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ABSTRACT

The Hortavær intrusive complex, Norway, is a layered igneous complex that was assembled by multiple injections of magmas that ranged from gabbroic through granitic in composition. Layering is defined by intrusive sheets that range from 10 cm to 2 m in thickness. Geopetal structures associated with these sheets indicate that the complex underwent 90°–120° of postsolidification tilting, and subsequent exhumation and erosion have exposed an oblique, 6-km-thick section through the complex. The complex is heterogeneous: at the outcrop scale a range of igneous rock types is exposed and host-rock xenoliths and screens are common. The overall zonation is, from the base upward (west to east), syenite zone (sheets of fine- to coarse-grained syenite), sheeted zone (interlayered syenitic and dioritic sheets), diorite zone (dioritic sheets with thin syenitic intercalations, massive to banded, clinopyroxene-rich cumulate rocks, scant olivine gabbro), eastern zone (dioritic sheets in predominant quartz-bearing monzonite and syenite), and the stratigraphically highest Kvingra alkaline granite. Although magmatic evolution was in batches, individual domains of the pluton and the overall magma evolution of the system display the pervasive influence of assimilation of carbonate-rich rocks, which resulted in the alkaline nature of the evolved magmas. Assimilative reaction between dioritic magmas and calc-silicate rocks resulted in partial melting of the calc-silicates and mixing of the Ca-rich melt into the host magma. Addition of Ca stabilized clinopyroxene (+ plagioclase) at the expense of olivine, which led to precipitation of clinopyroxene-rich cumulates and formation of syenitic residual magmas. Invasion of the calc-silicate rocks by silicate melts resulted in melanocratic garnet + clinopyroxene monzonitic and syenitic endoskarn and magmatic skarn.

Because magmatic evolution involved assimilation of calc-silicate rocks and because melt-bearing skarns and clinopyroxene-rich cumulates formed within the complex, magmatic processes responsible for forming the range of rock types in the complex are interpreted to have operated in situ. This interpretation implies that the core of the complex is a zone in which intense reaction of mafic magmas with calc-silicate rocks occurred. Successive emplacement and loading of additional mafic magma onto these zones squeezed the syenitic magmas laterally into tabular intrusions, one zone of which crops out at the exposed base of the complex. Magma loading is also demonstrated by the presence of magmatic foliation parallel to sheet margins in some sheets but the absence of foliation in adjacent sheets.

Waning stages of magma evolution were less influenced by assimilation of carbonate-rich rocks. Thus, late-stage magmas displayed silica enrichment and the presence of quartz in the uppermost syenites and monzonites. Ultimately, evolved magmas reached granitic compositions and accumulated in the highest level of the complex. Some granitic (feeder?) dikes extend into the center of the pluton, which indicates that formation of the granitic magmas was piecemeal and occurred in numerous parts of the complex, just as evolution of the less evolved part of the system occurred in batches.

INTRODUCTION

A fundamental tenet of modern igneous petrology is the importance of open system behavior in crustal magmatic systems. The precise nature of this behavior is, perhaps, as varied as the volcanic and plutonic systems available for study. As a result, the timing, mechanisms, and locations of open system magmatic process are still debated (e.g., Buddington, 1959; Fowler and Paterson, 1997; Coleman et al., 2004; Dumond et al., 2005; Žák and Paterson, 2005; Glazner and Bartley, 2006; Ciavarella and Wyld, 2008; Lackey et al., 2008). It is generally accepted that open system processes may involve repeated injection of mafic magmas into preexisting magma bodies, with consequent

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mixing or mingling (e.g., Eichelberger, 1975; Anderson, 1976; Vogel and Wilband, 1978; Reid et al., 1983; Barnes et al., 1986; Barbarin, 1988; Hill, 1988; Wiebe et al., 1997; Harper et al., 2004). If the pre-existing magmas formed by partial melting of crustal rocks, then mixing provides an effective way to hybridize crust- and mantle-derived magmas (e.g., Patiño Douce, 1999; Spera and Bohrson, 2001, 2004). The literature also contains examples in which contamination is interpreted to result from magma interaction with solid host rocks (e.g., DePaolo, 1981; Barnes et al., 1987; Foland et al., 1993), despite the added energy input necessary (e.g., Bowen, 1922; McBirney, 1979; Glazner, 2007). An interesting subset of this literature involves contamination of magmas by carbonate and calc-silicate rocks (e.g., Daly, 1910; Shand, 1930; Tilley, 1949, 1952; Sabine, 1975; Baker and Black, 1980). This type of contamination was discounted on the basis of early experimental studies (e.g., Watkinson and Wyllie, 1969), but recent experiments (e.g., Iacono Marziano et al., 2007, 2008) and field-based research (Fulignati et al., 2004, and references therein; Barnes et al., 2005; Freda et al., 2008) indicate that contamination of silicate magmas by carbonate-rich rocks and melts is a viable petrologic process.

Assimilation should be most effective when the host rocks are hot prior to interaction with the invading magma. Such conditions may occur in the lower crust, or in regions with a high geothermal gradient. Alternatively, the host rocks may be preconditioned by sustained injection of magma, such as underplating (Huppert and Sparks, 1988; Grunder, 1992, 1995) or intraplating (Annen and Sparks, 2002; Barnes et al., 2002). Clearly, magmatic systems that receive repeated input of mafic magma, with or without subsequent mixing and/or mingling, should be capable of preheating and then assimilating their host rocks.

Among the many examples that demonstrate episodic addition of mafic magmas, we focus here on an unusual example of a mafic-silicic layered intrusion. These intrusions are ones in which mafic magmas are injected into, and form sheets within, felsic magmas (e.g., Wiebe and Collins, 1998; Wiebe et al., 2001, 2004; Miller and Miller, 2002; Harper et al., 2004). Previous workers have shown that in mafic-silicic layered intrusions the mafic magmas typically pond on top of an aggrading crystal mush to form subhorizontal layers. Moreover, layering of denser mafic magma on less dense crystal-rich magma and/or mush results in syndepositional geopetal structures such as load casts, flame structures, and magmatic pipes. These structures provide information about original horizontal and "up" directions, and may be used to interpret the stratigraphic development of the pluton. This in turn permits evaluation of magmatic evolution as a function of stratigraphic height, and therefore of time.

Most examples of mafic-silicic layered intrusions reported in the literature consist of interlayered mafic and granitic rocks. In these systems, the granitic magmas are interpreted to be derived by crustal melting and transported to the site of emplacement. This paper describes a mafic-silicic layered intrusion in north-central Norway, the Hortavær intrusive complex, that is distinct in a number of ways. First, the felsic magma was predominantly syenitic, rather than granitic. Second, the syenitic magmas were not crustal melts, but formed in situ by a combination of assimilation and fractional crystallization (Barnes et al., 2005). In situ formation of syenitic magmas gave rise to a third distinctive feature, the presence of interlayering among evolved (syenitic and monzonitic) rocks.

The original studies of the Hortavær complex focused on magma interaction with carbonate and calc-silicate rocks. However, during the course of recent field work, geopetal features and therefore the mafic-silicic layered intrusion nature of the complex were recognized. In this contribution we document these field relationships and use them to reconstruct the complex to its original orientation. We also discuss the stratigraphic and temporal lithologic and petrologic changes in the complex and use them to assess the consequences of assimilation on magma differentiation. Detailed presentations of the mineralogical and geochemical characteristics of the complex will be presented elsewhere (also see Li, 2008; Barnes et al., 2008).

GEOLOGIC SETTING

The Hortavær complex is exposed on a series of small islands and skerries northwest of the island of Leka (north-central Norway; Figs. 1 and 2). Field work involved travel from Leka by fishing boat and then island hopping via shallow-draft boats. Such work is best done in fair weather and requires moderate to calm seas. The first visit to Hortavær by any of us was in 1970 (Gustavson and Prestvik, 1979); however, the work reported here is primarily based on intermittent field work that began in 1991 and culminated in concentrated activity from 2005 to 2007. More than 70 person-days were devoted to field work.

The Hortavær complex is part of the Bindal Batholith, a series of Ordovician and Silurian plutons intruded into the Helgeland Nappe Complex (Fig. 1; Nordgulen, 1993). The Helgeland Nappe Complex is the structurally highest nappe complex of the Uppermost Allochthon (e.g., Stephens et al., 1985), and consists of a number of nappes imbricated along east-dipping faults (Thorsnes and Løseth, 1991; Yoshinobu et al., 2002; Barnes et al., 2007) (Figs. 1 and 2). The earliest magmatism in the Bindal Batholith (at ca. 478 Ma) was dominated by peraluminous anatectic granites with minor mafic components (Barnes et al., 2007). The Hortavær complex was emplaced at ca. 466 Ma and marked a change from predominantly peraluminous to more diverse magmatism that continued until 423 Ma (Nordgulen, 1993; Nordgulen et al., 1993; Yoshinobu et al., 2002; Nissen et al., 2006; Barnes et al., 2007). Most of these diverse plutonic rocks are calc-alkalic to alkali-calcic (Nordgulen, 1993; classification of Frost et al., 2001). Few plutons aside from the Hortavær complex are truly alkalic.

