distances of ≤200 m along strike. The contact is concordant to marginal sheets of the mafic complex. A narrow carapace of the regionally structurally higher Napeequa unit separates the pluton from the Chiwaukum Schist (Fig. 4A), and likely was deflected downward in the structural aureole.

Host rock structures change outward from the western pluton contact. Lineations and hinge lines of tight to isoclinal folds plunge moderately to steeply (mostly 35°–70°) within 400 m of the contact, and folding increases in complexity relative to regional patterns, with refolding by variably oriented open folds. Farther from the Tenpeak contact, steep and gentle hinge lines and lineations occur in subequal amounts, and ~700 m from the contact, lineations in the Chiwaukum Schist have more typical regional orientations, plunging 10°–30° SSE. Collectively, the map, foliation, and lineation patterns imply that a structural aureole extending ~700–800 m from the northern boundary of the pluton formed during intrusion.

The *western and southern margins* of the Tenpeak pluton lie within the White River shear zone. In the structurally underlying Chiwaukum Schist and locally the Napeequa unit, the shear zone is marked by retrogression to lower amphibolite facies, and in the southernmost segment it contains greenschist-facies assemblages (Tabor et al., 1987; Raszewski, 2005). Along with a decrease in intensity, the width of the retrogressed zone decreases from 2 km in the south to <50 m in the extreme northwest. The extent of solid-state overprinting of the pluton–host rock contact is variable. In places, the contact is sharp, but elsewhere, sheets of Tenpeak tonalite intrude host rock, and xenoliths occur in the pluton.

The shear zone typically dips 30°–65° NE to N. In the host rocks, regional moderately NE-dipping foliation in the Chiwaukum Schist steepens, and subhorizontal mineral lineation swings toward a more down-dip orientation compatible with lineations in the margin of the pluton (Fig. 13B). In a ~200-m-wide zone in the southern margin of the pluton, NW-striking magmatic fabric is progressively transposed to an E-W orientation by high-temperature solid-state deformation as the host rock contact is approached, presumably by distributed shear in the White River shear zone. Kinematic indicators in the shear zone include C-surfaces marked by finely recrystallized quartz and aligned biotite in the pluton and extensional crenulation cleavage (C′ surfaces) defined by biotite and muscovite in the Chiwaukum Schist. These indicators, combined with the orientations of foliation and lineation, record dominantly reverse slip; the opposite shear sense is found locally, and conflicting indicators are present elsewhere (also see Raszewski, 2005).

On the regional scale, the shear zone lies along the Chiwaukum-Napeequa boundary, which initially may have been an unconformity (e.g., Brown and Dragovich, 2003) that has been inverted by reverse slip, such that the older Napeequa rocks are now structurally higher (Miller et al., 2009). Medium- to high-temperature non-coaxial fabrics in the pluton are compatible with syn-emplacement motion, as is the decrease in width of the shear zone where it deforms younger phases. Greenschist-facies assemblages in host rocks next to the southern part of the pluton imply that deformation there continued as the rocks cooled, but ended by 67.0 ± 0.6 Ma, the date of the closest Ar/Ar biotite age (Matzel, 2004). The presence of Tenpeak sheets in the host rocks and host rock xenoliths in the pluton indicate that post-emplacement displacement was probably not large and much of the inversion of the unconformity occurred before intrusion.

The *northeastern contact* of the tonalitic gneiss with Napeequa rocks is sharp. Where we examined this contact in detail, it dips 82° NE, compatible with the straight map trace, and is concordant to foliation in the pluton and host rock. A few concordant, 1–2-m-thick Napeequa bodies are exposed as far as 10 m inward from the main pluton–host rock contact, and tonalitic sheets of similar thickness intrude the Napeequa complex. In our most detailed host rock transect, foliation steepens slightly from 50° to 70° NE to consistently ~80° within a 400-m-wide aureole. Foliation strike similarly swings by ~30° (counterclockwise) into the contact-parallel zone.

