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INTERFLOW SEDIMENTARY ROCKS IN THE KEWEENAWAN NORTH SHORE VOLCANIC GROUP, NORTHEASTERN MINNESOTA

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INTERFLOW SEDIMENTARY ROCKS IN THE KEWEENAWAN NORTH SHORE VOLCANIC GROUP, NORTHEASTERN MINNESOTA

by

Mark A. Jirsa

ABSTRACT

Interflow sedimentary rocks occur as lenticular units and crevice fillings between and within lavas of the North Shore Volcanic Group (Keweenawan Supergroup, middle Proterozoic age) of northern Minnesota. Individual sedimentary units range in thickness from a few centimeters to 75 m. They consist of reddish, fine-grained, well-sorted sandstone, and lesser amounts of conglomerate, breccia, shale, and tuff.

Much of the sandstone is either lithic arkose or feldspathic lithic arenite. Major framework constituents include calcic plagioclase, mafic to felsic volcanic rock fragments and pyroxene. Fragments of agate, chert, and shale are present in minor amounts. Heavy minerals include magnetite, pyroxene, apatite, altered olivine, zircon, and sphene. The major cement and replacement minerals are zeolites, calcite, quartz, chlorite, epidote, prehnite, and hematite. The distribution of secondary minerals is zonal and presumably related to burial metamorphic processes.

Although the predominant source for the sedimentary rocks was the intercalated lava flows themselves, some Archean, lower Proterozoic, and older Keweenawan rocks contributed minor amounts of detritus. Detritus derived from pre-Keweenawan rocks is most abundant in the lower interflow units near the present extremities of Keweenawan exposures. This implies that the volcanic rocks may not have extended very far past the present outcrop limits during the early part of sedimentary deposition.

Sedimentary structures and paleocurrent measurements indicate that most units were deposited by streams that flowed generally toward the present Lake Superior basin. Paleocontours and stratigraphic and areal variations in rock type imply that some of the deposition occurred in two northeast-trending sub-basins, probably separated by a basement high.

INTRODUCTION

The volcanic and sedimentary rocks of the North Shore Volcanic Group are part of the Midcontinent rift system, a major linear tectonic feature which has geophysical and petrologic characteristics of continental rift zones (King and Zietz, 1971; White, 1972; Green, 1972 and 1977; Chase and Gilmer, 1973). White (1972) and Green (1977) have shown that the Keweenawan lavas in the Lake Superior region were deposited at different times in several locally overlapping accumulations. The North Shore Volcanic Group is a sequence of plateau lavas 6000 to 9000 m thick which was erupted during one stage of the rifting event.

Sedimentary rocks within the North Shore Volcanic Group (fig. 1) occur as lenticular units that crop out sporadically in Minnesota along the Lake Superior shoreline, in river valleys, and in road cuts. Sandstone is the most abundant rock type, but conglomerate, breccia, shale, and tuff occur in small quantities. A total of 379 m of sedimentary rocks was measured, described, and sampled in this study; this thickness accounts for 2 to 3 percent of the exposed volcanic-sedimentary sequence of the North Shore Volcanic Group. The sedimentary rocks were deposited primarily by streams and, to a lesser degree, in ponded water on the Keweenawan lava surfaces.

The objectives of this study were to: (1) determine the identity and provenance of clastic particles; (2) determine the directions of sediment transport; (3) analyze lateral and vertical variations in clast composition; (4) interpret paleoslopes and environments of deposition; (5) determine the orientation of tectonic stresses at the time of deposition; (6) interpret the location and extent of subsidence; (7) delineate the stages during which subsidence occurred in the construction of the flow-interflow sequence; and (8) interpret the postdepositional history of the clastic rocks.

GENERAL GEOLOGY

The lavas and interbedded sedimentary rocks in the North Shore Volcanic Group of the Keweenawan Supergroup are middle Proterozoic in age and accumulated during periods of both reversed and younger normal magnetic polarity during the interval 1200-1100 m.y. ago (Van Schmus and others, 1982) (fig. 2). In Ontario and Michigan, the polarity change from reversed to normal coincides with a stratigraphic break marked by the presence of clastic rocks (Halls, 1974; Hubbard, 1975). In Minnesota, this contact is either occupied by normally polarized intrusions or is not exposed; however, lavas with normal polarity appear to have been extruded directly onto the older reversed lavas (Green, 1977).

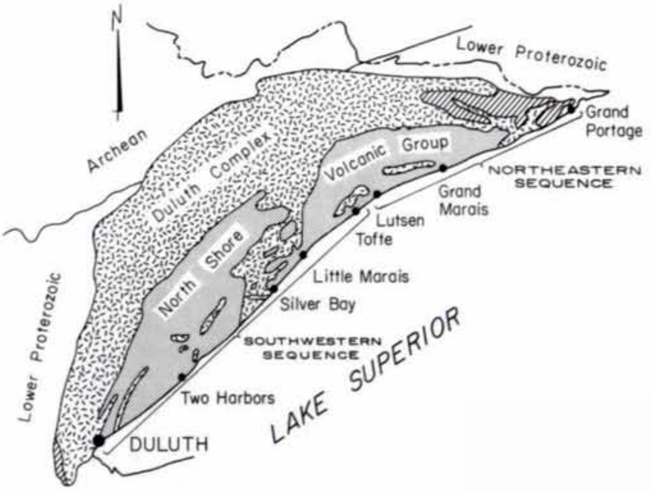

Figure 1. Generalized geologic map of northeastern Minnesota showing the two sequences of the Keweenawan volcanic and sedimentary accumulation. Irregular dashes, intrusive rocks; diagonal rule, volcanic rocks with reversed polarity; stipple, volcanic and interflow clastic rocks with normal polarity.

