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Geochemistry and tectonic setting of the Orvar Hill mafic volcanic rocks of the Tiveden area, south-central Sweden

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Abstract: The Orvar Hill formation in Tiveden, south-central Sweden, constitutes a unique low-strain window of well preserved Svecofennian mafic volcanic rocks on the southwestern border of the Svecokarelian orogen. The area can be considered as the southwestern border of the Bergslagen region of the Svecokarelian orogen. The Orvar Hill formation consists of coherent pillowed and non-pillowed basalts alternating with mafic volcaniclastic rocks in the lower part of the Lindberga supracrustal succession. Only minor felsic volcanic rocks occur in the upper part. Quartz-bearing metagreywackes comprise the top part of the Lindberga supracrustal succession. Geochemistry of lavas and volcaniclastic rocks suggests that the Orvar Hill mafic volcanic rocks were emplaced in a volcanic-arc setting. This demonstrates that the Tiveden supracrustal units probably formed in response to volcanism related to subduction. The Tiveden area may thus represent a 1.89 Ga primitive, sediment-starved volcanic arc at the margin of the continental volcanic arc of the Bergslagen district. The relationship between Tiveden and Bergslagen at the time of formation is not clear and Tiveden may represent a remnant of an arc that accreted to a continent at c. 1.88–1.86 Ga.
Keywords: Svecofennian, Tiveden, volcanic arc, mafic volcanic rocks, pillow lava, volcaniclastic.

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This paper presents new geochemical data on structurally well preserved Palaeoproterozoic mafic metavolcanic rocks from the Tiveden area in south-central Sweden. In particular, a sequence of mafic pillow lava and overlying volcaniclastic beds, the Orvar Hill formation (OHF), is described from a small outcrop at Lindberga. The OHF is a part of the Lindberga supracrustal succession (LSS), comprising both volcaniclastic rocks, as well as mafic and minor felsic lavas (Figs. 1, 2). The paper describes the chemical character and structural relations of these rocks, discusses their tectonic setting, and compares them with rocks of similar origin and age in the Bergslagen region.

Regional Geology

Metavolcanic and metasedimentary rocks with well preserved primary structures occur at Lindberga, southwest of Lake Unden at the northwestern tip of Lake Vättern (Fig. 1). Here, Svecofennian rocks outcrop in uniquely close proximity to the Southwest Scandinavian Domain (cf. Magnusson et al. 1960; Magnusson et al. 1963; Lundqvist 1991) of mainly Gothian crustal growth to the west. The two domains are elsewhere separated by the late- to post-Svecokarelian c. 1.65–1.85 Ga Transscandinavian Igneous Belt (TIB; Gorbatschev 1985; Larson & Berglund 1992; Persson & Wikström 1993; Connelly et al. 1996). The transition between the two domains is also generally obscured by Sveconorwegian ductile and brittle deformation along the Protogine Zone (Larson et al. 1986, 1990; Andréasson & Rodhe 1990; Wahlgren & Stephens 1993; Wahlgren et al. 1994; Stephens et al. 1996). The well-preserved supracrustal rocks discussed here provide a unique low-strain window that gives important information on the structures and geochemical signatures relating to the early volcanic evolution and tectonic environment in the southwesternmost Svecofennian crust.

In Tiveden the supracrustal rocks and a roughly coeval, calc-alkaline diorite-granodiorite-granite suite, are intruded by granitoids belonging to the Transscandinavian Igneous Belt (TIB). The former intrusives generally have ages between 1.90 and 1.88 Ga in the Bergslagen region (cf. Lundqvist 1991; Allen et al. 1996). The younger TIB granitoids have U–Pb ages between c. 1.65 and 1.85 Ga (Lindh & Persson 1990; Larson & Berglund 1992; Mansfeld 1991).

Early authors (e.g. Westergård & Johansson 1915; Westergård et al. 1926) first mapped out the c. 25 km long belt of greenstone, within which the Lindberga supracrustal succession (LSS) is situated. The greenstones of this belt and other smaller occurrences were reported to be intimately related to, and conformable with, the grey, so-called, Unden-gneisses, which correspond to the early orogenic gneissic calc-alkaline granitoids mentioned above. These rocks were all believed to be cut by younger granitoids, e.g., the Töreboda granite in the area around Lake Viken, and a satellite pluton of the Askersund granite east of Lake Unden (Fig. 1). The outcrops of these younger granitoids were also mapped by Hummel (1875), but the structural relationship to the surrounding gneisses was not described. These younger granitoids belong to the Transscandinavian Igneous Belt (TIB).

Recent age determinations in the Tiveden area indicate a complex tectonic relationship between the Unden gneiss and the Askersund granites east of Lake Unden (Wikström 1996). He reports a U–Pb zircon age of 1854±3 Ma for the coarsely porphyritic quartz monzonite at Långmossen, which probably belongs to the Askersund-type of TIB granitoids, and a U–Pb zircon age of 1850±1 Ma for a grey even-grained tonalite from Samfallet, belonging to the Unden gneiss complex. If correct, these ages indicate that no age difference exists between the calc-alkaline magmatism of the Svecokarelian domain and the more alkaline, oldest TIB-granitoids in this area. A further consequence is that the oldest "post-orogenic" TIB-granitoids may have experienced or are related to late-Svecokarelian deformation. The age of the post-orogenic Askersund granite, 1854±3 Ma, sets the younger age limit for the supracrustal rocks in the Lake Unden area.