The contact of the *White Mountain lobe* generally dips steeply. Magmatic foliation patterns in the lobe are complex, but foliation rotates into a margin-parallel orientation near the contact. In a ≥200-m-wide zone in Napeequa rocks next to the west side of the lobe, foliation changes from the regional NW to WNW strike to a NNW to N strike with moderate to steep (40°–65°) east dips beneath the pluton. In the northern margin, dips range from steeply outward to moderately to steeply inward (Fig. 4B). The structural aureole extends ~500 m from this part of the lobe, and is marked by: a swing in the strike of regional foliation to nearly margin parallel and a steepening of dip to 75°–85° as the contact is approached; deflection of regional mineral lineation; and deflection of a NW-trending contact between a biotite schist–rich unit and a dominantly quartzite unit (Fig. 2) (Cater and Crowder, 1967) of the Napeequa complex. The northeastern part of the lobe cuts slightly across the biotite schist–quartzite contact (Fig. 2). Foliation in the Napeequa rocks is generally moderately dipping, and steepens to subvertical in the 500-m-wide structural aureole. Lineation swings from its regional SE plunges to E plunges, steepens slightly, and becomes subparallel to lineation in the pluton. Lineation and fold hinge lines are also more variably oriented in the aureole, reflecting an increased complexity of folding. Kinematic indicators were recognized at only a few localities near the contact of the White Mountain lobe, and include biotite- and clinozoisite-defined C-surfaces, local biotite "fish", and asymmetric hornblende porphyroclasts in the Tenpeak rocks and asymmetric tails of biotite and muscovite on garnet in the host rocks; no consistent pattern of non-coaxial flow emerged.

The *Dirtyface pluton* has simpler patterns than the Tenpeak pluton. The southwestern contact of the intrusion dips moderately (~35°) NE and is concordant to foliation in the host schist and pluton, and to nearby sheet contacts. Sheets steepen to the northeast where the steeply (~70°) NE-dipping pluton contact is discordant to the typically gently dipping, but folded fabric in the Chiwaukum Schist (Fig. 4C). No structural aureole has been recognized next to the pluton.

Overall, contacts of the Tenpeak and Dirtyface plutons are moderate to steep, and most commonly dip inward. Ductile structural aureoles form around the Tenpeak pluton, but do not extend outward for more than a kilometer.

DISCUSSION

Pluton Geometry

The Tenpeak and Dirtyface plutons provide insights into several general aspects of the construction of magmatic bodies, particularly in the deeper levels of arcs. Pluton geometry at depths of >25 km is poorly known; some workers describe thin dike-sill arrays (e.g., Collins and Sawyer, 1996; Karlstrom and Williams, 2006), whereas others infer steep, vertically extensive systems (e.g., Saleeby et al., 2003).

The >1800 m of vertical relief provides a three-dimensional perspective on the geometry of the Tenpeak pluton (Figs. 2, 4A, 4B). The southern and southwestern margins of the Tenpeak pluton dip inward at moderate to steep angles. The isolated northern body has steep to vertical contacts on the west, and at its northern end probably dips steeply (60°–70°) inward. Similarly, the northeastern contact of the tonalitic gneiss dips steeply, the western and northern sides of the White Mountain lobe dip moderately to steeply inward, and the northeastern contact of the lobe is nearly vertical. Magmatic sheets and foliations in the pluton margin are subparallel to these contacts (Fig. 2; Table 1). These orientations of host rock and internal contacts (Fig. 2) indicate that the Tenpeak pluton is shaped like an asymmetric wedge or funnel (Miller et al., 2009) (Fig. 4; Table 1). This interpretation assumes that roughly planar contacts maintain the observed dips at greater depths (and upward before erosion). The Dirtyface pluton is also apparently shaped like an asymmetric wedge, as its southwestern contact dips moderately inward and its northeastern contact is considerably steeper.

The asymmetric, broadly wedge-like to funnel shape of the Tenpeak and Dirtyface plutons does not fit the model of a thin subhorizontal tabular body or lopolith, as is commonly envisioned for deeper-level plutons. We note, however, that such funnel shapes may be more common than typically recognized (e.g., Miller and Bowring, 1990; Paterson et al., 2017). In one scenario, the plutons were originally subhorizontal and have been folded into their present geometry. We do not rule out some tilting of the Tenpeak pluton, but several observations argue against this fold interpretation. Overall, contacts and foliations in the Cascades core are moderately to gently dipping (e.g., Miller et al., 2006) and steepen as the Tenpeak pluton contact is approached, implying that this steepening is related to pluton emplacement. Moreover, the only moderately dipping segment of the Tenpeak contact in the White River shear zone may have been rotated to shallower dips; that is, the western contact is subvertical where the shear zone decreases in width to the northwest (compare Figs. 4A and 4B).

The Dirtyface pluton is in the northeastern limb of a >6-km-wavelength antiform, and its southwestern contact is concordant to host rock foliation. The northeastern margin is steep and discordant. This discordance argues against a folded tabular body or a laccolith or lopolith. We propose that increments of Dirtyface magmas ascended in sheet-like channels, as illustrated by the northeastern margin, whereas in the southwest, sheets flattened to moderate angles at the emplacement level as a result of host rock anisotropy.