The North Shore Volcanic Group forms much of the northwest limb of the Lake Superior syncline (usage of Davidson, 1982), wherein strata dip lakeward at angles of 10°-25°. In general, the group has an arcuate shape, and the near-shoreline exposures provide a longitudinal cross section through this arc. The lowest (oldest) strata are exposed at the two ends of the arc structure near Duluth and near Grand Portage where their strike intersects the shoreline at relatively sharp angles. Progressively higher (younger) strata are exposed from these ends toward the midpoint of the arc between Tofte and Lutsen. Between Tofte and Lutsen the youngest flows in northeastern Minnesota strike nearly parallel to the shoreline. Because continuity of older flows across the midpoint of the arc has not been established, the North Shore Volcanic Group is here divided into two separate stratigraphic successions called the southwestern sequence, from Duluth to Tofte; and the northeastern sequence, from Grand Portage to Lutsen.

General trends are interrupted locally by intrusions and associated faults. One set of intrusions, the Beaver Bay Complex north of

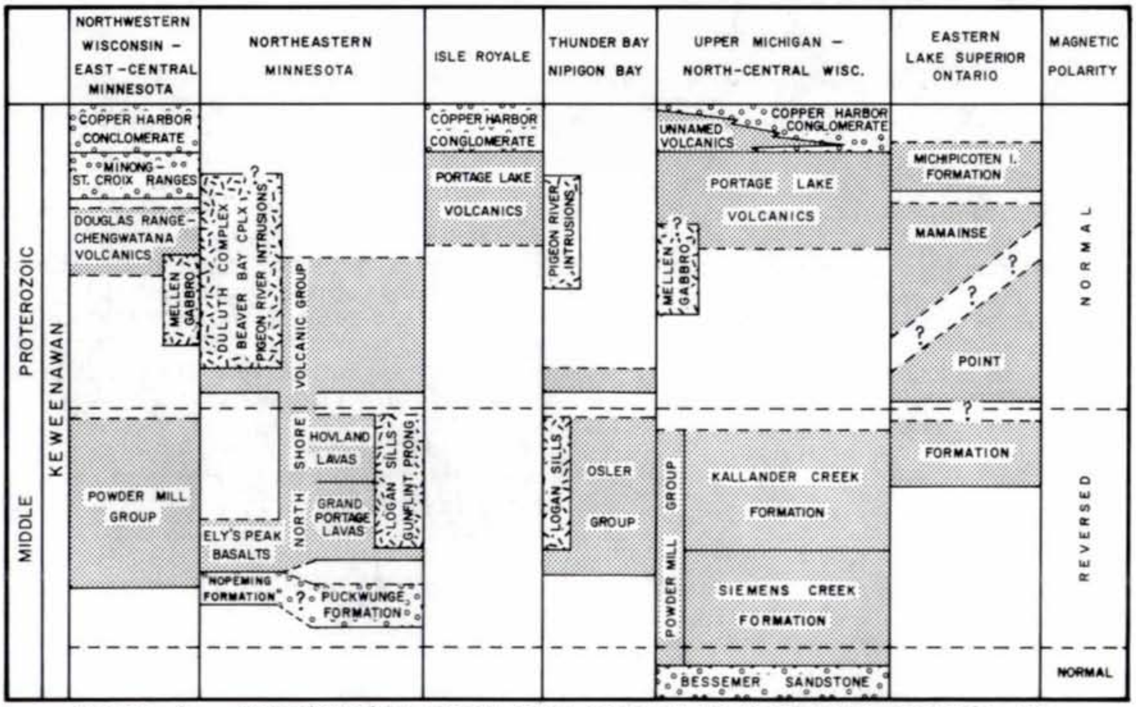

Figure 2. Stratigraphic correlation diagram of Keweenawan volcanic and sedimentary rocks (modified from Green, 1982); circles, sedimentary rocks; stipple, volcanic rocks; irregular dashes, intrusions.

Silver Bay, is considered to lie along a major structural discontinuity that separates plutonic and hypabyssal rocks into two terranes, each having different geological and geophysical characteristics (Weiblen and Morey, 1980).

Basaltic flows predominate in the North Shore Volcanic Group, but intermediate and felsic rocks occur in minor quantities. Ophitic and coarse-grained olivine basalts are most abundant, and some of these contain plagioclase phenocrysts. Other common types include transitional or weakly alkaline basalts and quartz tholeiites. Intermediate volcanic rocks are nearly all porphyritic with phenocrysts of plagioclase, augite, magnetite, and some Fe-olivine; compositionally they are trachyandesites and intermediate quartz latites. Flows of felsic composition include rhyolites and quartz latites, and most contain phenocrysts of quartz, plagioclase, and K-feldspar (Green, 1972).

The interflow sedimentary rocks are sandstone, conglomerate, breccia, shale, and minor tuff. Approximately 204 m of clastic rocks were measured in the southwestern sequence, and 175 m in the northeastern sequence. Table 1 shows the relative abundance and distribution of the various lithologies observed. Individual sedimentary units range in thickness from a few centimeters to 75 m. The sedimentary rocks may directly overlie relatively smooth-topped amygdaloidal or massive flows in places; elsewhere the contact is irregular and marked by a sand-filled flowtop breccia or conglomerate. On most flow surfaces there is no evidence of erosion prior to sediment deposition.