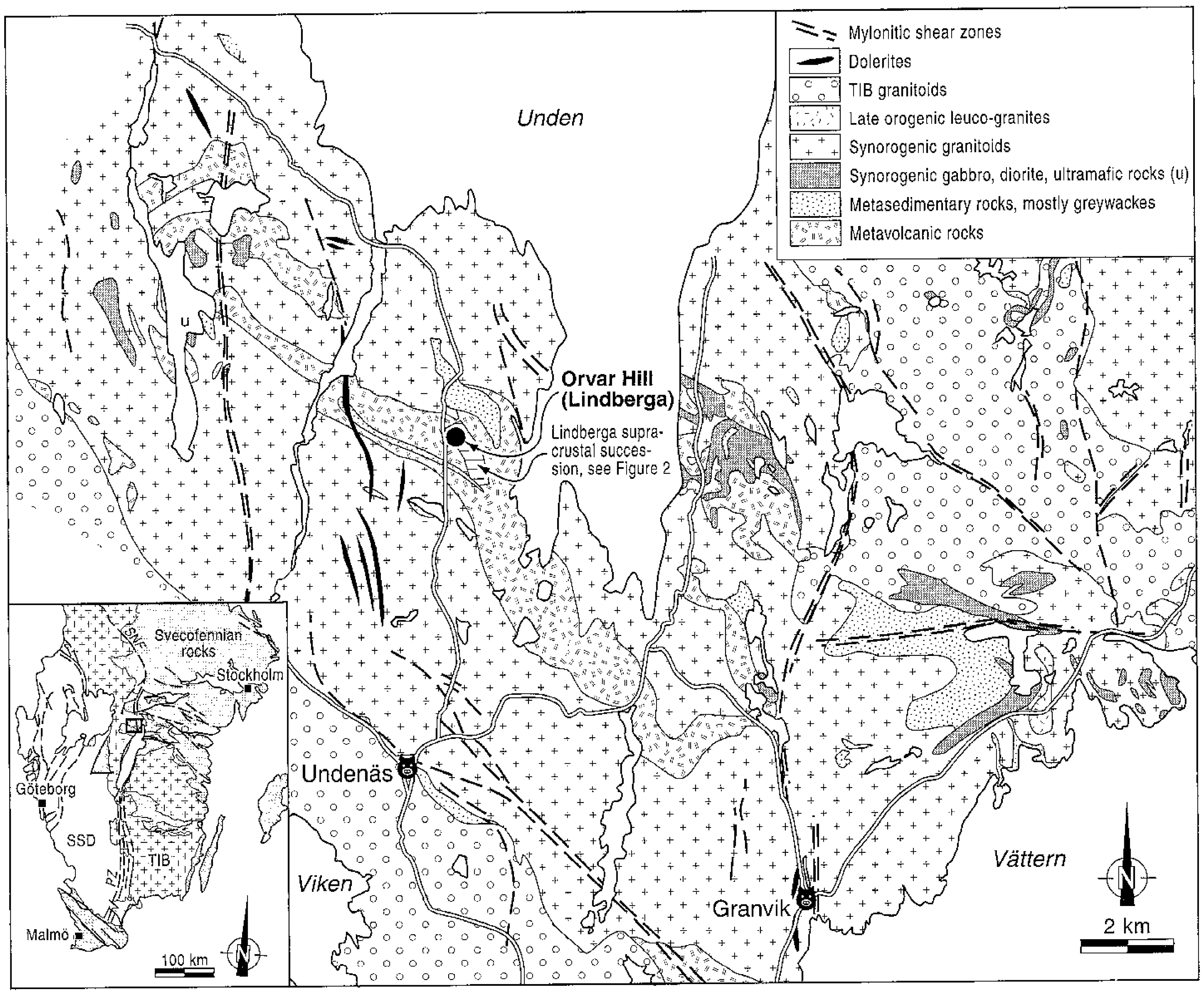


Fig. 1. Geological map of the Tiveden area compiled by L. Björklund from mapping by undergraduate students at the Dept. of Geology, Göteborg University. Orvar Hill formation (OHF) and Lindberga supracrustal succession (LSS) are indicated. Inset map (modified from Stephens et al. 1994) shows major geological units of southern Sweden. SSD = Southwest Scandinavian Domain, TIB = Transscandinavian Igneous Belt, PZ = Protogine Zone, and SNF = Sveconorwegian Front. Hatched areas refer to post-Sveconorwegian sedimentary cover rocks.

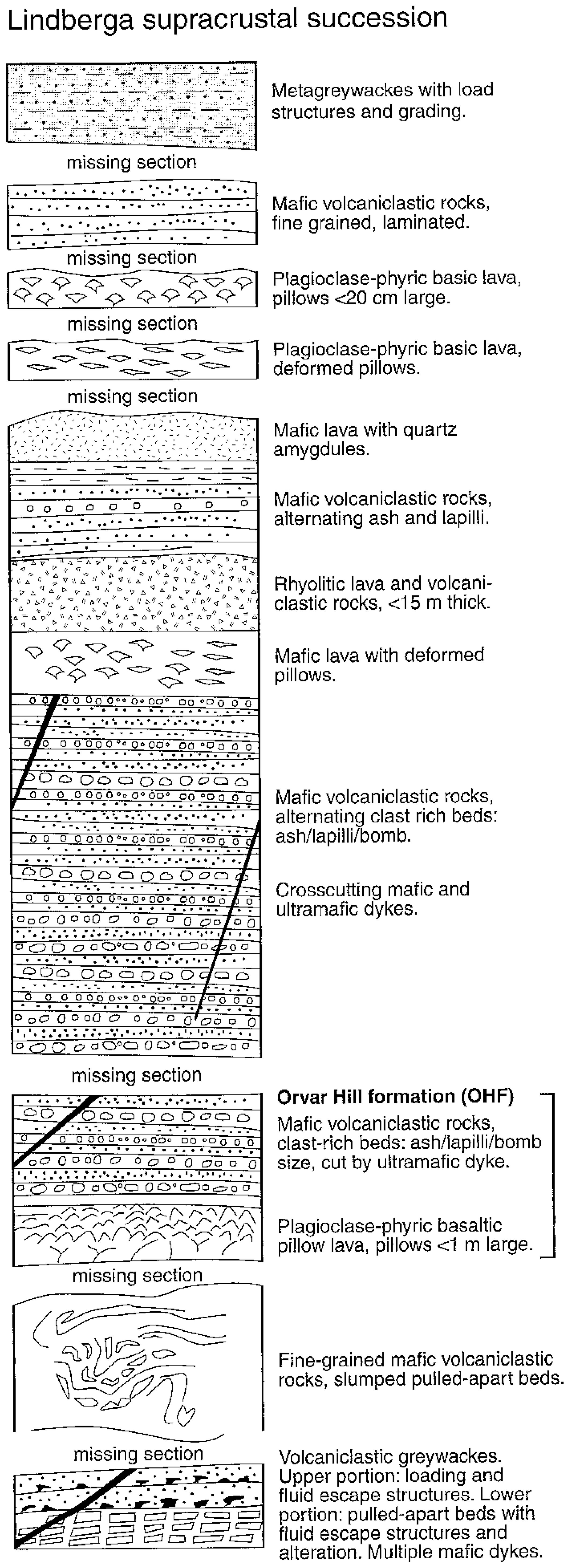


Fig. 2 (right). The Lindberga supracrustal succession. The section represents a NNW–SSE traverse with younging towards the SSE (see Fig. 1 for location). Note that the section is not to scale, but the total thickness is probably 400–500 m.

Mafic metavolcanic rocks and dykes occur only subordinately among the felsic metavolcanic rocks (leptites, hälleflintas), marbles and iron, manganese and massive sulphide stratabound ores of the Bergslagen area to the east (Lundqvist 1991). Notably, this relation is the reverse in the Tiveden area, where felsic metavolcanic rocks are very subordinate and no stratabound ores or marbles have been observed. Only one very small occurrence (<1 m^3) of calc-silicate rich marble is found directly related to the metabasic volcanic rocks, southwest of Igelstad, south of Lake Unden.