The shapes of magmatic increments into the Tenpeak system may have changed through time. During construction of the Schaefer Lake unit and mafic complex, magmas were probably largely intruded as sheets, particularly in the southwestern margin of the pluton, and as small irregularly shaped bodies, most of which were elongate subparallel to the NW strike of the orogen (see also Miller and Paterson, 2001a). Available age data indicate that some of the youngest sheets of the Schaefer Lake unit are in the sheeted complex, which was apparently localized by the White River shear zone (Chan et al., 2017). Construction of the White Mountain lobe diverged from this pattern; although sheeted in its margin, it protrudes outward from the planar segment of the northeastern contact, and parts of the lobe are relatively homogeneous. The significantly younger northern mafic tonalite and Indian Creek tonalite are bounded by narrow zones of sheeted mafic complex, but are weakly elongate (aspect ratios of 2:1–3:1) in map view and may have intruded as more irregularly shaped and homogeneous bodies (see above).

In summary, we speculate that, although the shape of the Dirtyface and Tenpeak plutons may have been weakly modified by Cretaceous shortening, the wedge-like geometry reflects their shape during growth, possibly influenced by host rock anisotropy and rheology, including the control of inward-dipping foliation (e.g., southwestern contact of the Dirtyface pluton) and outward expansion into weaker host rock (e.g., White Mountain lobe) at the emplacement level.

Sizes of Active Magma Bodies

The sizes of mushy magma bodies and magma chambers at all levels of the crust is a matter of debate between those envisioning large magma reservoirs (e.g., Paterson et al., 2011; Karakas et al., 2017) and others proposing small, short-lived magma bodies (e.g., Coleman et al., 2004; Annen et al. 2006). Any model for the Tenpeak pluton must account for the presence of strongly sheeted zones and large, relatively "homogeneous" domains with continuous magmatic fabrics, the two magma subtypes, and the ~2.6 m.y. interval for construction.

Field, geochemical, and geochronological data indicate that the Tenpeak and Dirtyface plutons were constructed by numerous magmatic increments. The hundreds-of-meters-scale or thinner sheets observed in the field support this interpretation, as do the mingling and local mixing of magmas in the sheeted complex. Geochemical evidence for multiple increments in the Tenpeak pluton includes the juxtaposition of the two distinct magma subtypes, which we suggest were derived from two sources. The presence of both the Indian Creek and Schaefer Lake subtypes in the interlayered unit, northern mafic tonalite, and locally the White Mountain lobe implies that the two magma subtypes were roughly coeval for part of the intrusive history. Finally, the apparent age breaks reaching >2 m.y. across contacts between map-scale units support different magma batches.

The Indian Creek tonalite and northern mafic tonalite may represent larger (>1 km^3 to tens of cubic kilometers) magmatic inputs or similar magmas intruded in smaller batches, but close enough in time to become relatively homogenized in a magma chamber at the emplacement level. This interpretation is based on the relative petrographic and geochemical homogeneity, scarcity of internal contacts, and continuity of magmatic fabrics of the Indian Creek tonalite. Parts of the northern mafic tonalite are relatively homogeneous, although other parts have sharp internal contacts, and the unit includes different geochemical subtypes.

The volume of magma and crystal-rich mush present during construction of the Tenpeak intrusion at any given time was clearly significantly less than the volume of the entire pluton. The sheets with sharp contacts imply a small, short-lived chamber during parts of the pluton construction, although some sheets mingled at the emplacement level (Fig. 5C). Ephemeral chambers are also supported by the length of time for construction (≥2.6 m.y.) and temporal gaps between adjacent units. These gaps may represent times when magma was not trapped at the Tenpeak level and ascended higher in the crust. The age gaps, truncation of older units by the Indian Creek and northern mafic tonalite units, and greater solid-state deformation of the older rocks are compatible with removal of material by rising magmas after the older units had partially to fully solidified. The presence of a larger (tens of cubic kilometers) chamber(s) during the later stages of pluton construction, however, is supported by the scarcity of pronounced internal contacts and the relative petrographic and geochemical homogeneity of the voluminous Indian Creek tonalite and northern mafic tonalite. In this scenario, the amount of melt versus solid fluctuated, and mush may have been remobilized during replenishments represented by mafic enclaves, leading to the relatively homogeneous domains (cf. Bergantz, 2000; Paterson et al., 2016).

Emplacement Mechanisms

Multiple host rock material transfer processes typically operate during emplacement of shallow-crustal plutons (e.g., Paterson et al., 1996), and ductile processes presumably become more important at deeper-crustal levels (e.g., Buddington, 1959). In contrast, we infer that processes commonly associated with shallower plutons also facilitated emplacement of the Tenpeak pluton and that the relative importance of different processes probably changed through time.