The Hortavær complex intruded a sequence of metasedimentary rocks referred to as the Horta nappe (Barnes et al., 2007). This nappe unit consists of an eastern sequence of marble, calc-silicate rocks, quartzofeldspathic gneiss, and sparse pelites and a western sequence of migmatitic quartzofeldspathic gneiss and diatexite (mobilized migmatite), quartzite, and sparse metapelitic rocks, marble, and calc-silicate rocks (Barnes et al., 2007). The U-Pb (zircon) ages of two leucosomes from the western sequence indicate deposition during Early Ordovician time and migmatization at ca. 477 Ma (Barnes et al., 2007). In contrast, marble in the eastern sequence has C and Sr isotopic features that are characteristic of Neoproterozoic deposition (Barnes et al., 2005, 2007). The contact between the two sequences within the complex cannot be precisely located. However, marble with Neoproterozoic isotopic compositions crops out on northern Burøya, and a large quartzite xenolith that is identical to quartzite in the northwestern host rocks crops out ~1800 m to the west (Fig. 2). The contact between sequences is thus inferred to be between these locations.

Original mapping (Gustavson and Prestvik, 1979) documented zoning from external felsic, primarily syenitic rocks, to interior dioritic to gabbroic rocks. This zoning pattern was presented in greater detail in Barnes et al. (2003), wherein it was shown that the complex consists of hundreds of sheet-like intrusions. In Barnes et al. (2003), it was assumed that the original orientation of the sheets was subvertical, and the islands at the far eastern side of the complex (Kvingra; Fig. 1) were interpreted as a distinct plutonic unit. Recent detailed observations on the magmatic sheeting and zoning patterns in the complex reveal that (1) it has been tilted at least 90°, (2) it grew by successive emplacement of subhorizontal mafic sheets accompanied by differentiation, and (3) evolved magmas vary from syenitic at the exposed base of the complex to alkali feldspar granite in the structurally highest level.

The earliest petrologic study of the Hortavær complex recognized the importance of assimilation of carbonates during magma evolution (Vogt, 1916; Gustavson and Prestvik, 1979). The early work was summarized in Barnes et al. (2005), and the source of carbon in magmatic calcite was identified as marble screens in the pluton: it was also shown, on the basis of Sr and Nd isotope ratios, that both carbonate and silicate material had been assimilated. The conclusion in Barnes et al. (2005) was that episodic, sheet-like emplacement of mafic magmas into the growing Hortavær plutonic system permitted extensive, albeit variable, amounts of assimilation.

STRUCTURE OF THE PLUTON

At the map scale, it is only possible to represent the most common plutonic rock type in the Hortavær complex. However, in detail, every outcrop larger than a few square meters is underlain by more than one rock type. This heterogeneity results from the sheeted nature of the pluton and from the abundance of xenoliths and screens. We first describe the overall zonation of the complex and then consider the outcrop-scale structures within each map unit.

Overall Zoning

The overall zoning of the Hortavær complex is shown in Figure 2, with nomenclature modified from Gustavson and Prestvik (1979) and Barnes et al. (2003, 2005). The western and northern parts of the complex constitute the syenite zone, which is underlain by syenite and sparse diorite. The syenitic rocks vary from fine to very coarse grained and in some localities are clearly interlayered, with sheets of fine-grained syenite in coarse-grained syenite (Fig. 3A). Quartz is generally lacking in the syenitic rock of the syenite zone. Screens and xenoliths include calcite and dolomitic marble, quartzite, rare quartzofeldspathic gneiss (Kvåholmen),

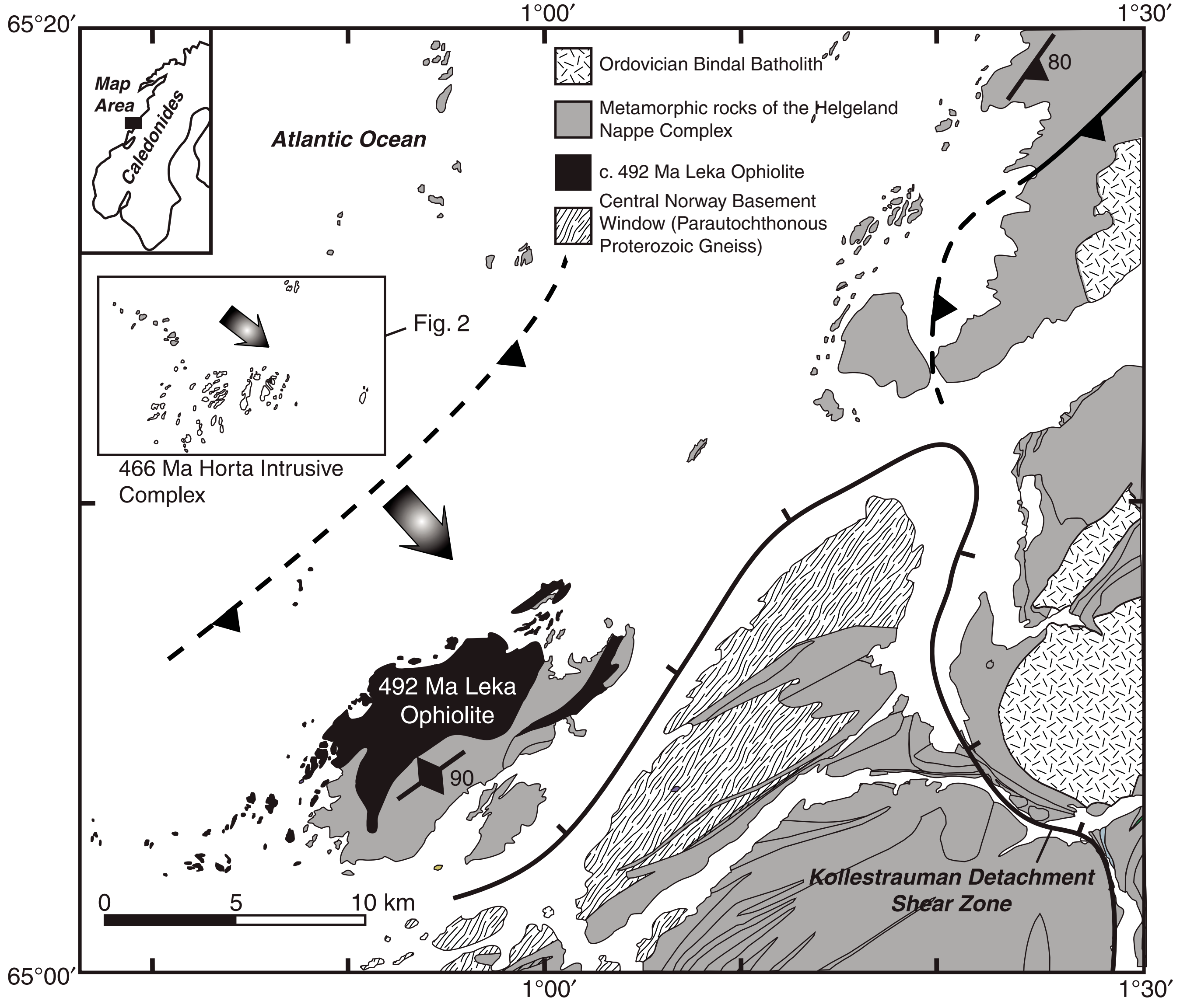

Figure 1. Regional geologic map showing the location of the Hortavær (Horta) intrusive complex. Shaded arrows indicate stratigraphic "up" directions in the Leka ophiolite and Hortavær complex.

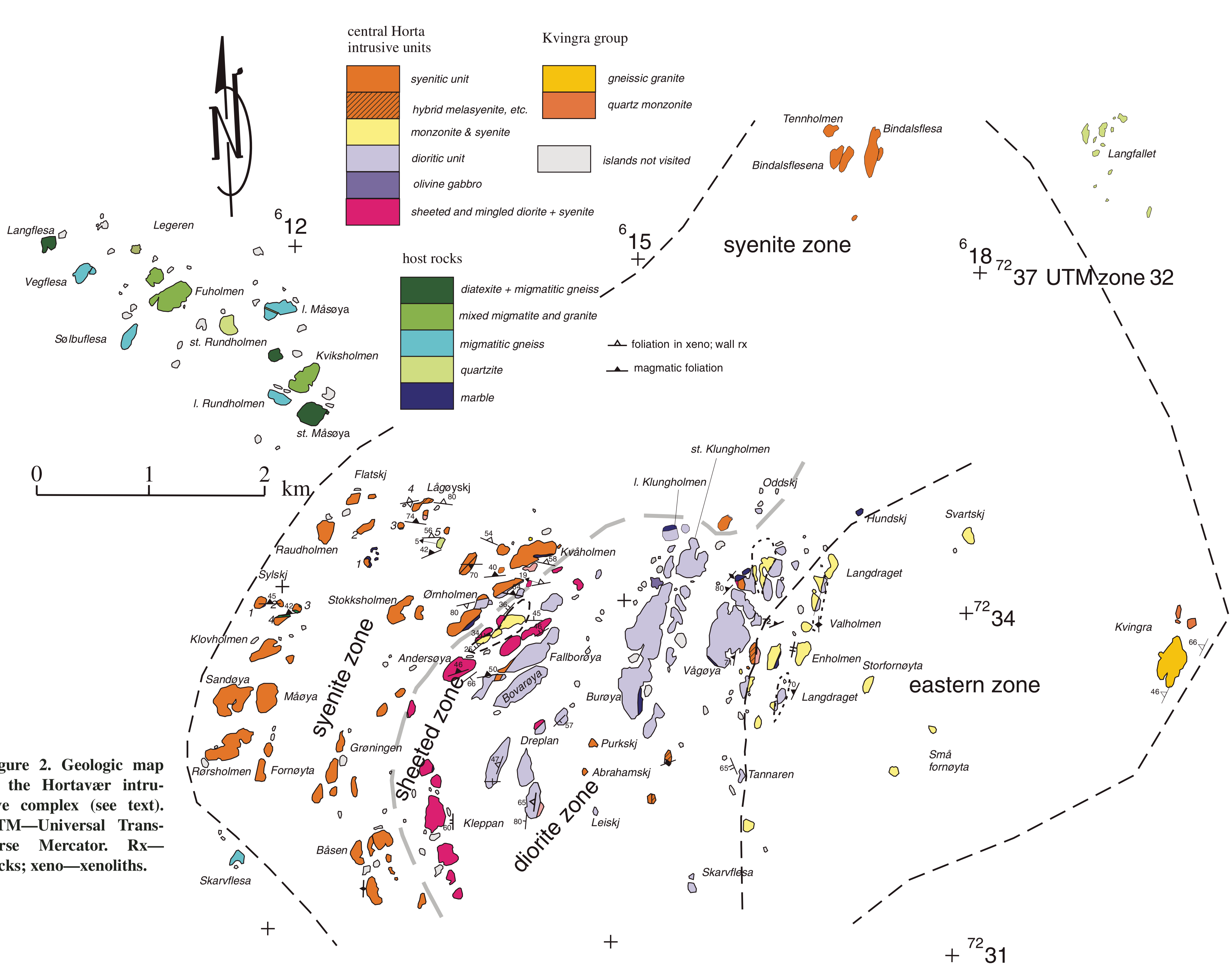

Figure 2. Geologic map of the Hortavær intrusive complex (see text). UTM—Universal Transverse Mercator. Rx—rocks; xeno—xenoliths.