The geometry of the interflow sedimentary rock units is difficult to ascertain because most exposures provide only a single, two-dimensional cross section. Many units appear to be sheetlike in form, with at least one end visibly pinching out. They are rarely traceable more than a kilometer, although one unit near Lutsen can be traced discontinuously for 2.5 km from its eroded lakeshore terminus where it is 30 m thick.

Table 1. Relative abundance of interflow sedimentary rock lithologies in the North Shore Volcanic Group

Sedimentary rock type	Thickness (meters) Southwestern sequence	Thickness (meters) Northeastern sequence
Sandstone	90.3	157.1
Flowtop breccia	55.0	1.0
Conglomerate	35.9	7.1
Shale	3.0	6.5
Volcanic breccia	17.5	2.1
Tuffaceous sandstone	2.3	1.0
TOTAL	204.0	174.8

PETROLOGY

The interflow sedimentary strata all consist predominantly of plagioclase and volcanic rock fragments, with lesser amounts of quartz, pyroxene, K-feldspar, and various heavy minerals. All have been altered and locally are composed almost totally of secondary minerals. Most are reddish brown, though color is dependent upon the degree of alteration and the composition of replacement minerals.

Sandstone

Sandstone units are composed generally of well-sorted, moderately well rounded detrital grains of plagioclase and rock fragments, with lesser amounts of pyroxene, quartz, and opaque minerals. The compositions of 68 relatively unaltered sandstone samples are given in Table 2. Sand grains range in size from 0.06 to 2.0 mm, but average 0.2 mm. Cement is more abundant than matrix, and most units are well to moderately well cemented, although weathering has presumably dissolved calcite cement in some outcrops. Much of the sandstone has a reddish color imparted by hematitic dust which coats grains and is included in some grain replacements. Partial to complete replacement of some of the plagioclase and lithic fragments by various combinations of zeolites, albite, K-feldspar, and prehnite implies that the sequence was affected by a low-grade metamorphic event. Some of these replacement minerals occur in much greater percentages in highly altered samples. The highly altered samples are not included in Table 2 because they are not representative of the primary lithologies. Under the classification scheme of McBride (1963), most of the interflow sandstones are either lithic arkose or feldspathic lithic arenite (figs. 3 and 4). Figure 5A is a photomicrograph of a typical interflow sandstone sample.

In the typical interflow sandstones, detrital quartz is ubiquitous, ranging in abundance from less than 1 percent to 40 percent and averaging about 6 percent. Unit quartz grains are angular to subrounded, and typically equant. They have few inclusions and dominantly exhibit sharp extinction (within 10°). Hexagonal (dipyramidal) volcanic quartz clasts were rarely observed. These characteristics imply a volcanic origin for most of the unit quartz (after Blatt, 1967). Many rhyolite flows in the North Shore Volcanic Group contain quartz phenocrysts of this type. Strained unit quartz clasts are less common and, except for their undulatory extinction, do not differ from unstrained unit quartz clasts. Rare polycrystalline quartz clasts are typically rounded to subangular, have both sutured and straight crystal boundaries, and exhibit undulatory extinction. Some recrystallized quartz characterized by straight, polygonal crystal boundaries occurs in minor amounts.

Table 2. Mineralogic composition of selected interflow sandstone samples from the North Shore Volcanic Group

[Results in percentages; T, less than 1%; nd, not detected]

Unit: shown on Figure 8. Samples not assigned to a stratigraphic unit were taken from units too thin (<2 m) to be included on Figure 8.

Sample number: see Figure 3 for key to sample locations.

Quartz: uu, unit unstrained; us, unit strained; pq, polycrystalline; TQ, total quartz.

Feldspar: pf, plagioclase; kf, K-feldspar; TF, total feldspar.

Rock fragments: mv, mafic and intermediate volcanic; fv, felsic volcanic; pl, plutonic; ms, mudstone, siltstone; ag, agate; ct, chert; TR, total rock fragments.

Other grains: opq, opaque minerals; px, pyroxene; hb, hornblende; ol, olivine (altered); mi, mica.

Cement: ca, carbonate; fs, feldspar; si, silica; ze, zeolite.

Matrix: cl, chlorite; hc, hematitic + sericitic clay.

TI: total interstitial cement and matrix.

Grain size: average of 10 largest grains per section.