Wedging of host rock by magmatic sheets intruded along foliation (cf. Weinberg, 1999; Brown, 2004; Tomek et al., 2015) likely helped accommodate the abundant, roughly parallel sheets in the interlayered unit, Schaefer Lake tonalite (particularly the sheeted complex), and mafic complex. Evidence for wedging includes the subparallel sheets containing magmatic to high-temperature solid-state foliation, which is parallel to contacts and to foliation in the rafts of host rock. Host rock wedging detached host rock, as recorded by rotated Napeequa xenoliths near larger concordant rafts (cf. Paterson and Miller, 1998a; Miller and Paterson, 2001a).

Syn-emplacement ductile flow occurred adjacent to much of the Tenpeak pluton. Vertical downward flow is illustrated by the 400–700-m-wide aureole next to the western margin of the northern mafic tonalite where the regionally structurally higher Napeequa rocks are deflected downward relative to Chiwaukum Schist (Fig. 4A), and in the ~800-m-wide aureole adjacent to the northern end of the pluton where foliations in host rocks steepen and dip beneath the intrusion. Downward motion of host rock in the White River shear zone is implied by the ~400-m- to 1 km-wide zone of steepening of foliation and deflection of lineation and fold hinge lines, and by mainly pluton-side-up kinematic indicators in the intrusion. It is difficult to determine how much of the strain resulted from pluton emplacement versus regional tectonism. Vertical host rock flow occurred in a 400–500-m-wide structural aureole next to the northeastern part of the pluton and the White Mountain lobe. Patterns of non-coaxial shear are complex. This uncertainty extends to the slight steepening and ~30° strike rotation of foliation in the 400-m-wide aureole next to the planar segment of the northeastern contact, and to the variable steepening and deflection of foliation in the up to 500-m-wide aureole next to the White Mountain lobe (Fig. 13A).

Host rocks and older parts of the pluton were stoped by younger magmatic inputs, but the amount of material transferred is difficult to quantify. The most direct evidence for stoping is provided by the 1 cm^2 to 1 km^2 xenoliths of host rock, which are found in most Tenpeak units. They are common in the pluton margin, but the largest volume of xenoliths occurs near internal contacts. Stoping of older parts of the pluton is clearest for the Indian Creek unit, which on the basis of the map pattern apparently truncated and removed part of the Schaefer Lake tonalite, and for the northern mafic tonalite, which cuts across the interlayered unit (cf. Paterson et al., 2016). Removal of parts of the mafic complex by tonalitic magmas is inferred from: the wide range in width of the complex; its absence along some segments of the pluton contact; the mafic plutonic xenoliths in tonalite; and the hornblendites disaggregated by trondhjemitic veinlets.

The marginal mafic complex has the most evolved isotopic signature of any unit in the Tenpeak pluton (Fig. 12), which is compatible with minor assimilation of host rocks during early pluton construction, perhaps as a consequence of disaggregation of stoped pieces of metasedimentary rocks of the Chiwaukum Schist and Napeequa unit, which are more isotopically evolved than the magmatic rocks. Given the low Rb and Sm values of the mafic magmas, even a small amount of contamination could significantly affect the isotopic signature. As subsequent tonalitic magmas intruded into mush or solidified magma, there may have been less contamination because of shielding of the host rocks by the mafic complex. This hypothesis is supported by the more evolved isotopic signature of the Dirtyface pluton; it is more mafic than most of the Tenpeak pluton, but much smaller, and its isotopic signature is closer to that of its host rock (Chiwaukum Schist).

In summary, (1) magma wedging, (2) vertical, commonly downward ductile flow, and (3) stoping all facilitated emplacement. The dominantly downward flow and stoping attest to the importance of downward movement of host rock around and in the area now occupied by the pluton (cf. Paterson et al., 1996, 2016; Cruden, 1998, 2006; Paterson and Farris, 2008). The emplacement mechanisms are similar to those commonly inferred for shallower plutons. In particular, multiple material transfer processes operated, vertical ductile flow was important as structural aureoles are narrow relative to the diameter of the pluton, and stoping played at least a modest role.

Origin of Compositional Diversity within the Pluton

The wide compositional range must be explained in any geochemical model of the Tenpeak pluton, such as high-pressure, closed system fractionation of mafic magmas formed in the mantle or mixing of mafic mantle and crustal melts. This compositional spectrum in the pluton includes basaltic rocks in the mafic complex (47–50 wt% SiO_2), mafic enclaves in the tonalites (50%–52% SiO_2), and a range of tonalite compositions (~55–66 wt% SiO_2; 2–8 wt% MgO). In the following, we address this range of compositions and the origin of the dominant tonalite.

Field relationships show that the mafic complex is in part older than, and in part synchronous with, the Schaefer Lake tonalite. Rocks of the complex associated with younger Indian Creek tonalite may be a younger mafic influx, synchronous with the Indian Creek tonalite, but field relationships are not definitive. However, mafic sheets and enclaves within both tonalite units were emplaced while tonalitic magmas were still mobile, and demonstrate the importance of intrusion of mafic magmas throughout the life of the intrusion.