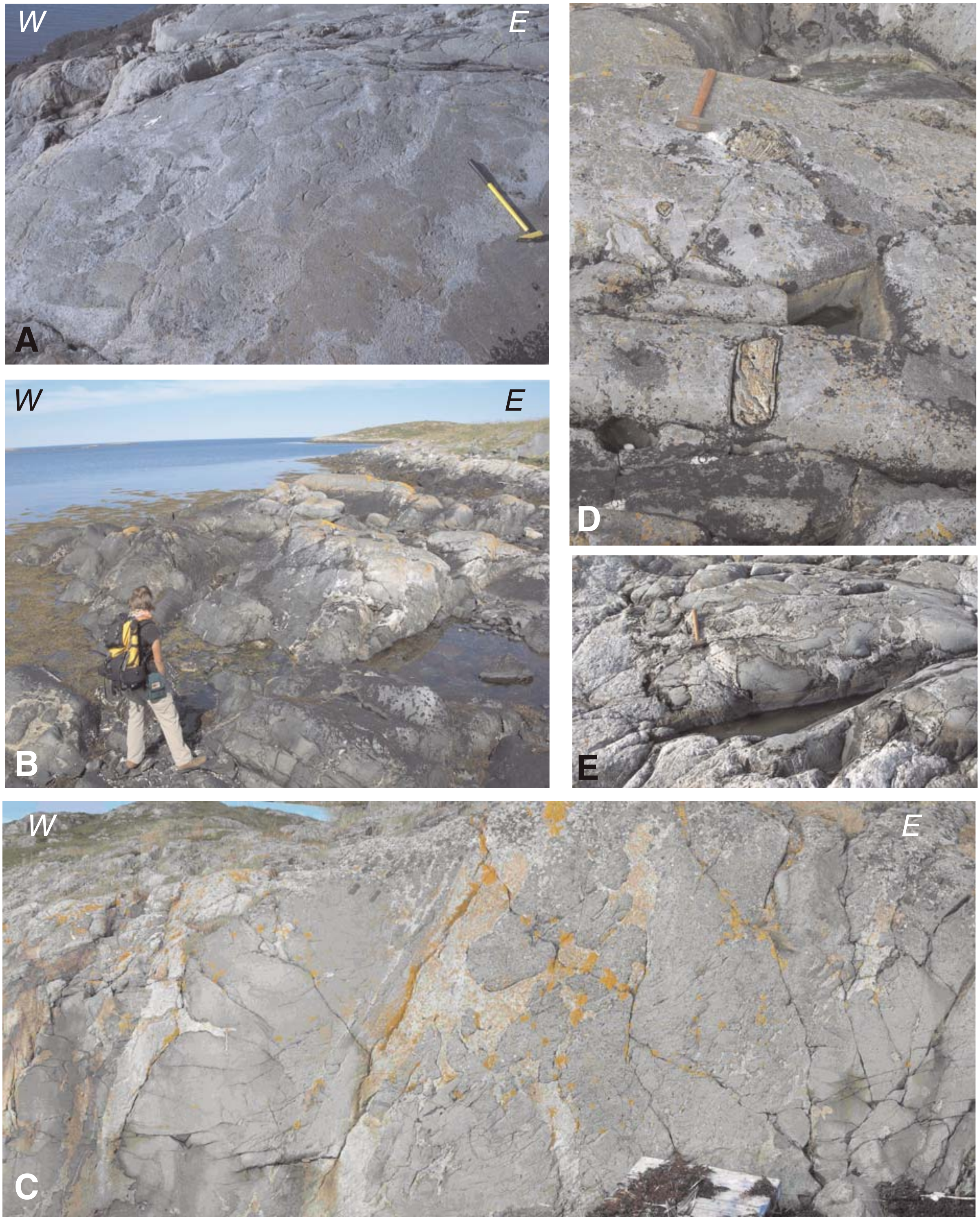

Figure 3 (***continued on next pages***). **Photographs of calc-silicate xenoliths, sheeting, enclaves, and geopetal structures. (A) Fine-grained (pale gray) syenitic sheets with bulbous contacts with white, coarse-grained syenitic host on their east sides and subplanar contacts on their western sides. View to north-northwest at Groningen (syenite zone). Hammer is 59 cm long. (B) Sheeting in the diorite zone along the western shore of Burøya. Thin (0.5–1-m-wide) dioritic dikes are separated by centimeter- to decimeter-scale syenitic stringers. (C) A south-facing outcrop on southern Kleppan (sheeted zone) shows a sequence of four west-dipping dioritic sheets. Three of the dioritic sheets are separated from one another by white syenite, which has flame-like structures penetrating eastward into the diorite. Also note the bulbous zones along the western side of the two central dioritic sheets. The flame structures and bulbous zones (load casts) indicate that original "up" direction was to the east in modern coordinates and that the sheets are overturned (see text). Pallet in foreground is ~1 m wide. (D) Blocky calc-silicate xenoliths in a dioritic sheet in the eastern part of the complex; from Svartskjæret (eastern zone). Hammer is 38 cm long. (E) Gray dioritic pillows in white syenite; from Langdraget (eastern zone). Hammer is 38 cm long.**

Figure 3 (*continued from previous page*). (F) A sheet that consists of subrounded, dark gray dioritic enclaves in pale gray to white syenite; from unnamed island west of Fallborøya (sheeted zone). Hammer is 38 cm long. (G) Angular, dark gray dioritic enclaves mingled with both medium gray monzonite and white syenite; from Kleppan (sheeted zone). Coin is 22 mm in diameter. (H) Fine-grained, rounded syenitic enclaves in medium-coarse-grained syenite; from Lågøyskjæret (syenite zone). Global positioning system receiver is 14.5 cm long. (I) A dioritic dike cutting a mingled sheet; from Kleppan. Hammer is 38 cm long. (J) A lobe of diorite intruding a syenitic sheet; from a low-tide islet east of Ørnholmen (syenite zone), view is downdip to northwest. Hammer is 38 cm long. (K) Close-up photo of a 1-m-wide sheet of intensely disrupted, foliated, medium-grained monzonite in coarse-grained syenite; from Dreplan (diorite zone). Hammer is 38 cm long.