Unit	Sample	Quartz				Feldspar			Rock fragments							Other grains		Cement	Matrix	TI	Grain
	number	uu	us	pq	TQ	pf	kf	TF	mv	fv	pl	ms	ag	ct	TR	% - type	opq	% - type	% - type		size
	JD-1	30	5	nd	35	39	1	40	nd	nd	nd	nd	nd	nd	nd	nd	2	7 - si	16 - cl	23	0.09
	JD-13	15	2	nd	17	41	3	44	nd	nd	nd	nd	nd	nd	nd	nd	T	3 - si	36 - hc	39	0.05
D4	JD-8	T	3	nd	3	59	T	59	9	nd	nd	nd	nd	nd	9	T - px	12	6 - si,ca	10 - cl	16	0.25
	JD-9	4	T	nd	4	59	1	60	10	nd	nd	nd	nd	nd	10	T - px	11	12 - ca,si	3 - cl	15	0.22
	JD-11	12	8	nd	20	46	3	49	10	2	nd	nd	nd	nd	12	1 - px	5	11 - si,ca	2 - cl	13	0.15
	JLW-1	2	4	nd	6	45	2	47	11	8	nd	4	nd	nd	23	nd	8	7 - si	9 - hc	16	0.35
	JLW-7	3	1	nd	4	52	5	57	14	1	nd	nd	nd	nd	15	nd	6	18 - si,ca	nd	18	0.12
	JLW-8	4	1	nd	5	48	2	50	20	nd	nd	nd	nd	nd	20	1 - ol	6	18 - si,ca,ze	nd	18	0.18
LW3	JLW-2	1	2	T	3	53	1	54	20	2	nd	2	nd	nd	24	T - ol	2	14 - ca,fs	2 - cl	16	0.38
	JLW-4	1	T	nd	1	50	1	51	25	nd	nd	nd	nd	nd	25	nd	8	11 - ze,si,fs	3 - cl	14	0.40
	JLW-6	4	1	T	5	44	2	46	18	1	nd	2	nd	1	22	1 - mi,px	8	17 - si	nd	17	0.20
	JLW-11	3	2	T	5	52	1	53	15	2	nd	nd	nd	nd	17	8 - px	4	12 - si	nd	12	0.15
	JLW-12	5	1	nd	6	40	T	40	12	3	nd	T	nd	nd	15	9 - px	13	16 - si,ze	nd	17	0.15
	JLW-15	4	1	nd	5	55	2	57	5	3	nd	nd	nd	nd	8	4 - px	8	18 - ze	nd	18	0.15
	JLW-16	6	1	nd	7	50	1	51	10	6	nd	nd	7	nd	23	2 - px	T	17 - ze	nd	17	0.25
	JLW-18	5	2	nd	7	50	2	52	13	2	nd	nd	1	nd	16	4 - px	11	4 - ze,si	6 - hc	10	0.12
	JLW-19	6	2	T	8	43	1	44	10	5	nd	1	6	nd	22	7 - px	3	15 - ze,si,fs	1 - hc	16	0.32
FR1	JFR-30	2	1	T	3	36	T	36	35	1	nd	nd	1	nd	37	T - px	11	11 - ze	1 - cl	12	0.20
	JFR-28	3	2	1	6	35	8	43	20	6	nd	nd	1	1	28	2 - px,mi	9	12 - fs,si	nd	12	0.25
FR12	JLW-22	2	T	nd	2	51	T	51	5	nd	nd	nd	T	nd	5	25 - px	8	10 - ze	nd	10	0.17
	JLW-23	2	T	T	2	46	nd	46	6	nd	nd	nd	2	nd	8	20 - px	10	14 - si,ze,fs	nd	14	0.20
	JLW-24	2	T	T	3	38	1	39	20	3	nd	nd	2	nd	25	7 - px	8	12 - si,ze	5 - cl,hc	17	0.26
	JLW-26	2	1	nd	3	50	nd	50	18	2	nd	nd	T	nd	20	7 - px	5	12 - ze	3 - cl	12	0.21
	JFR-5	1	3	nd	4	47	1	48	10	3	nd	nd	nd	nd	13	4 - px	11	20 - ze	nd	20	0.18
	JFR-12	1	4	T	5	59	2	61	5	3	nd	nd	nd	nd	8	6 - px,hb	3	14 - ze,fs,si	3 - cl	17	0.20
	JFR-17	7	3	nd	10	45	1	46	14	1	nd	nd	nd	1	16	5 - px	10	nd	13 - hc,cl	13	0.10
	JFR-24	nd	3	1	4	55	nd	55	9	1	nd	nd	nd	1	11	14 - px,hb	6	16 - ze	nd	16	0.10
	JFR-20	7	3	nd	10	46	nd	46	4	nd	nd	nd	nd	nd	4	9 - px,mi	11	2 - fs	18 - hc,cl	20	0.05
	JKR-1	6	4	1	11	33	nd	33	4	10	nd	nd	nd	nd	14	nd	3	39 - si,ze	nd	39	0.05
	JKR-5	8	T	T	9	55	1	56	8	nd	nd	nd	nd	nd	8	10 - px	8	nd	10 - hc	10	0.12
	JKR-6	7	2	nd	9	48	T	48	12	4	nd	nd	nd	nd	16	5 - px	5	13 - ze,si	4 - hc,cl	17	0.05
	JKR-8	4	nd	nd	4	42	1	43	15	3	nd	T	1	nd	19	13 - px	7	13 - ze,si	1 - cl	14	0.13