Because mafic magmas such as these, with their geochemical signature of arc-related high-alumina basalts, must be mantle derived, the Tenpeak pluton cannot have formed solely as the result of crustal melting, a scenario suggested by Zen (1988). This conclusion also applies to the Cretaceous Chelan Complex (Hopson and Mattinson, 1994; Dessimoz et al., 2012) and the 91–72 Ma Seven Fingered Jack, Cardinal Peak, and Entiat plutons of the Cascades core, which contain similar mafic complexes (Cater, 1982; Dawes, 1993; Parent, 1999; Miller and Paterson, 2001a).

The intrusion of the two magmatic subtypes (Schaefer Lake and Indian Creek) attests to the complex evolution of the Tenpeak system. The Schaefer Lake magmas are relatively enriched in MgO, Ni, and Cr and depleted in Y and P_2O_5 contents compared to the Indian Creek magmas, but the two subtypes have similar abundances and shapes of REE patterns at a given SiO_2 content (Figs. 7, 10). Their mafic end members are both hydrous, mantle-derived magmas. These different magma types may be related to distinct mantle sources in the mantle wedge beneath the Cretaceous arc, similar to the distinct mantle domains beneath the current Cascade arc (cf. Bacon et al., 1997). Their sources also have slightly different isotopic characteristics, as the Schaefer Lake subtype is slightly more isotopically primitive (Fig. 12).

If the mafic magmas represent distinct mantle components, then a fundamental question is: How do they relate to the much more abundant lithology of the pluton, the tonalites with ~55–66 wt% SiO_2? We suggest that most of the tonalites represent liquid to near-liquid compositions (basaltic andesite to dacite magmas). Small positive Eu anomalies are observed in a few samples and could be explained by minor plagioclase accumulation. However, these anomalies may also be produced from fractionation of hornblende ± sphene at deeper levels from high-alumina basaltic liquid.

Several hypotheses are typically proposed to relate this wide range of magma compositions: (1) closed-system fractionation at high pressures of wet mafic parental magmas originating in the mantle; (2) fractionation combined with minor crustal melting (e.g., Müntener and Ulmer, 2006; Jagoutz, 2010); or (3) variable mixing between mantle-derived mafic magma end members and crustally derived felsic end members (e.g., Pitcher, 1997; Hildreth and Moorbath, 1988; Annen et al., 2006). We describe in the following paragraphs why we favor the third hypothesis of complex mixing between hydrous mantle-derived magmas and abundant partial melts of a garnet-bearing amphibolite at lower-crustal depths.

In a high-pressure fractionation model, accumulation of abundant hornblende drives the remaining liquid toward a tonalitic composition. The hornblendite in the mafic complex indicates at least minor accumulation of hornblende, and for elsewhere in the Cascades core, Dessimoz et al. (2012) proposed that high-pressure fractionation of hornblende led to the formation of tonalite in the Chelan Complex, which contains much more ultramafic and mafic rock than the Tenpeak pluton. In the Tenpeak pluton, the strong pivoting of the REE patterns with differentiation (Fig. 11) strongly suggests that this mechanism was not significant.

In the magma-mixing model, which we favor, heat and H_2O provided by hydrous mantle-derived mafic magmas led to significant melting of garnet-amphibolite lower crust (perhaps metamorphosed intraplated and/or underplated arc basalts) to provide the more silicic magmas, which variably mixed with the mafic magmas to form the intermediate Tenpeak tonalites. Evidence for deep crustal melting to produce this silicic end member (as opposed to melting or assimilation at the current level of exposure) comes from its high Sr/Y and La/Yb (Figs. 9 and 11). These trace element characteristics require crustal melting from a source with abundant residual garnet, which is not observed at the current level of exposure. Mixing models (not shown) require 10%–56% silicic end member to produce the range of tonalite compositions present in the Tenpeak pluton. In a long-lived system, the amount of partial melt increases with time (e.g., Hildreth and Moorbath, 1988; Annen et al., 2006) and felsic magmas become more prominent, which is compatible with field relationships in the Tenpeak pluton; tonalitic rock subsumes earlier mafic complexes, and the tonalitic parts of the pluton contain relatively small volumes of contemporaneous mafic sheets and enclaves. Compositions of the most mafic rocks without obvious cumulus textures from the Schaefer Lake tonalite (samples 96TP64A and 98TP-128 in Table S2) and Indian Creek tonalite (sample 99TP-163 in Table S2 [footnote 1]) may approximate those of parental magmas to each of the suites in the mixing scenario, whereas the most felsic tonalite of the Tenpeak pluton (sample 96TP-29 in Table S2 [footnote 1]) is similar to crustal melt produced by dehydration melting of metabasalt via the reaction hornblende + plagioclase ↔ garnet + clinopyroxene (± hornblende) + tonalitic melt (e.g., Rapp and Watson, 1995; Müntener et al., 2001; Alonso-Perez et al., 2009). The distinct REE characteristics of these end-member types, and their intermediates, can be explained by simple mixing of the two end members (Fig. 11). In the sheeted complex, initial Sr and Nd isotopic ratios show a small progressive enrichment from the most mafic sheet (sample 96TP64A) to the most felsic sheet (sample 96TP64B2) (Fig. 12; Fig. S1 [footnote 1]). Differentiation within subtypes (e.g., sheeted complex, Indian Creek tonalite) progresses to slightly more isotopically enriched values, indicating that whatever crust is melting to produce the felsic end member, it is only slightly more isotopically enriched than the mantle source. This relationship fits for a crust made up of newly accreted terranes.