Dolerite dykes cut both the early gneissic granitoids and the supracrustal rocks (Westergård et al. 1926). These dykes strike mainly north and are commonly plagioclase porphyritic and commonly exhibit multiple intrusive mineral and geochemical zoning. Ljungstedt (1989) suggested two palaeomagnetic age groups for the dykes, with ages of 1250 Ma and c. 1000 Ma.

Sm–Nd and Pb–Pb isotopic data

Björklund & Claesson (1992) reported high and uniform $^{147}Sm/^{144}Nd$ values of 0.16–0.18 for 7 samples from the metabasic volcanic sequence from Orvar Hill. These values make calculated ages imprecise. Together with a cross-cutting ultramafic dyke, belonging to the sequence, the samples defined an age in the range of 1.7–1.9 Ga. However, with an assumed age of 1.85 Ga, an initial ε_{Nd} value of +2.1 was calculated, which varied only 0.5 units with a ±150 Ma age variation. The low potassium concentration and the good fit of all samples to an isochron suggested that the Nd isotopic composition reflect the mantle source, which was not altered significantly by assimilation of crustal material. The data indicate a mildly LIL-depleted mantle source (Björklund & Claesson 1992). The Nd-isotopic data from the Unden area may be compared to the much larger variation of initial ε_{Nd} between +2 and –2, and locally down to –13, for c. 1.88 Ga submarine felsic metavolcanic rocks from western Bergslagen (Valbracht 1990). The large variation in initial ε_{Nd} values can be explained by a combined effect of seawater-related hydrothermal alteration and contamination from Archaean crustal material. Valbracht (1991) also reported a Sm–Nd isochron at 1886±48 Ma with an ε_{Nd} of +1.1 for the least altered within-plate meta-tholeiites from western Bergslagen.

Mansfeld (1995) reports very primitive ε_{Nd} values at +5.2 to +4.0 for mafic volcanic rocks of the Fröderyd group in Småland, south of Bergslagen proper. The age of the Fröderyd group is, according to Mansfeld, between 1807 and 1850 Ma, i.e distinctly younger compared to ages for volcanic rocks in the Bergslagen proper (cf. Lundqvist 1991; Allen et al. 1996).

Pb-isotope data from galenas from the Tiveden area were reported by Sundblad (1994). These galenas were more primitive than Bergslagen galenas at the mean of $^{206}Pb/^{204}Pb = 15.62$, $^{207}Pb/^{204}Pb = 15.30$, $^{208}Pb/^{204}Pb = 35.18$, and a mean μ-value of 9.76.

Structural and metamorphic relations

The Lindberga supracrustal succession ("greenstone" of Westergård et al. 1926) is folded in large map-scale folds (LSS, Figs. 1 and 2). Near Lindberga, the rocks are sheared and strongly thinned in a N-striking limb along the western shore of Lake Unden. In this area, most primary structures are transposed to a planar S-L amphibolitic schistosity. A few remaining primary structures indicate stratigraphic younging towards the SW. In the W-NW striking limb including Lindberga, however, primary volcanic and sedimentary structures are abundant. In this area, layering generally strikes W-NW, with steep dips towards the S. The metamorphic fabric is penetrative and pronounced L-type. At Orvar Hill, the mineral lineation in the garnet amphibolite-facies rocks plunges c. 80°S. Thus, no distortion is experienced when viewing the primary structures down-plunge. All primary structures in the LSS across the W-NW limb, consistently indicate stratigraphic younging towards the S-SW. This argues against repetition of the layering by isoclinal folding, but fault-block repetition cannot be excluded.

The synorogenic granitoids are penetratively gneissic and commonly veined. By contrast, the TIB granitoids are generally nonfoliated and coarse-grained, with an undulating discrete foliation only towards the margins and in mylonitic shear zones.

The metamorphic grade apparently increases towards the SE, and the gneisses have a migmatitic character near Granvik. Sillimanite occurs in peraluminous metagreywackes c. 6 km north-northeast of Granvik (Fig. 1).

The Lindberga supracrustal succession

The LSS occurs, as stated above, in a low-strain window within the Protogine Zone (Figs. 1 and 2). The mafic volcanic units can be traced for c. 15 km in a roughly NW direction. The total thickness of the mafic volcanic rocks is probably 400–500 m, but this is uncertain because fault repetitions within the unit cannot be ruled out. The mafic volcanic rocks are structurally best preserved at Orvar Hill (Swedish national grid 6511660–1419330, Fig. 1), which therefore is used as the type locality for the mafic volcanic rocks of the LSS. Apart from the mafic volcanic rocks, units of greywacke turbidites and subordinate felsic volcanic rocks occur in the top part of the LSS (Fig. 2). The main rock types of the LSS are described below.

Pillowed and non-pillowed basalts

Four discrete pillowed lava flows occur in the LSS along the approximately N-NW striking Lindberga profile (Figs. 1, 2). The lower flow (Fig. 3A), at the type locality Orvar Hill, contains pillows (<1 m) in its upper part, with well developed triple junctions and a consistent southward younging. Pillows have chilled rims with alteration along cracks, which point inwards from the pillow surfaces. Skarn-altered material occurs in pockets between the pillows. Spilitization processes are indicated by geochemical data (below). The transition zone between the pillowed upper part and the lower massive part displays short (<2 m) joints joined at 120° triple points, which suggest shrinking as a result of cooling. The thickness of the lower flow is not known since its base is unexposed. The exposed part is c. 9 m thick. The lava consists of cm-sized, granoblastically recrystallized, cellular plagioclase in a matrix of amphibole, plagioclase, iron oxides, and ilmenite (Fig. 3B). All minerals are of metamorphic origin. Plagioclase composition is mainly andesine (An_{38-52}). No significant difference in An content is found between cores and margins of the plagioclase. The amphiboles are tschermakitic.

The pillowed flows that occur higher in the stratigraphy are similar in composition to the OHF flow. They contain smaller pillows, which locally are strongly elongated. The uppermost two flows are plagioclase porphyritic, in contrast to the third flow which is hornblende porphyroblastic.

A mafic lava flow with quartz amygdules occur in the upper part of the LSS (Fig. 2). The amygdules are larger towards the south (top) contact.