	JTH-7	4	3	nd	7	45	1	46	10	nd	nd	nd	nd	nd	10	3 - px,ol	13	nd	21 - hc,cl	21	0.06
	JTH-8	1	T	T	2	37	T	37	24	4	nd	nd	nd	nd	28	8 - px,ol	12	12 - ze	2 - hc	14	0.15
	JTH-9	T	2	T	2	44	T	44	16	2	nd	nd	nd	nd	18	4 - px	12	20 - ze	nd	20	0.15
	JTH-2	nd	3	nd	3	52	T	52	14	2	nd	nd	nd	nd	16	11 - px	4	14 - ze,si	T - cl	14	0.15
	JTH-12	1	T	nd	1	50	T	50	16	3	nd	nd	nd	nd	19	11 - px,hb,ol	7	12 - ze	nd	12	0.10
	JCD-2	2	T	T	3	38	nd	38	17	1	nd	nd	nd	nd	18	4 - px	26	nd	12 - cl	12	0.15
	JCD-3	1	1	2	4	37	2	39	23	7	nd	nd	nd	nd	30	2 - px	13	12 - ze,si	nd	12	0.15
CD4 —	JCD-14	nd	1	1	2	34	8	42	13	6	nd	nd	nd	nd	19	6 - px	18	13 - ze,fs,ca	nd	13	0.19
	JSB-4	nd	1	nd	1	48	3	51	16	2	nd	nd	nd	nd	18	3 - ol,px	13	14 - ze	nd	14	0.15
IC2	JIC-30	2	1	4	7	23	T	23	35	12	1	4	T	T	53	2 - px	3	12 - ze,ca	nd	12	0.25
	JIC-26	2	T	3	5	22	T	22	30	16	nd	nd	6	2	54	7 - px,ol	4	9 - ze	nd	9	0.30
	JIC-21	3	nd	nd	3	15	17	32	38	6	nd	nd	1	1	46	2 - px	7	10 - ca,fs,si	nd	10	0.17
IC4	JIC-5	6	2	1	9	25	10	35	8	18	nd	nd	nd	nd	26	T - px	10	20 - ca,ze	nd	20	0.20
	JIC-9	5	1	6	12	nd	11	11	5	54	T	nd	nd	nd	59	T - px	4	14 - ca	nd	14	1.0
	JIC-15	3	T	2	5	10	13	23	6	51	T	2	nd	nd	59	T - px	3	10 - ca,ze	nd	10	1.5
	JIC-1	3	5	nd	8	25	32	57	2	15	nd	nd	nd	nd	17	T - px	2	13 - ze,ca	3 - cl	16	0.10
IC8 —	JIC-23	4	1	T	5	10	5	15	6	49	nd	T	T	nd	55	T - px	7	16 - ca	2 - cl	18	1.8
	JIC-20	T	3	nd	3	31	20	51	2	3	nd	nd	nd	nd	5	nd	13	nd	28 - cl	28	0.07
LM1 —	JLM-6	1	T	nd	1	14	T	14	37	11	nd	4	nd	1	53	1 - px	5	26 - ca,fs	nd	24	0.20
LM2 —	JLM-12	1	2	T	3	53	T	53	21	1	nd	nd	nd	nd	22	1 - px,ol	6	15 - ca,fs	nd	15	0.10
	JT-2	4	2	nd	6	44	1	45	13	4	nd	nd	nd	nd	17	11 - px,ol	8	14 - fs,ca	nd	14	0.10
	TOFTE LUTSEN																				
DY2	JDY-12	4	nd	2	6	41	1	42	6	23	nd	2	1	nd	32	2 - px	5	13 - ze,ca	nd	13	0.35
	JDY-10	1	2	nd	3	40	T	40	24	9	nd	nd	1	T	34	6 - px,ol	5	12 - ze	nd	12	0.25
DY1	JDY-1	2	1	1	4	45	5	50	23	2	nd	nd	nd	nd	25	T - px	7	14 - fs,ze,ca	nd	13	0.20
	JDY-3	1	1	2	4	45	T	45	24	5	nd	1	1	nd	31	1 - px	5	12 - ze,ca	2 - hc	14	0.15
	JDY-6	5	T	2	8	28	1	29	17	17	nd	nd	3	nd	37	T - px	12	13 - ca,fs	1 - hc	14	0.20
	JDY-7	5	2	1	8	39	9	48	12	9	nd	nd	2	3	26	T - px	6	11 - ca	1 - hc	12	0.15
	JDY-8	4	T	nd	4	31	1	32	22	19	nd	T	T	2	43	1 - px	3	16 - si	1 - hc	17	0.15
GH1	JGH-14	4	1	1	6	44	T	44	11	1	T	3	nd	nd	15	10 - px	5	9 - ca,ze	11 - hc	20	0.16
	JGH-10	nd	1	nd	1	58	T	58	13	3	nd	nd	nd	nd	16	3 - px	4	19 - ze,ca	nd	19	0.15
	JGH-7	nd	2	nd	2	58	2	60	11	1	nd	nd	nd	nd	12	3 - px	8	16 - ze,ca	nd	16	0.22
	JGH-5	2	T	T	2	49	T	49	18	4	nd	nd	nd	nd	22	8 - px,ol	10	9 - ze,ca	nd	9	0.13
	JGH-2	5	nd	T	5	46	1	47	22	3	T	1	nd	nd	26	8 - px	5	7 - ze	1 - hc	8	0.15
	JGM-2	5	T	nd	5	37	1	38	36	6	nd	nd	2	T	44	nd	1	3 - ca	9 - hc	12	0.21
MI2 —	JMI-2	nd	nd	2	2	23	nd	23	24	5	nd	6	17	4	56	nd	3	15 - ze	nd	15	0.50
	JGP-18	14	19	5	38	33	8	41	4	nd	nd	1	nd	4	9	3 - px	2	4 - ca	4 - hc	8	0.20

Feldspar is the most abundant detrital constituent of the interflow sandstones and constitutes an average of 45 percent of the framework grains. Plagioclase comprises nearly two-thirds of the feldspar in most sandstone units. Plagioclase grains are angular to rounded, generally elongate, and twinned. By the Michel-Levy statistical method of identification (Heinrich, 1965), labradorite appears to be most common and andesine is rarely present. Plagioclase of other compositions may be present but not identified because of extensive alteration or the absence of twinning. More than three-quarters of the plagioclase in the 68 modes of Table 3 is altered to kaolinite or partly replaced by albite, zeolite, prehnite, or sericite. Albite occurs only as a grain replacement; no primary albite clasts were identified. Potassium feldspar occurs in three-quarters of the 68 modes in abundances of as much as 30 percent, but it averages about 3 percent of the framework grains. Orthoclase is the most abundant K-feldspar and occurs as subangular to subrounded grains which are partly replaced by zeolite. Except for rare microcline with distinctive gridiron twinning and clasts of perthitic feldspar, the feldspar clasts appear to have been derived from mafic to felsic volcanic rocks and perhaps some Keweenawan intrusive bodies.