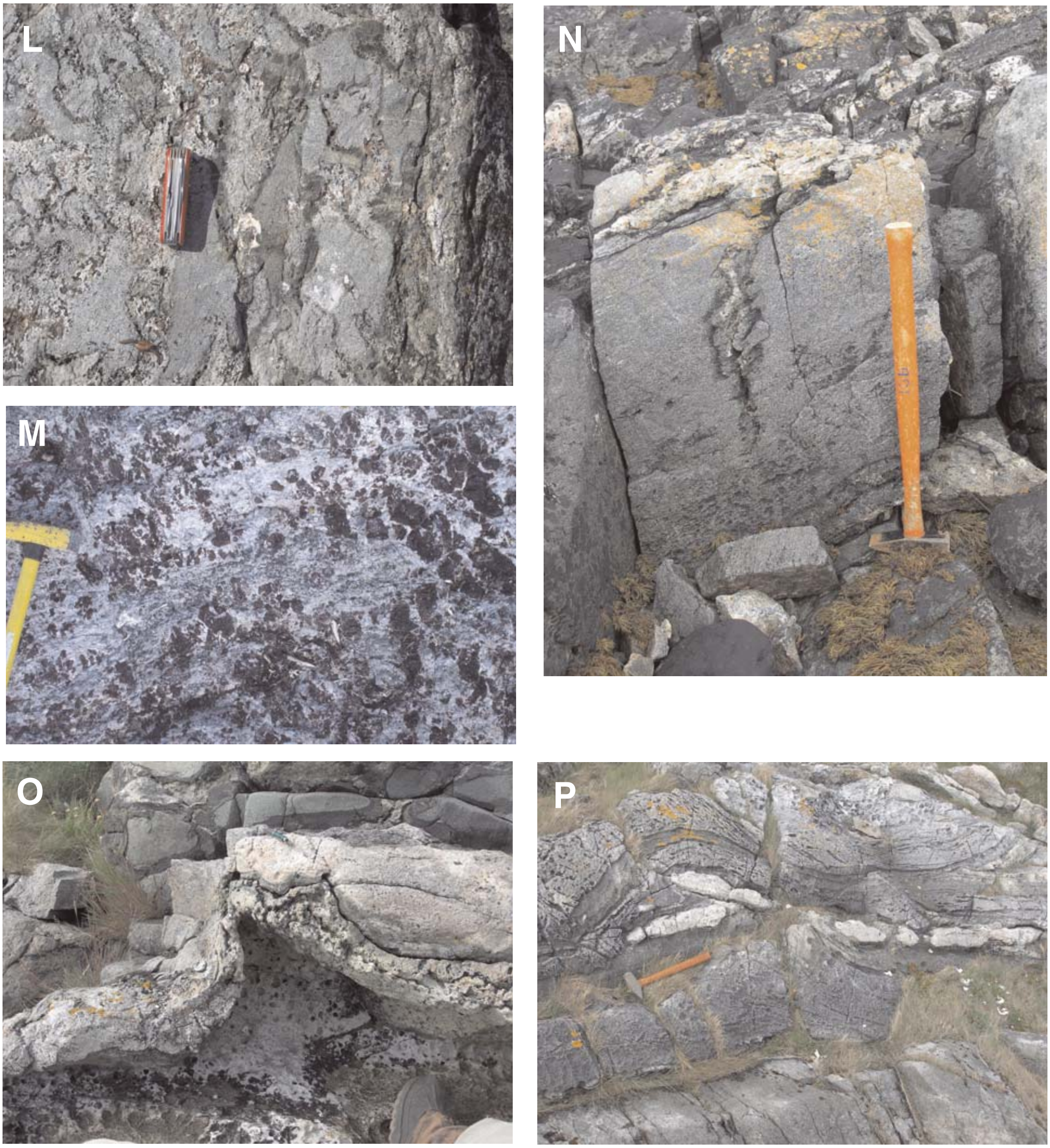

Figure 3 (*continued from previous page*). (L) Close-up photo of a 10-m-wide zone with fine-grained monzonitic enclaves in garnet pyroxene melasyenite (magmatic skarn); from northern Vågøya (diorite zone). (M) A pegmatitic garnet pyroxene magmatic skarn, part of a larger endoskarn and/or magmatic skarn screen; from Lågøyskjæret (syenite zone). Hammer is 59 cm long. (N) The hammer is adjacent to a dioritic sheet with magmatic foliation that is parallel to layering. The view is to the northwest, so the sequence is overturned. The dioritic sheet is cut by a deformed flame structure from the syenite above; from Ørnholmen (syenite zone). Hammer is 38 cm long. (O) Asymmetric, west-plunging fold in marble (below) and syenite (above); from Andersøya (sheeted zone). (P) Folded, boudinaged leucosyenite in marble in a west-plunging fold; from Andersøya. Hammer is 38 cm long.

layered endoskarn, and magmatic skarn. Skarn terminology used here follows that of Fulignati et al. (2004) for skarn samples in the ejecta from Mount Vesuvius. Exoskarn refers to skarns developed beyond pluton contacts via hydrothermal exchange. Such skarns were not observed in the Hortavær complex. Endoskarn refers to skarn developed from rocks in direct contact with magmas. Magmatic skarn refers to skarn rocks that contain, or once contained, a melt phase. In Barnes et al. (2005), endoskarn was referred to as melasyenite or melamonzonite because it consists of medium- to coarse-grained K-feldspar + hedenbergite + sphene + calcite ± plagioclase ± grossular–andradite garnet ± Fe-rich amphibole. Apatite is a common accessory phase, wollastonite occurs in a few samples, and inverted bustamite was found in one location.

The central zone of the pluton is called the diorite zone, and it is separated from the syenite zone by the so-called sheeted zone. The diorite zone is primarily underlain by diorite and monzodiorite, but also contains olivine gabbro, syenite, monzonite, and granite. Sheeting is also common in the diorite zone, but the proportion of syenite is much smaller (Fig. 3B). Moreover, some parts of the diorite zone consist of medium- to coarse-grained, massive to laminated rocks that lack sheeting. These rocks range from olivine gabbro through pyroxene monzodiorite to melanocratic garnet hornblende pyroxene monzodiorite and monzonite, and some are rich enough in clinopyroxene to be classified as pyroxenite. This group of rocks is characterized by abundant sphene and calcite, amphibole crystals that reach 3 cm in length, and garnets that reach 10 cm in diameter (e.g., on Vågøya; Fig. 2). Vogt (1916) recognized these coarse-grained rocks as a peculiar part of the intrusion and applied the term "hortite" to them. Although this rock name was abandoned by the International Union of Geological Sciences, we use it here as an informal name to refer to the peculiar mineral assemblage, the abundance of clinopyroxene and sphene, and the mode of origin, which is discussed in a later section.

The sheeted zone is ~500 m wide (original thickness; see following) and consists of intimately interlayered syenite, diorite, and monzonite in various stages of mingling and disruption (Fig. 3C; see following). Xenoliths and screens in the sheeted and diorite zones consist of marble, banded to massive endoskarn, magmatic skarn, and sparse pelitic and semipelitic rocks. Granitic dikes are sparsely present in the diorite zone; most have approximately east-west strikes and steep dips.

Syenite, monzonite, granite, and sparse diorite of the eastern zone underlie the islands east of the diorite zone (Fig. 2). This part of the pluton is distinct from the western syenite zone because (1) it contains a greater abundance of diorite and monzonite, (2) syenitic and monzonitic rocks are commonly quartz bearing, and (3) east-striking, steeply dipping granitic dikes are common; some are >15 m in width. Sheeting typifies the western part of the eastern zone and xenoliths and screens are identical to those in the diorite zone. However, the island of Svartskjæret (Fig. 2) is distinct because instead of parallel sheets, the outcrop is characterized by dikes with a variety of orientations. Moreover, unlike the parts of the complex to the west, in which screens and xenoliths are parallel to sheeting, calc-silicate xenoliths on Svartskjæret are subrounded to subangular clasts enclosed in individual dikes (Fig. 3D).

The easternmost part of the complex (Kvingra, Fig. 2) is underlain primarily by foliated to massive alkali granite. The granitic rocks enclose xenoliths of leucocratic monzonite and quartz monzonite, the textures and chemical compositions of which are identical to monzonite sheets exposed elsewhere in the eastern zone. Moreover, the alkali granite contains biotite + white mica (zinnwaldite) ± riebeckite ± fluorite, as do many of the east-west–striking granitic dikes in the eastern zone. Therefore, we consider the rocks of Kvingra to be part of the Hortavær intrusive complex, as originally mapped by Gustavson and Prestvik (1979).

Magmatic Sheets

With the exception of Kvingra, every exposure of igneous rock in the pluton displays evidence of magma emplacement as sheets, many of which have undergone various amounts of magmatic disruption. The sheets are generally parallel to one another (see following), and range in width from ~15 cm to 2 m. The boundaries of mafic sheets are asymmetric throughout the intrusion, and particularly in the sheeted and diorite zones. This asymmetry is shown in Figure 3C, in which dioritic sheets bulge westward into syenitic sheets and flame-like projections from syenitic sheets intrude eastward into dioritic sheets. Such features were documented by Wiebe and Collins (1998), and Harper et al. (2004) to be geopetal structures. In the case of Hortavær, the bulges on the west side of the dioritic sheets are interpreted to represent load casts of dioritic magma into an underlying syenitic mush, and the flames that penetrate from syenite sheets eastward indicate upward injection of syenitic magma into, and in some instances through, the overlying dioritic magma. Because this asymmetry is consistent within the pluton, we interpret such structures to be geopetal indicators. This interpretation means that, because the magmatic sheets dip to the west, the Hortavær complex is overturned and rotated by 90°–130° such that a structural thickness of ~6–9 km is now exposed.

Wiebe and Collins (1998) showed that in some layered intrusions the tops of mafic sheets vary from planar to bulbous. The bulbous tops commonly grade into zones or swarms of enclaves. Such upward transition of a sheet to enclaves is also common in the Hortavær complex and is not limited to mafic sheets. Figure 3A shows an example from the syenite zone in which fine-grained syenitic sheets are interlayered with coarse-grained syenite. The eastern (top) side of the fine-grained sheets shows development of rounded enclaves.

Many of the sheets are entirely disrupted. Locally, this disruption results in formation of classic pillow-like enclaves (Fig. 3E) similar to those seen during disruption of synplutonic dikes (e.g., Barnes et al., 1986). It is much more common for disrupted sheets to result in angular to subangular enclaves. Figure 3F shows an example in which an entire sheet consists of mingled dioritic and syenitic rocks. Figure 3G shows a more complicated example in which angular to subangular mafic enclaves are mingled with both intermediate and felsic (syenitic) rocks. Similar mingling also occurs in the syenite zone: Figure 3H shows subrounded, fine-grained enclaves mingled in a coarse-grained syenitic host. The field evidence for magma mingling such as seen in Figures 3G and 3H suggests the possibility of magma mixing in the Hortavær complex, a topic discussed in a later section.

In contrast to the sheets that display geopetal features, a smaller number of dikes and/or sills clearly crosscut older sheeted rocks. Examples of crosscutting mafic dikes and/or sills are most apparent in the sheeted and diorite zones. For example, Figure 3I shows a dike that truncates a mingled sheet, crosscutting a mafic enclave in the sheet to the right of the hammer head. Moreover, some outcrops in these zones provide permissive evidence that mafic magma was injected between existing sheeted structures. Figure 3J shows a tongue-like dioritic body that we interpret as the tip of a mafic sheet (sill) intruding a syenite sheet. In contrast to these intrusions that are subparallel to layering, granitic dikes cut the sheets at a high angle. As noted above, these granitic dikes have approximately east-west strike, near-vertical dip, and increase in abundance eastward from the diorite zone.