Volcaniclastic rocks

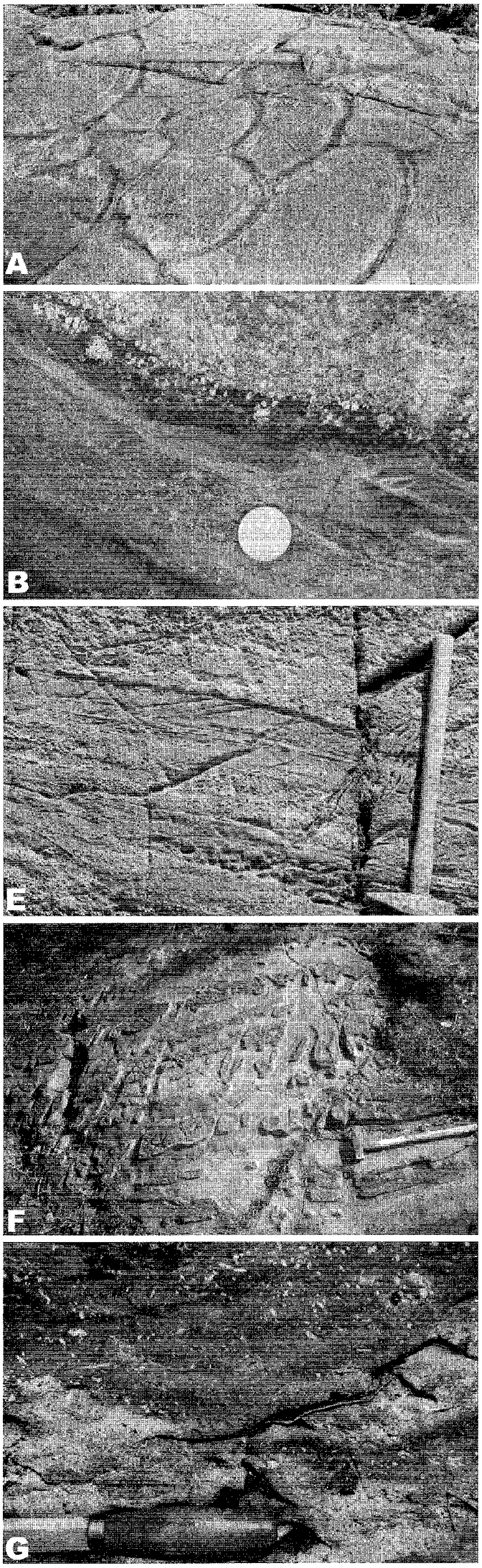
Several units of volcaniclastic material occur in the LSS (Fig. 2). The thickest units, occurring at the type locality, are mafic and at least 150 m thick (Fig. 3C). Individual beds vary in thickness between 10 cm and 1 m. Coarse, clast-rich beds are thickest (Fig. 3D). Finer-grained beds are well laminated, whereas clast-rich beds are massive or show diffuse lamination. The clast population of the coarse layers is monomict to polymict with lithic clasts that vary in size from a few mm to 20–30 cm. Many of the clasts are texturally and compositionally similar to the plagioclase phyric lavas. The clasts are generally sub-rounded to rounded with long axes parallel to bedding. Larger clasts commonly deform immediately underlying lamination of fine-grained beds. Alternation of laminated and massive intervals of in places scour-based beds, suggests deposition from turbidity flows (Kneller & Branney 1995; Hiscott et al. in press). Laminated intervals are deposited by traction from less concentrated flows, whereas more massive intervals reflect fall-out from high-density flows (Kneller & Branney 1995; Kneller 1995). Strong a-axis and local imbricate fabric of coarse clasts is typical in the more massive coarse-grained units. Clasts with a-axis fabric are most likely transported by sliding and rolling beneath high-density turbidity currents (e.g. Arnott & Hand 1989; Hiscott & Middleton 1980; Kneller & Branney 1995; Hiscott et al. in press).

In the upper part of the LSS, lava flows are separated by thin (<2–3 dm) bedded, fine-grained mafic volcaniclastic turbidite units (<10 m thick).

The uppermost unit consists of silty to sandy quartz-bearing metagreywackes. These are well-bedded turbidites, typically displaying normal grading, scouring, fine lamination, and load structures.

Only one felsic unit (<15 m thick) occurs in the LSS. This unit is finely laminated, with evidence of scouring and cross-bedding that suggest deposition by turbidity currents. Only one other occurrence of felsic volcaniclastic rocks is known in Tiveden, at Friskelstorp, east of Lake Unden. This rock type is less well laminated and contains skarn lenses.

In the lower part of the LSS, below the OHF, two units occur with evidence of a period of high fluid pressures. The lowest unit shows pulled-apart, fine-grained beds, with boudins surrounded by massive sandy material. Separation between boudins is at a c. 60° angle to bedding (Fig. 3F). Fractures between not fully