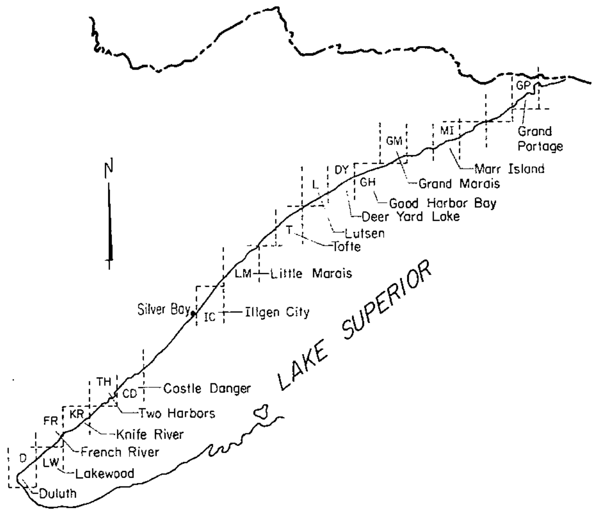

Figure 3. Location diagram to 7½-minute quadrangles used as prefixes in sample numbers.

Rock fragments are present in nearly all samples, comprising an average of 30 percent of the framework grains. Mafic and intermediate volcanic rock fragments are most abundant, and felsic volcanic clasts are rare (fig. 4B). The volcanic rock fragments (fig. 5B) display textures and mineral compositions that are common to the subjacent flows.

Fragments of plutonic rocks are not readily identifiable in the sandstone units. Three of the 68 modes contain a few clasts with large (>2 mm long) plagioclase and pyroxene crystals; these may be of mafic intrusive derivation. Some coarse-grained clasts of intergrown quartz and K-feldspar may have been derived from Archean felsic plutonic rocks.

Fragments of amygdule quartz (agate) are subrounded to subangular and consist of clear undulatory quartz and clouded, light-brown chalcedony with cockscomb structures (fig. 5C). The agate clasts typically have sutured crystal boundaries, and some are banded with concentric rings of chalcedony, quartz, and/or zeolite. These agate clasts were probably derived from amygdules or veins in the volcanic rocks.

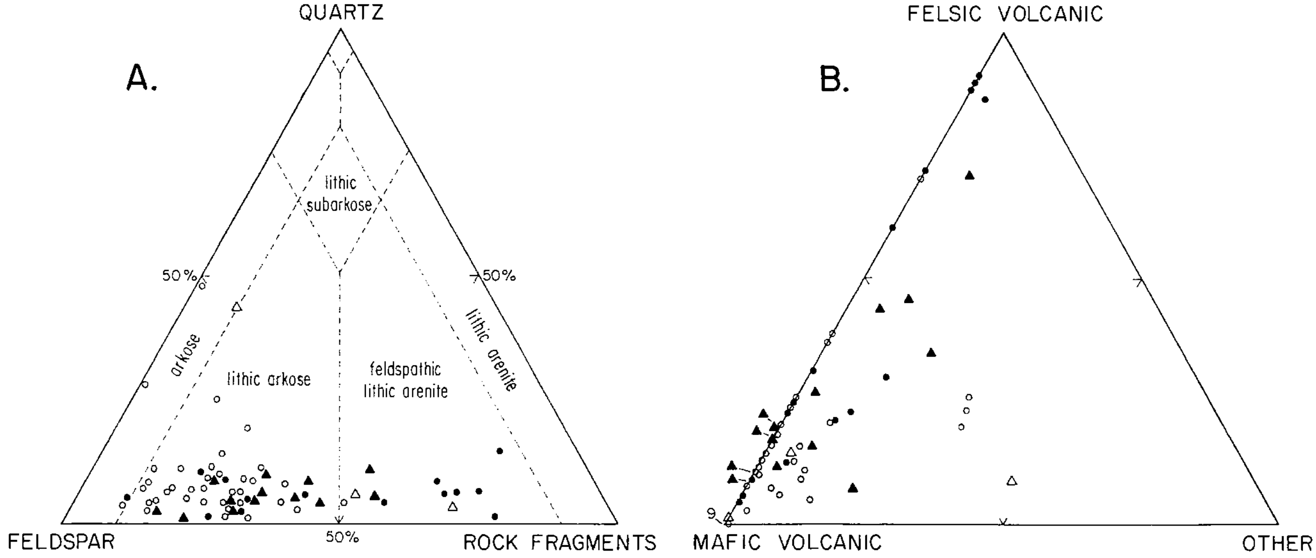

Figure 4. Summary of mineralogic composition of interflow sedimentary rocks in the North Shore Volcanic Group; A, modes of 68 sandstones; B, modal plot of rock fragments (relative grain percentages converted from table 2). △ , sample prefixes GP, MI, GM; ▲, DY, GH; ●, CD, SB, IC, LM, T: o, D, LW, FR, KR, TH; the most mafic data point (o) in B represents nine samples.