One of the unusual and intriguing features of the Hortavær complex is shown in Figure 3K, which is a close-up view of a sheet that consists of centimeter- to decimeter-sized angular monzonitic clasts in a syenitic matrix. This brecciation is not tectonic, because sheets on either side are not fragmented. A more complicated form of disruption is shown in Figure 3L. This photograph is a close-up view of a 10–15-m-wide zone in which dioritic magma was mingled with garnet-bearing syenitic skarn. The western side of this zone consists of syenitic skarn with fine-grained dioritic enclaves. The zone grades eastward into fine-grained diorite with abundant decimeter-scale, rounded to subangular clasts of syenitic skarn. Figure 3L is from the interior, transitional part of this zone, with angular to subrounded dioritic enclaves in coarse-grained skarn that contains garnets as much as 3 cm in diameter. This relationship is interpreted to indicate intrusion and disruption of dioritic magma into the skarn, with consequent entrainment of skarn clasts in the diorite sheet. The ability of the dioritic magma to intimately mingle with the skarn strongly suggests that the skarn was partly molten (magmatic skarn) and capable of enclosing dioritic enclaves. According to Li (2008) and Li et al. (2008), mingling occurred because development of the magmatic skarn involved partial melting of the skarn protolith and extrusion of the resultant carbonate-rich partial melt into the host dioritic magma. This initial melt extraction was followed by invasion of the resulting porous magmatic skarn framework by silicate melts. This entire process is consistent with the melasyenitic mineral assemblages of the magmatic skarns (K-feldspar + clinopyroxene + calcite ± garnet ± amphibole ± wollastonite) and also of the layered endoskarns in the complex. We suggest that the magmatic skarns and endoskarns share a similar origin, but that high degrees of partial melting resulted in mobilization of rocks now referred to as magmatic skarn, whereas smaller melt fractions preserved layering in endoskarn. An extreme example of magmatic skarns is shown in Figure 3M, which shows a pegmatoidal magmatic skarn. This skarn is a 5-m-wide zone within a larger endoskarn screen in the syenite zone. In general, the presence of an interstitial silicate melt during skarn formation is consistent with the massive to pegmatoidal textures of many of the endoskarns (e.g., Fig. 2d in Barnes et al., 2003).

Sheet Orientation, Foliation, and Folding

Figure 4 displays the orientations of magmatic sheets (Barnes et al., 2003; McCulloch, 2007). In the southern part of the complex, sheets have an average orientation of ~N15W, 54SW and in the northern part they are oriented ~N53E, 37NW. When taken together, the sheets define an average great circle with an orientation of N14E, 40NW (Fig. 4). Some sheets contain a magmatic foliation, particularly those in the sheeted and diorite zones. At the outcrop scale, a magmatic foliation is defined by planar orientation and flattening of enclaves, deformation of flame structures, and at the outcrop and microscopic scale by alignment of plagioclase laths (e.g., Fig. 3N) and locally by alignment of elongate augite and amphibole (McCulloch, 2007). This foliation is not pervasive, and foliated sheets may be surrounded by sheets in which foliation is absent. Poles to foliation planes are also plotted in Figure 4. At the outcrop scale, foliations are parallel to igneous sheet margins; however, taken as a population, magmatic foliations have an average orientation of N56E, 39W (Fig. 4). Because of the lack of discordance observed at any of the outcrops, we view the discordance in strike direction between the igneous sheets and magmatic foliations to be a function of the greater number of magmatic foliation observations made in the northern area as compared to the south.

Outcrop-scale folds were observed locally in the sheeted zone and adjacent islands to the east (Figs. 3O, 3P). All of the folds involve carbonate or calc-silicate rocks and intrusive sheets. In some cases, igneous sheets are folded, preserving relict igneous microstructures indicative of ductile, high-temperature (melt present) deformation (e.g., Fig. 3O). However, in other folds (e.g., Fig. 3P) the igneous sheets are broken, indicative of lower-temperature brittle failure or high-strain-rate, high-temperature deformation. The few fold axes measured are plotted in Figure 4; they have moderate plunges to the west or northwest. While the data are few, the fold axes appear to fall within an enveloping surface defined by the magmatic foliations and igneous sheets. Therefore it is permissible that the folds represent hypersolidus flow along planes parallel to the sheet margins.

Discussion: Geopetal Structures and Pluton Construction

The widespread presence of geopetal structures indicates that the great majority of magmatic sheets in the Hortavær complex were emplaced subhorizontally. This recognition in turn makes the complex comparable to mafic-silicic layered intrusions (e.g., Wiebe and Collins, 1998; Harper et al., 2004). In these examples, pipes and flame structures generally penetrate individual mafic sheets, but do not continue into overlying mafic sheets. This observation and the characteristic presence of load casts at the base of mafic sheets have been interpreted as evidence for magma emplacement as an upward-growing stack of mafic sheets separated by and deposited on mushy, felsic

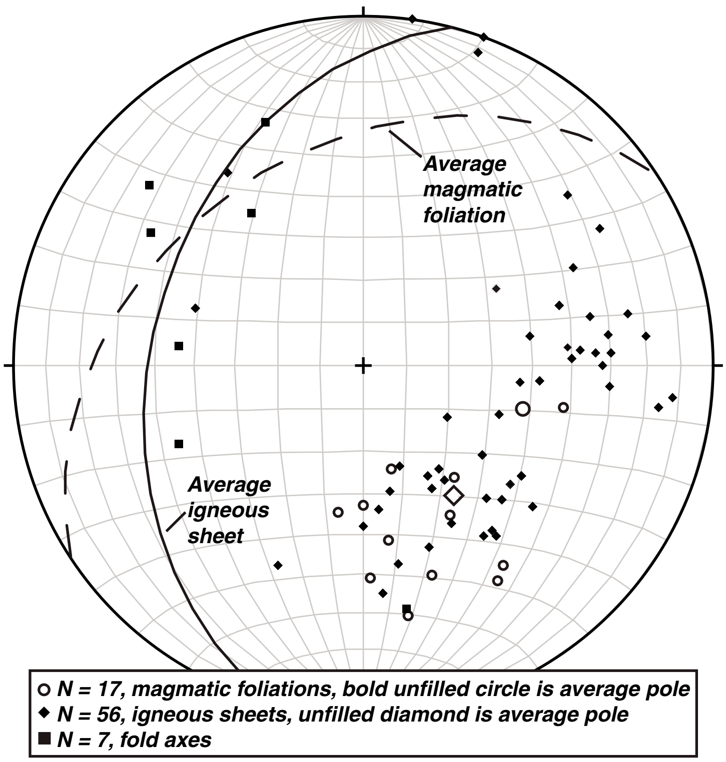

Figure 4. Equal-area stereoplot showing orientations of sheets, foliation, and fold axes.

magma. Flame structures in the Hortavær complex are similar to those seen elsewhere in that they do not penetrate more than one mafic sheet. We therefore conclude that growth of the complex may, at least in part, be explained by deposition of mafic sheets on crystal-rich syenitic magma. However, this explanation does not explain the sheeted nature of the syenite zone, in which nearly all magmatic sheets are syenitic. Evidently, the process that forms alternating mafic–felsic layering can also produce layered felsic zones, with the possibility of similar styles of ductile (Fig. 3A) and brittle (Fig. 3H) magmatic disruption.

It is also evident that some layers were capable of ductile deformation longer than others. This is apparent because magmatic foliation is parallel to the orientation of the sheets (Fig. 4), yet foliated sheets are between nonfoliated ones. This relationship suggests that foliation developed as the result of flattening due to magma loading, with some layers capable of deforming by flattening in the magmatic state. The presence or absence of magmatic foliations within individual sheets may reflect the episodic nature of sheet intrusion, loading, and crystallization. In such a scenario, if sheets are intruded sequentially on top of each other, the lower sheet may deform in the magmatic state and preserve sheet-parallel magmatic foliations. Alternatively, unfoliated sheets may represent later sill-like intrusions into largely solidified rocks. A few such intrusions with symmetrical chilled margins were observed, but are uncommon.

In contrast, the timing of folding is not clear. Some outcrop-scale folds suggest that igneous sheets behaved in a ductile manner (Fig. 3O), which suggests high-temperature, melt-present deformation during cooling of the complex. Others (Fig. 3P) suggest brittle behavior of the magmatic sheets but ductile deformation of the surrounding marble. At present, it is unclear whether these folds are related to sagging of the complex toward its central region during magmatism or are related to regional tectonics. Limited observations of asymmetric flame structures that verge toward the center of the complex are consistent with the notion that sagging of the center of the intrusion occurred during crystallization. However, there are not sufficient data to evaluate this hypothesis.

The presence of consistently oriented geopetal structures, and the assumption that magmatic sheets with geopetal features were emplaced subhorizontally, means that a west to east transect across the Hortavær complex is an oblique base-to-top cross section of the magmatic system. Figure 5 is a schematic stratigraphic column of the exposed part of the complex that illustrates the compositional zoning along with the array of rock types present. This reconstruction emphasizes the compositional zoning, with syenite at the exposed base, granite at the top, and an abundance of dioritic rocks in the middle structural level. In addition to the lithologic zones illustrated in Figure 5, there are a number of subtle upward changes in mineral assemblage and chemical composition in the complex. (1) Syenitic rocks in the lower syenite zone lack quartz and are nepheline- to quartz-normative. In contrast, syenite and monzonite in the eastern zone are quartz-normative and many contain modal quartz. These observations indicate an upward increase in activity of SiO_2 among evolved magma compositions. (2) Modal nepheline is present sparsely; its occurrence is limited to nepheline monzodiorite to rare nephelinolite (i.e., nepheline foidite lacking feldspar) from the northern part of the diorite zone. (3) The magmatic assemblage vesuvianite + garnet occurs in igneous sheets at structural levels within and above the upper diorite zone. (4) Blue amphibole, zinnwaldite, and fluorite occur in the Kvingra granite, in quartz monzonite sheets in the eastern zone, and in some east-west granitic dikes.