The origin of the high Sr/Y and La/Yb signature in the most silicic end members is important for the petrogenesis of the Tenpeak and Dirtyface tonalites. The decrease in Y and Yb and increase in La/Yb with greater weight percent SiO_2 (Figs. 6, 10), and the high Dy/Yb (Fig. 6), are compatible with involvement of garnet during melt production or fractionation of mafic magmas at high pressures. Alternatively, medium- to high-pressure fractionation of hornblende from a basaltic melt may account for most of these characteristics (e.g., Davidson et al., 2007; Jagoutz, 2010; Dessimoz et al., 2012). The $(Dy/Yb)_N$ ratio, which helps distinguish garnet versus hornblende fractionation, is essentially flat or increases slightly with SiO_2 (Fig. 6). The ratio does not decrease with SiO_2, as expected for hornblende fractionation, but also lacks the marked increase characteristic of garnet. Thus, fractionation of both minerals and/or their presence in the residue of partial melting may have been important in the Tenpeak and Dirtyface systems. Thorough modeling of the geochemical data is needed to evaluate the relative importance of these phases in the petrogenesis of the plutons, which is beyond the scope of this paper. Regardless, the clear mixing trends shown in Figure 11 support a model of mixing of mantle-derived mafic magmas with these highly silicic fractionates.

The thickness of the North Cascades arc also bears on melting and fractionation during intrusion of the Tenpeak pluton. Several workers have noted that thick continental arcs are more likely to undergo lower-crustal partial melting than thinner ones (e.g., Dufek and Bergantz, 2005), and resulting magmas are likely to have high Sr/Y (Feeley and Hacker, 1995; Chapman et al., 2015; Chiaradia, 2015; Profeta et al., 2015), as in the Tenpeak pluton. Major mid-Cretaceous contraction preceded and accompanied Tenpeak emplacement, and the zenith of pluton intrusion and regional metamorphism in the North Cascades occurred between ca. 96 and 88 Ma (e.g., Walker and Brown, 1991; Matzel et al., 2006; Miller et al., 2009). The crystallization depths of the deepest plutons (30–35 km), the present crustal thickness in the Cascades of as much as 40 km (Mooney and Weaver, 1989), and the dominance of metamorphosed supracrustal rocks at the deepest exposed levels (~11 kb) imply that the Cretaceous arc crust was thick (≥55 km; Miller and Paterson, 2001b; Miller et al., 2009) at the time of intrusion. This value is based on the assumption that there was no significant subsequent post-Tenpeak thickening of crust by magmatic or tectonic addition, such as regional contraction or relamination.

Synthesis Model for the Tenpeak Pluton

The Tenpeak pluton was constructed over ≥2.6 m.y. during regional shortening and the volumetrically largest flareup of magmatism in the thick Cretaceous–Paleogene North Cascades arc. The initial stage of subduction-driven magmatism was marked by hydrous mafic magma, which interacted with relatively felsic (tonalitic) magmas in the mafic complex. Injection of Mg-rich tonalitic magmas of the Schaefer Lake subtype accompanied or shortly followed this magmatism. Early magmatism was marked by intrusion of many moderately to steeply dipping sheets along host rock foliation and into earlier sheets, and the narrowness of some of the sheets and compositional and textural contrasts between sheets imply that a sizable magma chamber did not form at this stage. During sheet emplacement, magma wedging isolated and rotated host rocks. This type of construction is also well illustrated by the strongly sheeted Dirtyface pluton, which was derived from the Schaefer Lake subtype source. The relatively small volume of the Dirtyface pluton may explain its more enriched isotopic signature compared to the Tenpeak pluton (Fig. 12); assimilation of even small volumes of the Chiwaukum Schist, the host to the Dirtyface pluton, could have swamped its isotopic signature. We infer that vertical, mostly downward flow of host rock and older plutonic material, along with stoping, were also important during construction of most of the Schaefer Lake tonalite and the White Mountain lobe (Fig. 14).