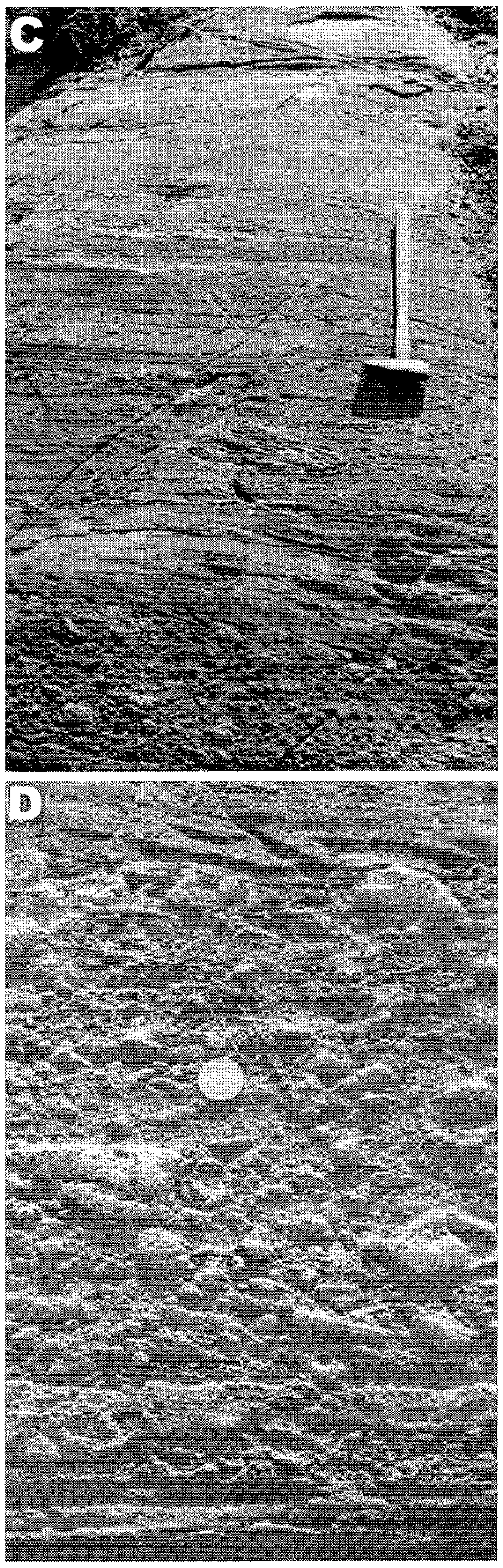


Fig. 3. Main lithologies of the LSS. **A**. Lower pillow basalt of the OHF. Individual pillows up to 1 m with younging towards the SSE (to the right) **B**. Cm-sized, granoblastically recrystallised, cellular plagioclase at the margin of a pillow in the lower flow of OHF. **C**. Overview of the volcaniclastic units directly overlying the lower pillowed flow in the OHF. Individual beds are distinct and vary in thickness from c. 0.5 to 1 m. Individual clasts vary from mm to 20 cm (left below hammer). **D**. Close up of the coaser volcaniclastic unit in the OHF. Clasts are rounded to subrounded and are mainly composed of plagioclase phyric mafic lavas. **E**. Laminated volcaniclastic unit in the OHF. This unit also show a weak grading indicating younging to the S (up in photo). **F**. The lowest unit of the LSS shows pulled-apart, fine-grained beds, with boudins surrounded by massive sandy material. **G**. Quartz-filled amygdules in lava from the upper part of the LSS.

pulled-apart beds have the same angle to bedding. The boudins are all mineralogically altered along the margins. A plausible explanation for these structures may be gravity-induced down-slope extension of beds in combination with escape of, possibly hot, fluids. Thin quartz-filled fractures occur in the centres of the gaps between boudins (Fig. 3F). This suggests a final stage of hydrothermal fracturing. Thin, <20 cm thick, laminated fine-grained beds, display load structures and break-up by fluid escape. The upper unit below the OHF shows slumping of disrupted, fine mafic volcaniclastic beds in a sandy matrix, suggesting mass-flow deposition.

Synvolcanic (?) dykes

Ultramafic and mafic dykes cut the volcaniclastic flows at high angles. Multiple dykes occur in the lowest unit.

Depositional environment

The coexisting pillowed flows and the volcaniclastic gravity flow deposits are interpreted as submarine. The areal extent of the deposits is not known since correlation between the scattered outcrops of pillow lava and pillow breccia in the area has not been possible. The occurrence of coherent rocks rich in amygdules (Fig. 3G), although equivocal, suggests that part of the LSS rocks have been emplaced at water depths of less than 2000 m. The general rounding and absence of angular pillow lava clasts in the gravity-flow units (Fig. 3D) suggest rounding during transport. The volcaniclastic gravity flow deposits and their clastic constituents are distinctly chemically different (see below) from the spilitic pillow lavas and, hence, are not products of the same eruption. The non-spilitic character of the volcaniclastic units and the presence of less or non-spilitized lava clasts, suggest that the clastic material was cold when entering and interacting with the sea-water.

The physical environment during emplacement of the supracrustal units is thus interpreted as submarine. The non-spilitized character of most volcaniclastic material suggests input from a subaerial source. However, no indications of subaerial deposits, e.g., associations of welded or non-welded ignimbrites, accretionary lapilli, have been observed in the Tiveden area. More volcanological and sedimentological work is required to clearly define the depositional environments.

Geochemistry

25 samples were collected from mafic volcanic rocks at the type locality Orvar Hill. Both major and trace elements were analysed at SGAB in Luleå by the XRF method. Of these samples, five were reanalysed to test the reproducibility. FeO was determined by wet chemical methods.

Six samples were taken from the interior of pillow lavas, three from pillow rims, five from fine-grained volcaniclastic units, eight from coarser clast-bearing volcaniclastic units, one from a clast very similar in mineralogy and texture to the plagioclase phyric pillow lava, one from interpillow skarn, and one was taken from an ultramafic dyke cutting the volcaniclastic beds.

Spilitic reactions and alteration

Common diagrams for classification of volcanic rocks make use of mobile elements such as alkalis and Ca. In the alkali diagram of Hughes (1973), samples from pillow margins, pillow interiors, and the non-pillowed lower part of the OHF lava, plot outside of the igneous spectrum within the spilitic field (Fig. 4). Samples of the coarse clast-rich flows and the single clast plot within the spilitic field or close to the upper margin of the igneous spectrum. All samples of the fine-grained volcaniclastic units and the ultramafic dyke plot within the igneous spectrum. The chemical spread of the coarse clast-bearing volcaniclastic units is consistent with the interpretation that these units contain material from two sources: plagioclase-phyric lava flows spilitised to varying degrees, and the possibly non-spilitised fine-grained mafic volcaniclastic rocks.

Rims of pillows are relatively higher in Na/Ca with higher SiO_2 contents, compared to the interior of pillows and non-pillowed parts which have SiO_2 contents between 49 and 52% (except one sample). The volcaniclastic rocks show a more variable and generally lower SiO_2 content between 46 and 51% (excluding one sample). In the Harker diagrams (Fig. 5) samples of the lava and volcaniclastic rocks display different and clearly separate trends indicating different origins. This is most obvious in the Al_2O_3 *vs.* SiO_2 diagram (Fig. 5) where the samples of the lava show distinctly higher Al_2O_3 compared to the clastic units. The latter, on the other hand, show a well defined trend with the clast-rich flows generally on the high-SiO_2 end of the trend. The analysis of the coherent plagioclase phyric clast from the clastic unit plots in between the lava and the volcaniclastic units. This indicates that the clast is derived from a different unit than the pillow lava of the OHF. The dyke cutting the volcanic sequence has a SiO_2 content of 45.2% and a MgO content of 16.7%. This demonstrates that the dyke is not related to the lavas or volcaniclastic rocks of the the OHF and, thus, is not part of a feeder dyke system to the lavas or volcaniclastic rocks.

Both the lavas and the volcaniclastic rocks are basaltic in composition. In a SiO_2 *vs.* Na_2O+K_2O diagram (Fig. 6A) all samples plot as basalts and basaltic andesites (except for the two altered samples with high SiO_2). If the lavas are spilitized as indicated by Fig. 4, they have too high Na_2O+K_2O values in the SiO_2 *vs.* Na_2O+K_2O diagram which means that they probably should plot even more centrally in the basaltic field. A similar classification is evident from a SiO_2 *vs.* Zr/TiO_2 plot in Fig. 6B. All but a few samples plot in the subalkaline basalt field. In Fig. 6C all rocks plot in the tholeiitic field using Zr and P as discriminant elements.