The mode of pluton emplacement and growth interpreted on the basis of geopetal structures poses an interesting dilemma with regard to magmatic evolution. All previous workers interpreted the rocks of the Hortavær complex as the result, at least in part, of carbonate assimilation (Vogt, 1916; Gustavson and Prestvik, 1979; Barnes et al., 2005). The petrogenetic model presented by Barnes et al. (2005) followed that of the classic literature on carbonate assimilation (e.g., Daly, 1910; Shand, 1930; Sabine, 1975), in which enrichment of CaO due to carbonate assimilation results in stabilization of augite at the expense of olivine. Fractionation of augite + plagioclase then causes enrichment of the alkalis, and particularly K_2O, relative to SiO_2. This process was subsequently confirmed by the

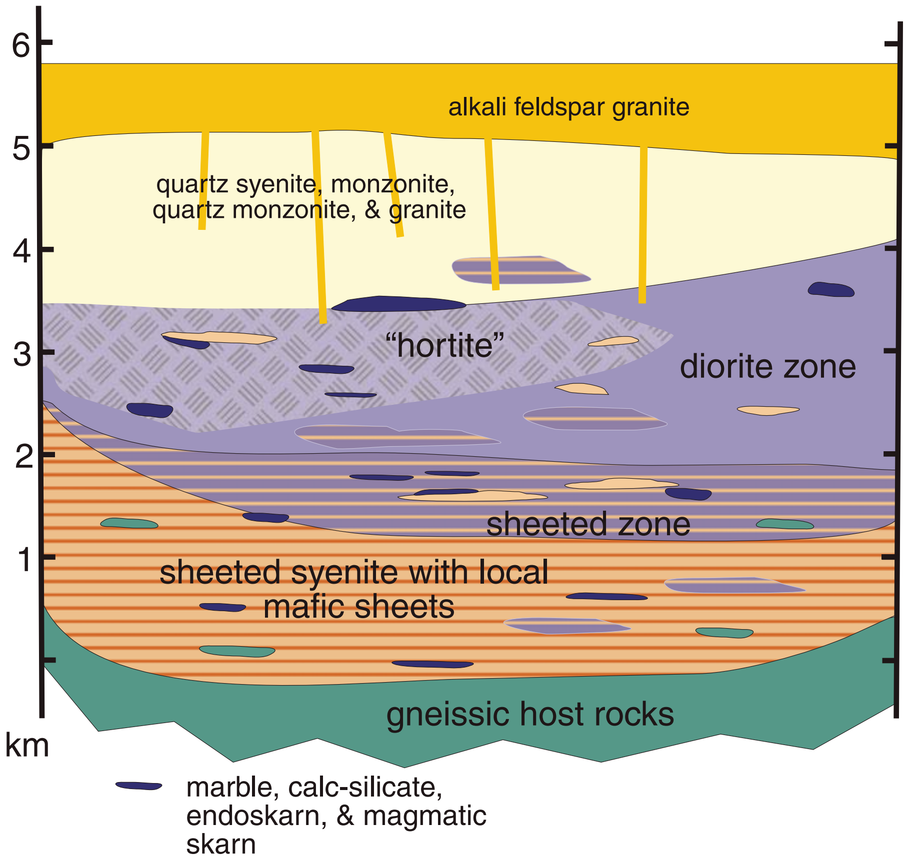

Figure 5. Downdip view of Horta complex with 90°–120° of tilt restored; view from the western host rocks to the east-southeast. This figure shows the overall layered nature of the complex. In addition, layering on approximately the meter scale is characteristic except in the upper alkali feldspar granite and the "hortite" (Vogt, 1916; see discussion in text) zone. Granitic dikes cut the diorite and higher zones; they generally have approximately east-west strikes and steep dips.

experiments of Iacono Marziano et al. (2007, 2008). Barnes et al. (2005) showed that fractionation of carbon isotope ratios during differentiation was consistent with carbonate assimilation. However, they also found that the low ε_{Nd} values of most Hortavær complex rocks (as low as −10 at 466 Ma) had to result from assimilation of silicate material. Thus, differentiation of the complex involved assimilation of carbonate and silicate components combined with fractional crystallization of an assemblage initially dominated by Ca-clinopyroxene and plagioclase.

In the petrogenetic interpretation in Barnes et al. (2005), the oldest, structurally lowest rocks should be mafic. However, restoration of the pluton to a pretilting orientation (Fig. 5) shows syenite to be at the exposed structural base of the complex and, by inference, the oldest magma type. This discrepancy may be explained in at least two ways: (1) the syenitic magmas did not form at or near the level of emplacement, but instead formed in deeper crustal levels, or (2) the syenitic magmas formed within the Hortavær complex, but in a zone not currently exposed. We prefer the latter explanation for two reasons. The first is that with the exception of the Hortavær complex and volumetrically minor parts of the Hillstadfjellet pluton (Barnes et al., 1992), alkaline syenite is absent in the Bindal Batholith (cf. Nordgulen, 1993). It is noteworthy that the Hillstadfjellet pluton intruded marble and encloses large marble screens, along which syenitic selvages occur. The second reason is that within the Bindal Batholith, the Hortavær rocks are distinct in their combination of low initial $^{87}Sr/^{86}Sr$ and ε_{Nd} and their high $\delta^{18}O$ values (Barnes et al., 2005). The Helgeland Nappe Complex nappes had amalgamated prior to Hortavær magmatism (Barnes et al., 2007); therefore, if formation of dioritic to syenitic magma compositions with these distinctive isotopic signatures were related to lower crustal processes, one would expect wider distribution of such rocks within the Bindal Batholith. We therefore conclude that the syenitic magmas were the result of assimilation of crustal rocks into dioritic magmas at the level of emplacement (Barnes et al., 2003, 2005).

CONSEQUENCES OF ASSIMILATION

Recent experimental studies have investigated carbonate assimilation (Iacono Marziano et al., 2007, 2008; Freda et al., 2008). These studies have shown that such assimilation is possible, that it is most effective when the parental magmas contain H_2O, and that evolved alkaline residual magmas are produced. The experiments also confirmed the observation made on the basis of petrographic and geochemical studies (e.g., Barnes et al., 2005, and references therein) that clinopyroxene replaces olivine as the principal high-temperature ferromagnesian phase fractionated from the parental magma. Furthermore, because the solubility of CO_2 in magmas at crustal pressures is low (e.g., Holloway, 1976; King and Holloway, 2002), another consequence of assimilation is evolution of a mixed $H_2O + CO_2$ fluid phase (Iacono Marziano et al., 2007, 2008). The increased stability of clinopyroxene and the evolution of a mixed fluid phase consequent to assimilation of carbonates help explain a number of the physical and petrologic characteristics of the Hortavær complex, as discussed below.

Presence of Syenitic Magmas

As suggested by many workers (e.g., Meen, 1990; Barnes et al., 2005, and references therein), fractionation of clinopyroxene + plagioclase from a mildly alkaline basaltic magma should result in alkali enrichment, particularly K_2O, with little or no silica enrichment (also see Iacono Marziano et al., 2007, 2008). Thus, assimilation-induced forcing of clinopyroxene stability results in evolution to syenitic magmas. Residual cumulates of this process should be clinopyroxenite and clinopyroxene-rich gabbro and diorite. Such rocks are present in the diorite zone (these rocks are the hortite of Vogt, 1916; also see Gustavson and Prestvik, 1979; Barnes et al., 2003) and are characterized by high CaO (>18 wt%) over a range of MgO from ~3 wt% to >9 wt% (Fig. 6A) and total alkali content <4 wt%. This compositional range contrasts with that of the other CaO-rich rocks of the complex, the melasyenitic to melamonzonitic endoskarns and magmatic skarns. These skarns have low MgO contents (<2 wt%) over a large range of total alkali values (from 3 wt% to 11 wt%; Fig. 6B).

Fragmentation of Mafic Sheets

Formation of a mixed fluid phase after even minor amounts of assimilation means that most magmas in the system were fluid saturated. In the case of mafic sheets, evolution of a mixed fluid during and after emplacement on an aggrading syenitic mush could result in formation of fluid bubbles and compositional undercooling, which would raise the solidus and viscosity of the magma. These effects would lead to fragmentation, and thereby explain the relative paucity of pillow-like structures and the abundance of angular enclaves (e.g., Figs. 3G, 3I). In extreme cases, complete fragmentation of a sheet occurred, as seen in Figure 3K.

Paucity of Abundant Intermediate Compositions

One of the characteristic features of the Hortavær complex is the relatively low abundance of intermediate rock compositions compared to the abundance of diorite and syenite. This feature is partly illustrated in Figure 6, in which the small number of data points for monzonitic rocks actually represents oversampling of that rock type. In many mafic-silicic layered intrusions, magma hybridization is commonplace, particularly above thick mafic sheets (e.g., Wiebe and Collins, 1998). In contrast, evidence for magma mixing is sparse at Hortavær, both in terms of bulk rock compositions (McCulloch, 2007) and reversed mineral zoning (Li, 2008). This lack of mixing is consistent with the idea that fluid exsolution of mafic magmas causes fragmentation and rapid solidification of the mafic magmas, thus inhibiting mixing.