Table 3. Heavy mineral data for interflow sedimentary rocks
[T, <0.1 percent; cpx, clinopyroxene; opx, orthopyroxene; ol, olivine; ap, apatite; zi, zircon; ru, rutile; sp, sphene; hb, hornblende; ep, epidote (product of metamorphism of sediment); HM, percentage (by weight) of heavy minerals in each sample (including opaque); OPQ, approximate percentage of each heavy mineral concentrate (HM) that is opaque (mainly magnetite and minor hematite, ilmenite, and leucoxene)]

Sample	Relative percentage of non-opaque heavy minerals										
Number	cpx	opx	ol	ap	zi	ru	sp	hb	ep	HM	OPQ
JD-9	1.6	-	1.6	4.1	0.8	0.8	-	-	91.1	25.4	70
JFR-28	12.6	-	1.0	3.2	3.2	-	1.0	-	78.9	35.1	95
JKR-7	97.8	-	T	1.2	0.6	-	-	0.3	-	13.4	35
JTH-3	93.0	-	0.9	2.3	0.9	-	-	2.8	-	0.1	60
JCD-14	98.7	-	T	0.4	0.8	-	-	-	-	24.0	50
JIC-26	98.1	-	-	0.5	1.0	-	-	0.5	-	19.6	90
JLM-7	97.5	-	0.3	-	1.2	0.6	-	0.3	-	7.8	40
JT-1	96.0	0.7	2.1	1.1	-	-	-	-	-	13.3	65
JL-2	55.8	-	2.5	40.0	1.7	-	-	-	-	1.0	50
JDY-11	99.2	0.1	-	0.4	0.3	-	-	-	-	19.9	40
JGH-2	97.7	T	0.8	1.2	0.4	-	-	-	-	18.3	55
JGM-2	68.7	0.2	T	2.0	1.9	-	5.6	1.6	-	2.5	25
JMI-2	92.8	1.0	T	-	3.7	-	-	2.5	-	10.0	60
MEAN	77.7	0.1	0.6	4.4	1.4	0.1	2.0	0.6	13.1	14.6	

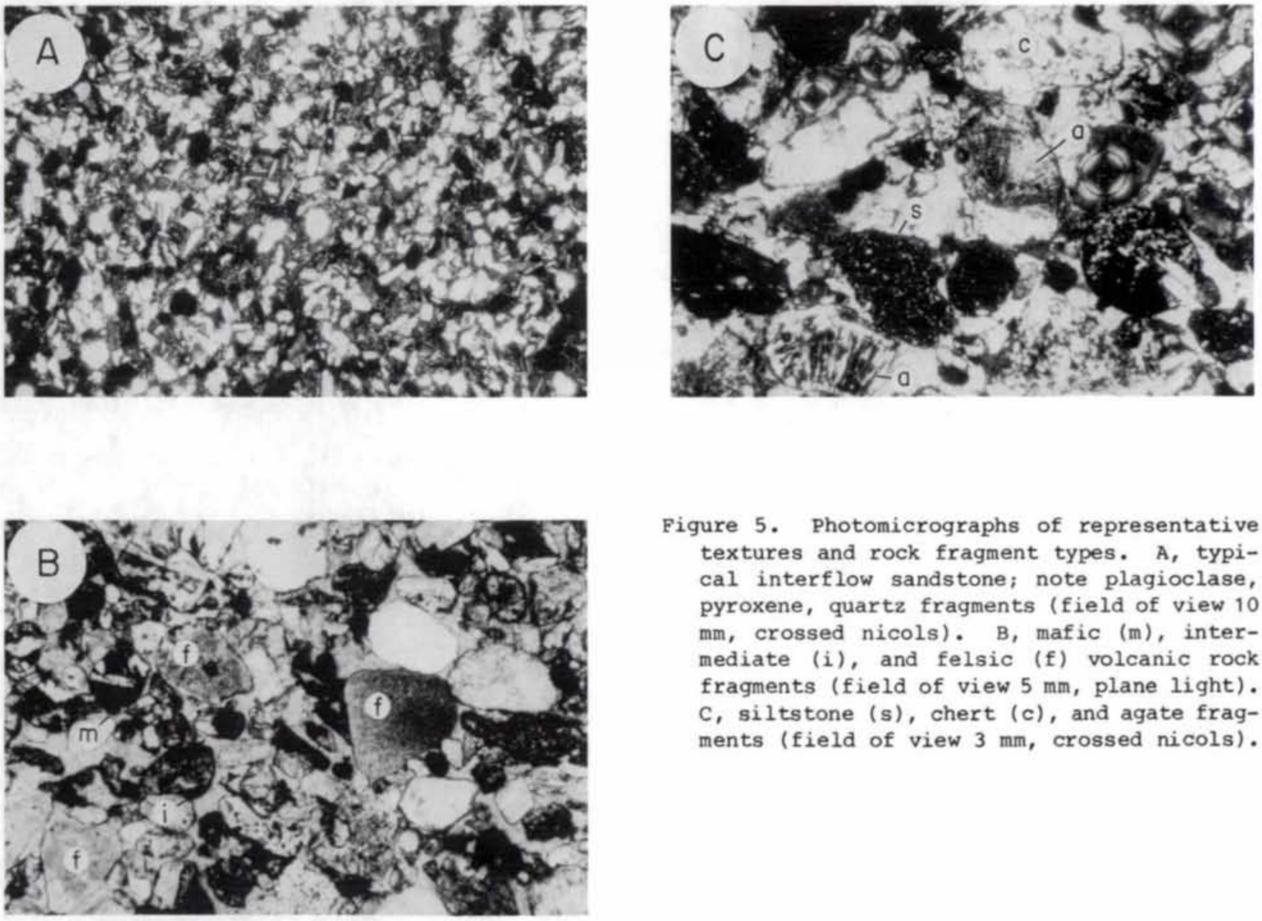

Figure 5. Photomicrographs of representative textures and rock fragment types. A, typical interflow sandstone; note plagioclase, pyroxene, quartz fragments (field of view 10 mm, crossed nicols). B, mafic (m), intermediate (i), and felsic (f) volcanic rock fragments (field of view 5 mm, plane light). C, siltstone (s), chert (c), and agate fragments (field of view 3 mm, crossed nicols).