Tectonic setting

In Fig. 6D–E the rocks are plotted in commonly used tectonic discrimination diagrams. All rocks have low contents of high field strength (HFS) elements like Ti, Zr, and Y. The analyses of Y are for many samples below detection limit (10 ppm) and should therefore be treated with care. As indicated in Fig. 4, the lavas seem to be spilitically altered and although some of the analyses of the volcaniclastic rocks plot within Hughes igneous spectrum, discrimination diagrams based on large ion lithophile (LIL) elements should also be treated with care. In diagrams based on elements which are compatible during melting *versus* incompatible elements (Fig. 6D–E) all, but one sample of a volcaniclastic rock, plot as volcanic-arc lavas (although the lavas have an Y content below dectection limit). Using a Ti–Zr plot (Fig. 6E) with two HFS elements which are considered conservative during subduction (Pearce 1996), most samples plot as volcanic-arc lavas, but some fall within the mid-ocean ridge basalt (MORB) field. However, from Fig. 6E it is clear that the Orvar Hill mafic volcanic rocks are not within-plate basalts. In a ternary plot of TiO_2–MnO–P_2O_5 (Fig. 6F) all rocks again fall within the fields of island-arc tholeiites and calc-alkaline basalts.

With the information from tectonic discrimination diagrams described above, it is suggested that the Orvar Hill mafic volcanic rocks were emplaced in a volcanic-arc setting. There is no evidence for a MORB or within-plate character of the rocks in the Orvar Hill formation. This demonstrates that the Tiveden supracrustal units probably formed in response to volcanism in a volcanic-arc related to subduction.

Discussion

Few modern papers have been published on the chemistry and tectonic setting of mafic volcanic rocks from the Bergslagen region in south-central Sweden. This is obviously in part due to the fact that the Bergslagen region is overwhelmingly felsic in character and part of the region is in upper amphibolite facies making observations on origin of different rocks types difficult (cf. Lundström 1987; Allen et al. 1996). Hellingwerf & Oen (1986) published geochemical data on metabasites from the Saxå area in Bergslagen. They interpreted the composition of the mafic rocks as indicative of a rift-stage with the chemistry of the rocks resembling continental tholeiites. Valbracht et al. (1991) presented more data on mafic rocks from western Bergslagen, and considered the least altered mafic rocks to be tholeiitic and related to a continental within-plate tectonic setting. The Fröderyd Group of mainly mafic volcanic rocks, situated southeast of Lake Vättern is described by Sundblad et al. (in press), who show them to be younger than the main Bergslagen volcanic rocks, at 1.81–1.85 Ga. Sundblad et al. (in press) also demonstrate that the mafic volcanic rocks have a MORB-like geochemistry and suggest a rifted continental margin as a tectonic environment for the emplacement of the Fröderyd Group

Based on published work on Sm–Nd isotope systematics and whole-rock Pb, some interesting observations can be made. The mafic volcanic rocks from the Bergslagen region, *sensu lato*, show varied but generally mildly positive to slightly negative (–0.5 to +2.6) ε_{Nd} values calculated at c. 1.88 Ga (e.g. Valbracht 1991). These values have been attributed to melting of a LREE enriched mantle in a continental rift environment at 1.88 Ga. Recently, Mansfeld (1995) published ε_{Nd} values for the MORB-like mafic volcanic rocks from Fröderyd which, until now, have the most primitive values at +5.1 to +5.2 at 1.85 Ga. Mansfeld

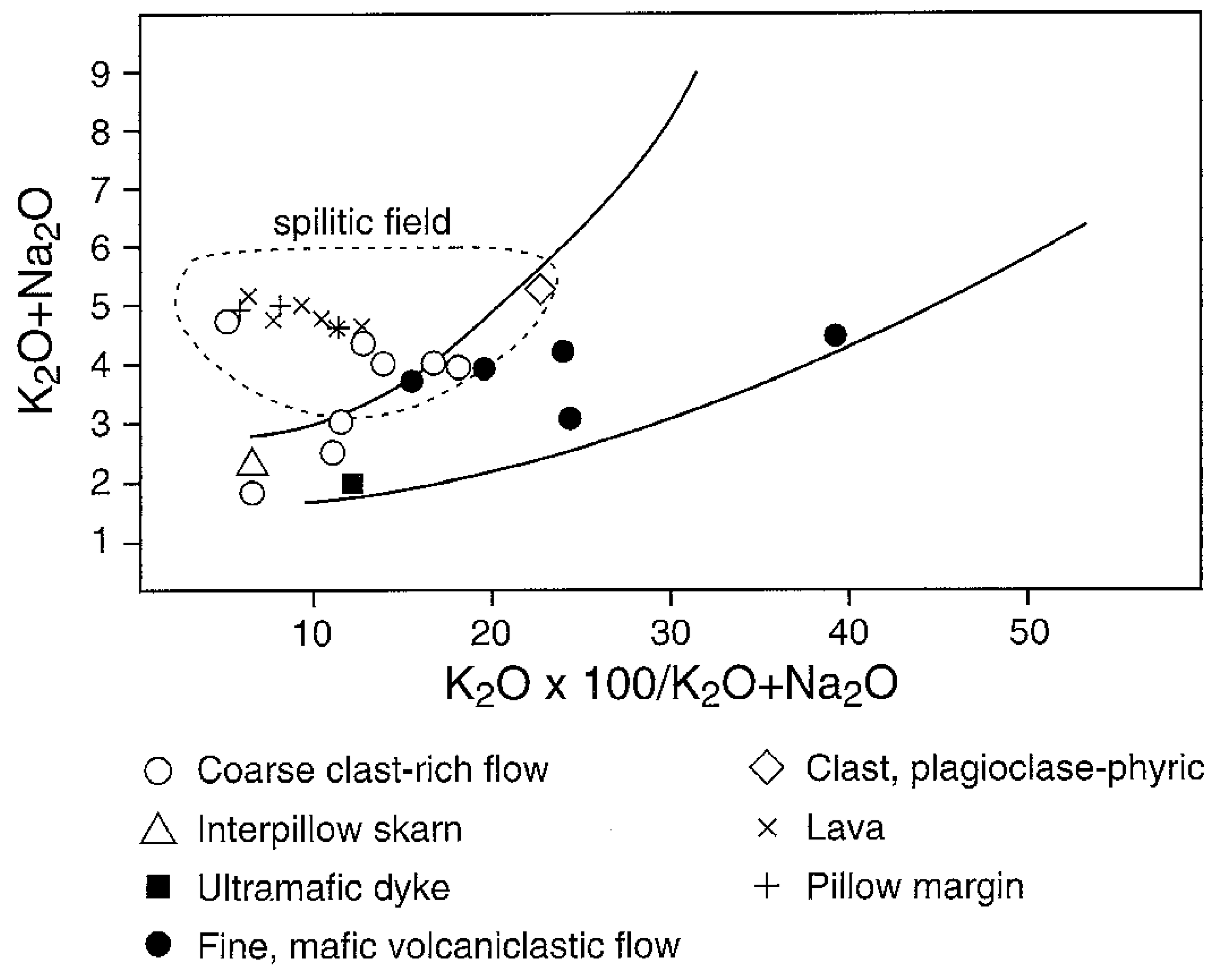


Fig. 4. "Igneous spectrum" after Hughes (1973). See text for discussion.