What was the mechanism of carbonate assimilation? Although it is clear from experimental studies that contamination of the magmas by carbonate-rich rocks may occur by reaction-assimilation (e.g., Beard et al., 2005; Barnes et al., 2005), field evidence from Hortavær suggests an alternative mechanism. The relationship between dioritic enclaves and their host melasyenitic magmatic skarn shown in Figure 3L is difficult to explain unless the host skarn was partly molten at the time the dioritic magma intruded. This relationship suggests the possibility that many skarns in the complex were partially molten during pluton construction (e.g., see Lentz, 1999; Fulignati et al., 2004; Li, 2008), which would explain their petrographic features (e.g., acicular apatite, common poikilitic amphibole and garnet; Li, 2008), the local homogenization of compositional layering, and the presence of pegmatoidal magmatic skarn (Barnes et al., 2003; Fig. 3M). In theory, the melts derived from partial melting of endoskarn could have been either carbonate or Ca-rich silicate in composition. In either case, when such Ca-rich melts escaped from their sources and mixed with adjacent mafic magmas (olivine gabbro to diorite compositions), they would have reacted with the mafic magmas to form clinopyroxene at the expense of olivine. We interpret the clinopyroxene-rich cumulate rocks of the central diorite zone (hortites of Vogt, 1916) to be the cumulates that formed as the result of such reactive mixing of mafic silicate magmas with local, Ca-rich, skarn-derived melts.

Origin of the Granitic Rocks

Contamination of Hortavær magmas was not entirely by Ca-rich material (Barnes et al.,

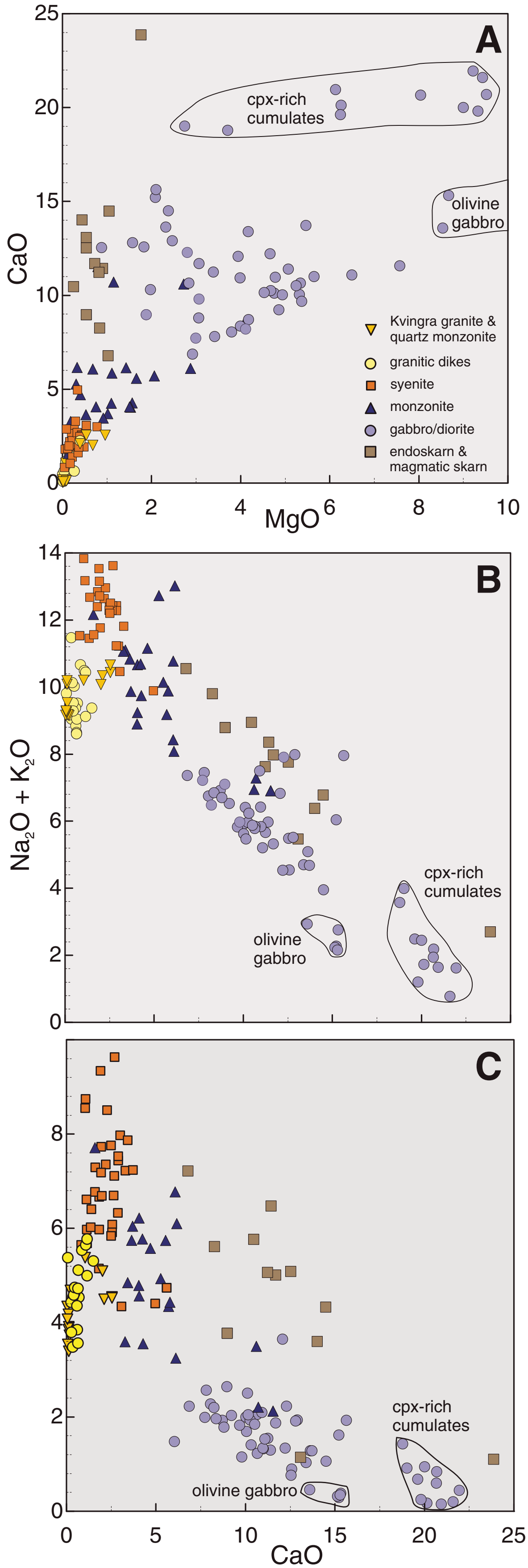

Figure 6. Compositional variations; data from Barnes et al. (2003), McCulloch (2007), and Li (2008). (A) The plot of CaO versus MgO (wt%) shows the highly variable values of CaO at a fixed MgO content. The field of olivine gabbro compositions extends to slightly higher MgO values at approximately constant CaO. The field of clinopyroxene (cpx) rich cumulates corresponds to "hortite" (Vogt, 1916; see discussion in text) rocks and spans a wide range of MgO contents over a narrow CaO range. In contrast to the hortite rocks, melasyenitic and melamonzonitic endoskarns and magmatic skarns are characterized by low MgO and widely variable CaO. (B) Plot of total alkalies versus CaO. (C) Plot of K_2O versus CaO. B and C show the compositional fields outlined in A. The total alkali contents of the skarns range from <6 wt% to nearly 11 wt%. The skarn compositions define a trend that is distinct and more alkali rich than that of the magmatic rocks of equal CaO content. The broad overlap of granitic dikes and the composition of Kvingra alkali granite are noteworthy.

2005). This conclusion was originally made on the basis of the sharp decrease in ε_{Nd} within the Hortavær suite (from +4.5 to –10; Barnes et al., 2005; Li, 2008), because the Nd abundances in pure carbonate rocks are too low to cause such a shift. The isotopic data are consistent with field and petrographic evidence that suggests a shift from quartz-absent, typically nepheline-normative rocks west of and including Burøya, to quartz-normative and quartz-bearing rocks east of Burøya, culminating in the alkali granites exposed at Kvingra (Fig. 2). Moreover, the increase in abundance of granitic dikes east of Burøya and the compositional and petrographic similarity of these dikes to the Kvingra granite (Fig. 6) suggest that the dikes fed granitic magmas from the main mass of the Hortavær complex upward to the overlying granitic cap (Fig. 5).

The processes responsible for these changes are complex, require detailed information about mineral chemistry, and will be presented elsewhere (also see Li, 2008). In brief, we suggest that the simplest way to explain the upward transition from undersaturated to oversaturated compositions is as follows. Early mafic magmas engulfed and interacted with calc-silicate host rocks, thereby forming magmatic skarns, clinopyroxene-rich cumulates, and alkaline, silica-undersaturated residual magmas. As magmas in the complex evolved, continued interaction with partially molten magmatic skarns (e.g., Fig. 3L) locally resulted in an increase in SiO_2. This is because evolved magmas lack the ability to assimilate Ca-rich minerals or melts, but are readily capable of assimilating SiO_2-rich minerals or melts (see Barnes et al., 2005, for further discussion). Once assimilation of SiO_2-rich contaminants caused magma compositions to cross the low-pressure thermal divide between silica-undersaturated and silica-oversaturated compositions (Foland et al., 1993; Landoll and Foland, 1996; Riishuus et al., 2008), fractional crystallization could result in residual magmas of alkaline granite composition. These magma batches then migrated upward and collected at the highest structural level of the complex.

MODEL FOR EMPLACEMENT OF THE HORTAVÆR COMPLEX

Figure 7 is a schematic interpretation of the construction and magmatic evolution of the Hortavær complex. This interpretation has as its basis the conclusion that differentiation from mafic parental magmas similar in composition to the olivine gabbro occurred at or near the level of emplacement. Reasons why in situ differentiation is considered likely include the unusual petrologic evolution of Hortavær magmas (i.e., the trend to abundant syenite, which