As the system evolved, another major source was tapped to produce the more isotopically evolved, typical calc-alkaline magmas of the Indian Creek subtype. This subtype is recognized locally in the White Mountain lobe, and became an important magma source by ca. 90.6 Ma when the northern mafic tonalite was intruded. The Schaefer Lake subtype source continued to provide melt

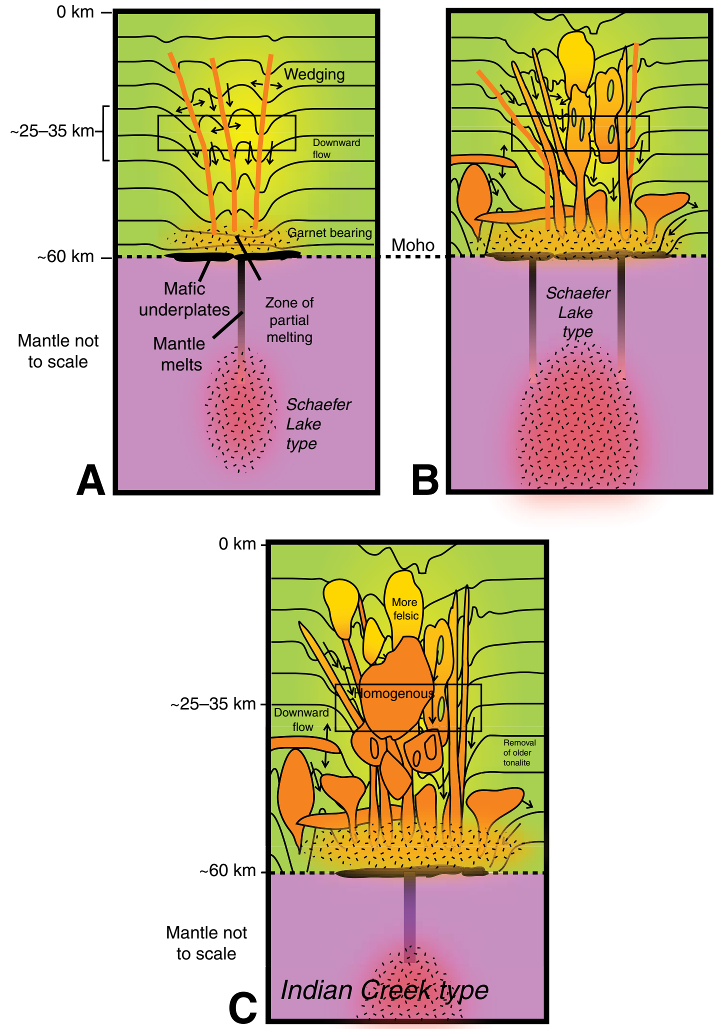

Figure 14. Simplified model for the evolution of the Tenpeak pluton. Box indicates the approximate location of the Tenpeak pluton. Arrows show the transport direction of host rock. Lines in host rock are schematic traces of foliation. (A) Initial emplacement of narrow sheets with magma wedging and accompanying downward transport of host rock. Melts of the Schaefer Lake subtype mantle source interact with melts from garnet (gt)-bearing lower crust. (B) Intermediate stage. Larger volumes accumulate, forming elongate bodies with moderate to steep contacts. Magmas are accommodated by downward flow and some stoping of host rock. Magmas use the preexisting "plumbing system" to rise to higher crustal levels. Melts from the Schaefer Lake source continue to dominate. (C) Transition to the Indian Creek subtype mantle source and formation of large, relatively homogeneous tonalite. Note truncation and postulated downward transport of older magmatic rocks. The location of the Indian Creek mantle source relative to the earlier Schaefer Lake type source is unknown. The speculative larger size of the Indian Creek source reflects the larger size of the Indian Creek unit. See text for more detail of the model.

for the mafic tonalite, but melting of this source terminated, or magmas from the source were trapped at a different crustal level and/or were overwhelmed by the Indian Creek subtype, which makes up the youngest (ca. 89.7 Ma) and largest unit, the Indian Creek tonalite. Mafic magmas represented by enclaves and probably younger parts of the mafic complex continued to contribute to the system, although the depths at which they initially interacted with the more felsic magmas is unknown. A major but unresolved issue is whether the relatively homogeneous Indian Creek tonalite and to a lesser extent the northern mafic tonalite formed from a few large increments that ascended as large batches, or from many smaller increments that mixed extensively. In either scenario, sizable magma and mush bodies formed at least intermittently, and magmas of the northern mafic tonalite and Indian Creek tonalite removed and recycled older solidified and deformed (solid state) magmatic rocks. Host rock continued to accommodate these magmas by multiple processes.