regarded these values as representing the composition of the depleted mantle at 1.85 Ga. This is in contrast to the reported values of +2.1 at 1.85 Ga for the Orvar Hill mafic volcanic rocks reported by Björklund & Claesson (1992). The +2.1 ε_{Nd} value of the mafic rocks was attributed to melting of an only mildly depleted mantle compared to the mantle of De Paolo (1981). The values from Fröderyd indicate that at least the mantle melts that gave rise to the Fröderyd mafic volcanic were no less depleted than De Paolo's, at 1.85 Ga. Similar highly positive values have been reported from the Skellefte district (Billström & Weihed 1996) and from the Palaeoproterozoic Flin-Flon belt in Canada (cf. Syme et al. 1996). This indicates that the mantle beneath the Svecofennian rocks in Sweden, if not very heterogeneous, indeed was depleted and that ε_{Nd} values at +2 to +3 indicate a contamination of only slightly older crustal material. If this is the case, the mafic volcanic rocks of the OHF in Tiveden may come from a source that was contaminated by slightly older continental crust. This is in good agreement with the chemical composition of the mafic volcanic rocks indicating that the rocks were formed in a volcanic-arc environment, possibly developed on the margin of a slightly older continent in Bergslagen.

The question about the absolute age of the OHF is still open since no age determinations have been performed on the rocks. The results by Wikström (1996) indicate that the Askersund-type granitoids in the Tiveden area are 1854±3 Ma in age and, as these are considered to intrude the supracrustal sequence (Björklund & Claesson 1992), the age of the latter must exceed c. 1855 Ma. On the other hand, Wikström's (1996) age of 1850±1 Ma of a calc-alkaline tonalite of the Unden-gneiss type is interesting since a genetic relationship between the volcanic rocks and these old tonalitic intrusions has been proposed (e.g., Westergård & Johansson 1915; Westergård et al. 1926) from this area and elsewhere in the Svecofennian of Sweden (cf. Lundqvist 1979, 1991). If such a relationship exists, the age of the supracrustal units need not be much older than 1855 Ma.

In his study of Pb isotope compositions of galenas from Bergslagen, Sundblad (1994) reported primitive and distinctly different compositions of galenas from Tiveden compared to the Bergslagen district proper. He concluded that the Tiveden galena represents the primitive metavolcanic end-member of a mixing line between Pb in the southern margin of Bergslagen and a more sediment-dominated source represented by the Stockholm archipelago. The fact that the Tiveden galena Pb composition is distinctly more primitive in character than Bergslagen galenas is compatible with a different tectonic setting for the Tiveden area. This area could represent a sediment-starved part of a 1.89 Ga tholeiitic volcanic arc indicated by the chemical composition of the mafic metavolcanic rocks of the OHF.

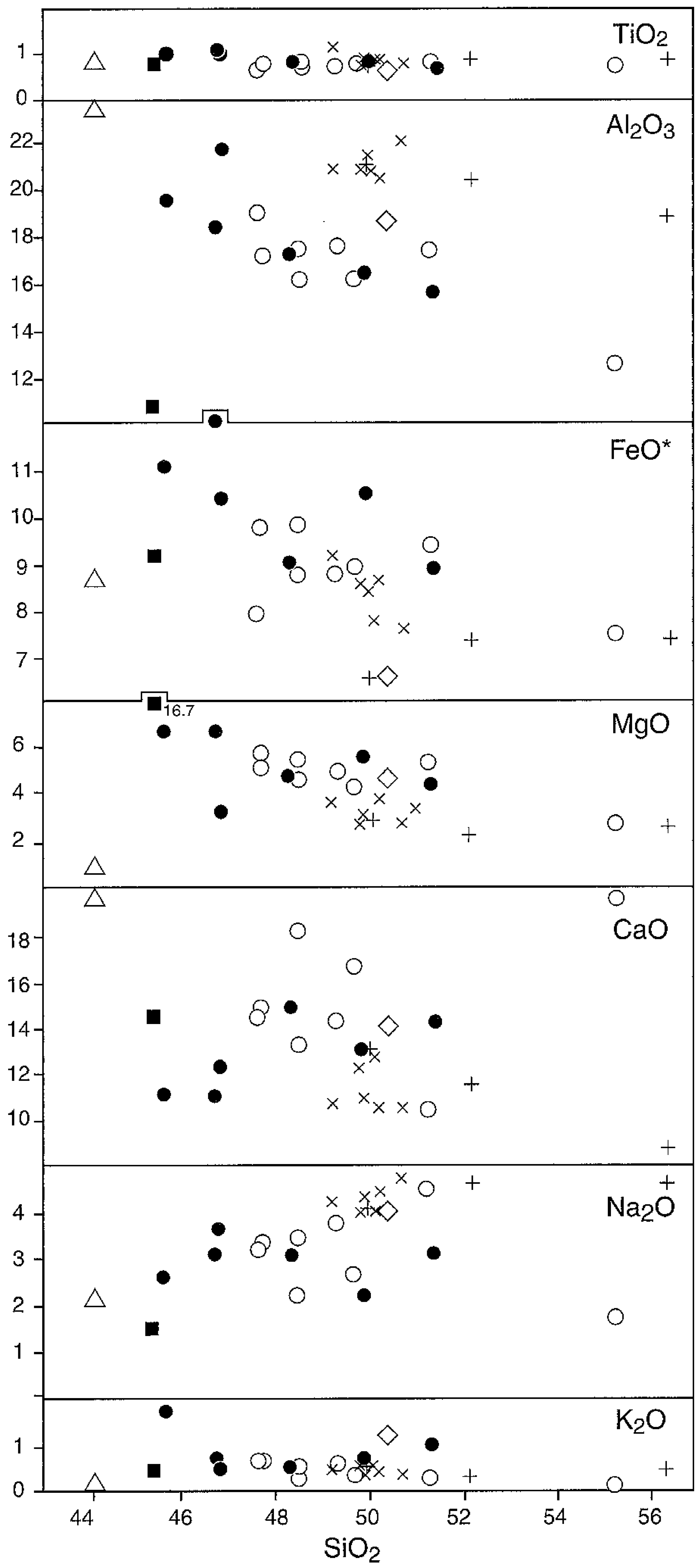


Fig. 5. Harker diagrams of SiO_2 *vs.* other main elements for the analysed samples from the Orvar Hill formation. Symbols as in Fig. 4.