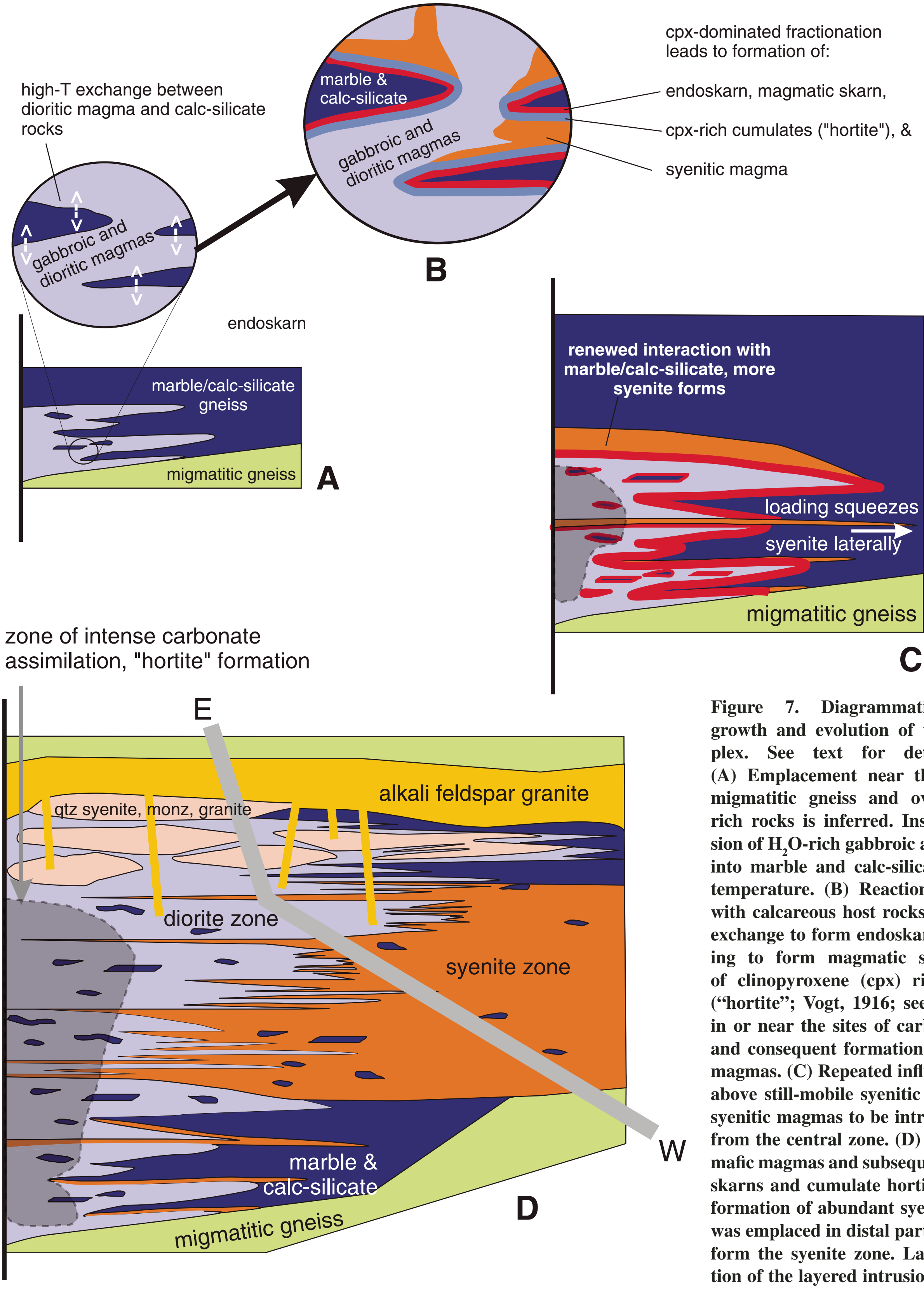

Figure 7. Diagrammatic illustration of growth and evolution of the Hortavær complex. See text for detailed explanation. (A) Emplacement near the contact between migmatitic gneiss and overlying carbonate-rich rocks is inferred. Inset illustrates intrusion of H_2O-rich gabbroic and dioritic magmas into marble and calc-silicate host rocks. T—temperature. (B) Reaction of mafic magmas with calcareous host rocks results in chemical exchange to form endoskarn and partial melting to form magmatic skarn, precipitation of clinopyroxene (cpx) rich cumulate rocks ("hortite"; Vogt, 1916; see discussion in text) in or near the sites of carbonate assimilation, and consequent formation of syenitic residual magmas. (C) Repeated influx of mafic magmas above still-mobile syenitic magmas causes the syenitic magmas to be intruded laterally away from the central zone. (D) Continued influx of mafic magmas and subsequent reaction to form skarns and cumulate hortite rocks resulted in formation of abundant syenitic magma, which was emplaced in distal parts of the intrusion to form the syenite zone. Late-stage differentiation of the layered intrusion resulted in quartz bearing monzonitic magmas in the upper parts of the system and finally alkali granite (qtz—quartz; mon—monzonite). Post-emplacement tilting, folding, and erosion have exposed the pluton, as shown by the broad gray line.

is virtually unique in the Bindal Batholith), evidence for significant amounts of assimilation of material that was Ca-rich, contained CO_2, and was capable of lowering magmatic ε_{Nd} values (i.e., melts from calc-silicate rocks), the abundance of calc-silicate host rocks that could provide the necessary assimilated material, carbon isotope evidence that the source of carbonate in the plutonic rocks matches that of the host rocks (Barnes et al., 2005), and the presence of the cumulate products of magmatic reaction (hortites of Vogt, 1916). Because the structurally lowest exposed part of the complex is composed of syenite, it follows from these observations that assimilation of carbonate-rich material occurred in a nearby part of the system at the same structural level as the basal syenite, and resulted in formation of syenitic residual magma. Intense chemical exchange (inset, Fig. 7A) involved extraction of Ca-rich melts and/or fluids from the calc-silicate host rocks (Li, 2008); this material reacted with the mafic magmas, resulted in stability of clinopyroxene in favor of olivine (Barnes et al., 2005; Iacono Marziano et al., 2007, 2008; Freda et al., 2008) and development of endoskarn and magmatic skarn from the calc-silicate protoliths. Separation and accumulation of clinopyroxene-dominated assemblages (hortite) gave rise to syenitic magmas, which we infer to have collected along the upper parts of the zone of reaction (Fig. 7B). As recharge of new mafic magmas occurred, we infer that these new recharge magmas were emplaced within or above the syenitic magma. Loading of the dense mafic magmas on still-mobile syenitic magma caused the syenitic magma to be emplaced laterally away from the central injection and reaction zone (Fig. 7C). These syenitic magmas formed the layered syenite zone at the exposed base of the complex (Fig. 5).

Further recharge of mafic magmas led to continued reaction to form syenite. Some mafic magmas flowed laterally onto aggrading syenitic magma to form sheets (Fig. 7D). Repeated intrusion (flows) of mafic magma formed the sheeted zone and, where the proportion of mafic magma was much larger than that of the syenite, the dioritic zone (Fig. 7D). The dense mafic magma formed load casts in the underlying syenitic mush, and syenitic melts and magma (crystal mush) intruded upward into the mafic sheets as flame structures. In many instances, as the mafic magmas lost heat to the cooler syenitic magma, exsolution of a mixed volatile phase resulted in fragmentation of the mafic sheet rather than the formation of lobate pillows. Some mafic magmas remained mobile long enough to develop magmatic foliation, whereas others did not. This observation suggests that foliation formed in response to flattening deformation and explains the parallelism of magmatic sheets and foliation (Fig. 4).

Sparse monzonitic sheets were emplaced in the same manner; we infer that the monzonitic magmas originated in the same way as the syenitic ones, but were slightly more mafic. We also infer that production of syenitic magmas had not ceased, but was ongoing in the core of the complex, because pyroxene-rich cumulates (hortite) and melasyenitic endoskarns and magmatic skarns crop out at structurally intermediate levels (e.g., Vågøya; Fig. 2).

Differentiation of the syenitic magmas resulted in formation of quartz syenite to alkali granite magmas. According to our reconstruction of the pluton, the quartz syenite magmas were emplaced as layers and lenticular zones above the diorite zone, and the alkali granite magmas collected at the (exposed) top of the system (Fig. 7D). It is noteworthy that construction of a plutonic system composed of hundreds of individual magma batches that subsequently underwent variable degrees of contamination is unlikely to result in a uniform, coherent liquid line of descent. This lack of uniformity of process is evident from the compositional scatter of major element compositions (Fig. 6). Evolution was toward silica oversaturation for at least two reasons: (1) few of the Hortavær magmas were critically undersaturated, and (2) the assimilated material contained both carbonate and silicate components (Barnes et al., 2005; Li, 2008). Thus, late-stage differentiation was toward alkali-rich, silica-oversaturated compositions, specifically quartz monzonite and alkali granite. Some of these residual magmas were voluminous enough to segregate into subvertical dikes, and they then migrated upward to form sheets of quartz monzonite and ultimately the structurally highest alkali granite zone (Kvingra granite).

The cause of the broad folding of the complex around a shallowly northwest-plunging axis is unclear. This folding may be related to regional deformation, but could also be the result of sagging of the complex as parental magmas were withdrawn from deeper levels.

CONCLUSIONS

The Hortavær intrusive complex is an unusual example of a mafic and silicic layered intrusion in which syenitic magma was an important part of the differentiation history and granitic magmas formed only in the latest stages of the complex. Differentiation to syenitic compositions was the result of intense interaction with, and assimilation of, calc-silicate metasedimentary rocks. This interaction was, in part, driven by evolution of a mixed H_2O-CO_2 fluid early in the history of the complex; even the mafic magmas were fluid saturated. Geopetal features that are commonplace in mafic-silicic layered intrusion–type plutons are common in the Hortavær complex and permit reconstruction of its original orientation. In addition, many mafic layers are fragmented rather than pillowed, a result of fluid exsolution during cooling and crystallization. Evolution of mafic parental magmas was by assimilation of calc-silicate rocks combined with fractional crystallization. The latter process was dominated by clinopyroxene + plagioclase, owing to excess Ca derived from the assimilated calc-silicate material. Thus, assimilation resulted in thorough modification of metasedimentary host rocks into melasyenitic endoskarn and magmatic skarn plus formation of clinopyroxene-rich cumulate rocks, i.e., the hortites of Vogt (1916).

The conclusion that evolution from olivine gabbro to syenitic magmas involved assimilation–fractional crystallization of calc-silicate rocks indicates that assimilation was at or near the site of emplacement, and that recharge of new mafic magma batches loaded existing underlying mushes and squeezed syenitic magma laterally away from the mafic core of the intrusion. This zone of syenitic magmas permitted mafic magmas to be emplaced as flows on an aggrading syenitic mush, with subsequent deformation and/or disruption. In contrast to this lateral emplacement of mafic and syenitic magmas, late-stage quartz monzonite and alkali granite magmas were emplaced at the top of the complex, with broad, subvertical dikes feeding the uppermost granitic zone.

It is our view that the Hortavær complex provides an instructive, if unusual, example of assimilation of carbonate-rich metasedimentary rocks into hydrous mafic magmas. In cases where hydrous, mafic arc magmas intrude crustal rocks rich in carbonate and calc-silicate sedimentary rocks, evolution to alkaline, CO_2-rich magmas may be expected, as has been proposed for some potassic volcanic systems in the Roman Volcanic Province and the Somma-Vesuvius system (Dallai et al., 2004; Piochi et al., 2006; Iacono Marziano et al., 2007, 2008; Freda et al., 2008).

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