The juxtaposition of magmas of the Schaefer Lake and Indian Creek subtypes, and removal and/or recycling of older magmas by younger increments, indicate that magmas from different sources utilized the same conduit for a protracted time interval. Magma probably ascended through the Tenpeak system to form shallower, larger, and relatively more homogeneous intrusions in the arc. These ascending magmas were likely filtered and homogenized by processes operating at the level of the Tenpeak pluton. For example, some magmas may have thoroughly mixed at this level and then subsequently ascended in response to changing strain fields (e.g., strain-induced pumping; Weinberg et al., 2009), or some of the tonalitic magmas that stalled at the emplacement level may have lost felsic melt that ascended to shallower levels where coeval granodiorites are more common in the voluminous Mount Stuart batholith (Tabor et al., 1982, 1987) and Black Peak batholith (Adams, 1964; Shea et al., 2016). Apparent age gaps in the pluton probably represent periods of minimal melting or ineffective melt segregation at deeper levels, and/or when melt ascended efficiently to shallower levels leaving no record in the pluton. Removal of material by younger magmas may also have contributed to the age gaps. The transition in the system from ascent to emplacement with the accumulation of magma at the level of the Tenpeak pluton may reflect fluctuations in the magma flux or changes in the shape of the magma conduit system. Magma may have utilized rheologically weaker parts of the host rock to expand outward and potentially lead to the White Mountain lobe (cf. Weinberg et al., 2004; Brown, 2010). The end result was a pluton shaped like an elongate asymmetric funnel, which together with shallower plutons resulted in a vertically sheeted, irregularly shaped system (Fig. 14).

The large size of the Indian Creek tonalite, the youngest unit in the pluton, suggests that inputs of mantle-derived magma led to more vigorous differentiation and/or crustal melting that fed the system as it matured. This pattern is similar to that of the Mount Stuart batholith to the south, where maximum intrusion rates occurred in the youngest, ca. 91 Ma intrusions (Matzel et al., 2006), and in many other shallow plutons (e.g., de Silva and Gosnold, 2007; Karakas et al., 2017). In contrast, intrusion rates in the coeval (92–87 Ma) Black Peak batholith increased with time, peaking at ca. 89 Ma, but then waning with relatively small volumes of magma for ~2.0 m.y. after the peak (Shea et al., 2016).

We can only speculate on what localized the long-lived Tenpeak magmatic system. In one scenario, initial magmatism exploited the major anisotropy represented by the boundary between the Napeequa complex and Chiwaukum Schist. Subsequent magmas may have continued to rise along this preheated pathway (e.g., Marsh, 1982; Cao et al., 2016).

CONCLUSIONS

The Tenpeak pluton was constructed over ~2.6 m.y. in the lower mid-crust of a thick continental magmatic arc from inputs of two mafic, mantle-derived magmatic subtypes that differentiated, and mingled and mixed with more felsic end members (most likely crustal melts of garnet amphibolite) to produce the range of compositions observed in the pluton. The relative importance of the different subtypes changed during construction of the pluton. Mafic magmas were intruded throughout the evolution of the Tenpeak pluton, and the relative volume of differentiated tonalitic magma increased with time. The Dirtyface pluton was formed by magmas of the Schaefer Lake (high MgO, Ni, and Cr) subtype early in the process.

Widespread sheeting marked early Tenpeak magmatism, which probably formed small, short-lived magma chambers that were more strongly affected by contamination by their host rocks. Sizable (>1 km^3 to tens of cubic kilometers), intermittent chambers likely developed during construction of the younger, larger, and more homogeneous units that were armored from interaction with the host rock. The extensively sheeted Dirtyface pluton is analogous to the early stages of the Tenpeak pluton. Host rock accommodated magma intrusion by multiple processes, including magma wedging, vertical (mostly downward) ductile flow, and stoping. Host rocks and internal contacts of the Tenpeak pluton are moderately to steeply dipping. The final solidified pluton (and the Dirtyface intrusion) is shaped like an asymmetric funnel or wedge, and is envisioned as part of a steeply sheeted to irregularly shaped magmatic system.

Magmas from different sources utilized this conduit system for a protracted time interval. Much magma probably ascended through the Tenpeak system to form shallower, larger, and relatively more homogeneous intrusions. These ascending magmas were likely filtered and homogenized by processes operating at the level of the Tenpeak pluton, leading to plutons with larger volumes of more felsic magma at shallower levels.

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