Considering the chemical character of rocks from Fröderyd and Tiveden, these could have been emplaced at the margin of a

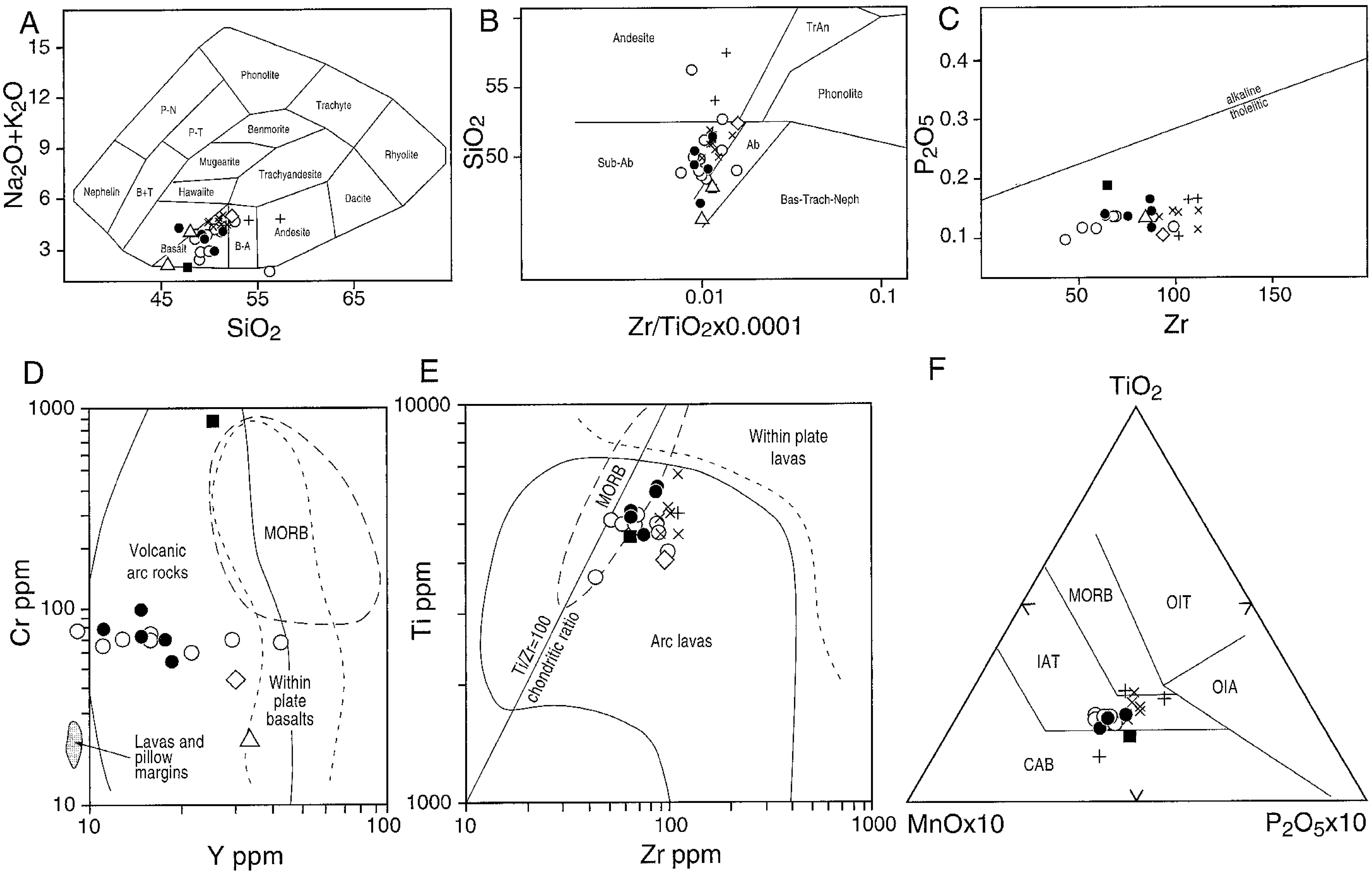


Fig. 6. Geochemical diagrams for rock classification and tectonic discrimination diagrams. Symbols are the same as in Fig. 4. **A.** Na_2O+K_2O *vs.* SiO_2 plot from Cox et al. (1979). **B.** Plot of SiO_2 *vs.* Zr/TiO_2 from Winchester & Floyd (1977). **C.** Plot of P_2O_5 *vs.* Zr from Winchester & Floyd (1976). **D.** Plot of Cr–Y from Pearce (1982). **E.** Plot of Ti–Zr from Pearce (1982). **F.** Ternary plot of TiO_2–MnO–P_2O_5 from Mullen (1983).

continent to the north. The Tiveden mafic volcanic rocks could represent the products of volcanic arc magmatism which possibly accreted to the continental margin at 1.88–1.85 Ga, while the Fröderyd mafic volcanic rocks were emplaced some 30 to 50 Ma after the main magmatism in the Bergslagen area.

Conclusions

The mafic metavolcanic rocks of the Orvar Hill formation are composed of well-preserved pillowed basalts and unrelated basaltic gravity-flow deposits. The lavas and the volcaniclastic rocks have distinctly different chemical compositions indicating that they do not belong to the same magma series. Although the volcaniclastic rocks were deposited in a submarine environment, their syn-depositional structures and geochemical character indicate a significant subaerial input. Frequent amygdules in the coherent rocks of the LSS, further support our interpretation of moderate emplacement water-depths.

The chemical composition of the rocks indicates that they are tholeiitic basalts of a volcanic-arc origin. This is further corroborated by ε_{Nd} values of c. +2.1 (Björklund & Claesson 1992) and Pb isotope signatures of galenas distinctly more primitive than the Bergslagen galenas (Sundblad 1994).

The Tiveden area may thus represent a 1.89 Ga sediment-starved, primitive volcanic arc at the margin of the continental volcanic arc of the Bergslagen district. The relationship between Tiveden and Bergslagen at the time of formation is not clear. It cannot be excluded that Tiveden represents a remnant of an arc system that accreted to the continent at c. 1.88–1.86 Ga. An even younger accreted terrane may be represented by the Fröderyd area to the SE which is interpreted as to have formed by a MORB-type magmatism at 1.85 to 1.81 Ga.

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