Detrital chert grains are rounded, and commonly have thin iron-rich laminae (fig. 5C). These typically appear to have been recrystallized to polygonal textures and may have been derived from iron-formations.

Mudstone and siltstone clasts are present in a few samples as subangular to subrounded grains of reddish-brown to gray, microcrystalline clay supporting angular to rounded silt-size particles of quartz, plagioclase, and K-feldspar (fig. 5C). A few siltstone fragments have a chloritic matrix surrounding silt-size grains of quartz. Unlike typical Keweenawan siltstone, these fragments lack hematite and contain only quartz grains, implying derivation from lower Proterozoic or Archean metasedimentary rocks.

Detrital pyroxene is commonly associated with opaque minerals and zircon in heavy mineral laminae, and is dispersed throughout many samples. Pyroxene grains are subrounded to rounded, and most are clear in thin section. Clinopyroxene (augite) is most abundant; orthopyroxene is present in only a few samples in minor amounts.

Small amounts of several other minerals are present in the sandstones. Subrounded grains of a very finely crystalline, green mineral (chlorite or serpentine) with magnetite rims are inferred to be altered olivine clasts. Brown to greenish, subangular, elongate grains of hornblende are rare. Detrital biotite occurs in trace amounts of less than 0.5 percent in a few samples.

Opaque minerals are ubiquitous in the interflow sandstones. Most are subrounded to rounded grains of magnetite, hematite, and leucoxene-altered ilmenite that has hematitic rims. Some magnetite in samples from stratigraphically lower horizons appears secondary. As much as 2 percent of interstitial native copper is present in thin sections that contain abundant prehnite.

Coarse-Grained Rocks

Conglomerate and breccia make up about 30 percent of the total sedimentary accumulation on the North Shore. They consist largely of pebble- to boulder-size volcanic clasts in a sandstone matrix. Nearly all are clast supported and well cemented. There are only minor compositional variations in most of the coarse-grained sedimentary rocks. Typical examples are shown in Figures 6A and B.

Conglomerate units vary from well to poorly sorted. Most contain angular to subrounded clasts derived from the flow underlying the deposit and subangular to rounded clasts that are typically more felsic than the underlying flow.

Flowtop breccias, previously called amygdaloidal conglomerates (Van Hise and Leith, 1911), consist of angular fragments from the subjacent flowtop in a matrix of sand or a cement of calcite or zeolite (fig. 6C). The fragments are amygdaloidal basalt and andesite, and range in size from 1 mm to 30 cm. Flowtop breccias range in thickness from less than a meter to 6 m, and generally grade downward into fractured amygdaloidal lava as the volume of matrix decreases. They record the autobrecciation of lava flows that produced an aa structure and the subsequent infilling of the fractured flowtops by sand.

Pyroclastic Rocks

Tuffaceous sandstones and volcanic breccias make up about 6 percent of the interflow clastic rocks in the North Shore Volcanic Group. The tuffaceous sandstone beds are generally well sorted and consist of various amounts of sand-size, angular, lunate detritus (fig. 6D). All shards and pumice fragments are replaced by zeolites, calcite, or microcrystalline silica, and most are not welded or deformed. In several of the units, pyroclastic particles form thin laminae separated by laminae of epiclastic detritus.

The volcanic breccias consist of angular blocks of amygdular or scoriaceous lava set in a matrix of devitrified glass and small lithic fragments. Breccia blocks range from 2 mm to 10 cm in size, and generally are elongate and matrix supported (fig. 6E). In some of the breccia units, elongate blocks have a subparallel orientation. The matrix consists of various proportions of magnetite-rich scoria, fragments of vesicle walls, angular dark-colored glass shards, and minor amounts of fragmented plagioclase and quartz crystals. The breccias are moderately well cemented with calcite and zeolite.

Heavy Minerals

The 13 samples analyzed for heavy mineral content (table 2) were selected from outcrop localities distributed between Duluth and Grand Portage. Heavy minerals comprise an average of 14.6 percent by weight of samples analyzed. Over 25 percent of each concentrate consists of aggregates of opaque and semi-opaque minerals including hematite, magnetite, ilmenite, and leucoxene. Clinopyroxene is the most abundant nonopaque, detrital heavy mineral. Apatite, zircon, orthopyroxene, and altered olivine are present in lesser amounts. Rutile, sphene, hornblende, and epidote are present locally. Thin section petrography indicated that epidote is probably a metamorphic product in the clastic rocks, and not a primary constituent of the heavy mineral assemblage.

Diagenesis and Metamorphism

Diagenetic effects in the interflow sedimentary rocks are the result of compaction and burial beneath the pile of accumulating Keweenawan lava and sedimentary rock. The depth of burial ranged from a few hundred meters to more than 8000 m (Green, 1977), and the sediments were subjected to at least one circulating ground-water system. The sedimentary rocks are generally well cemented and well compacted. Most primary constituents are altered to, replaced by, or cemented with various secondary minerals including zeolites (laumontite and heulandite), albite, K-feldspar (probably adularia), quartz, chalcedony, calcite, sericite, epidote, prehnite, hematite, magnetite, leucoxene, native copper, and possibly pumpellyite.

The distribution of secondary minerals in the sedimentary rocks indicates a general zonation (fig. 7) that is presumably related to burial depth. The most deeply buried clastic

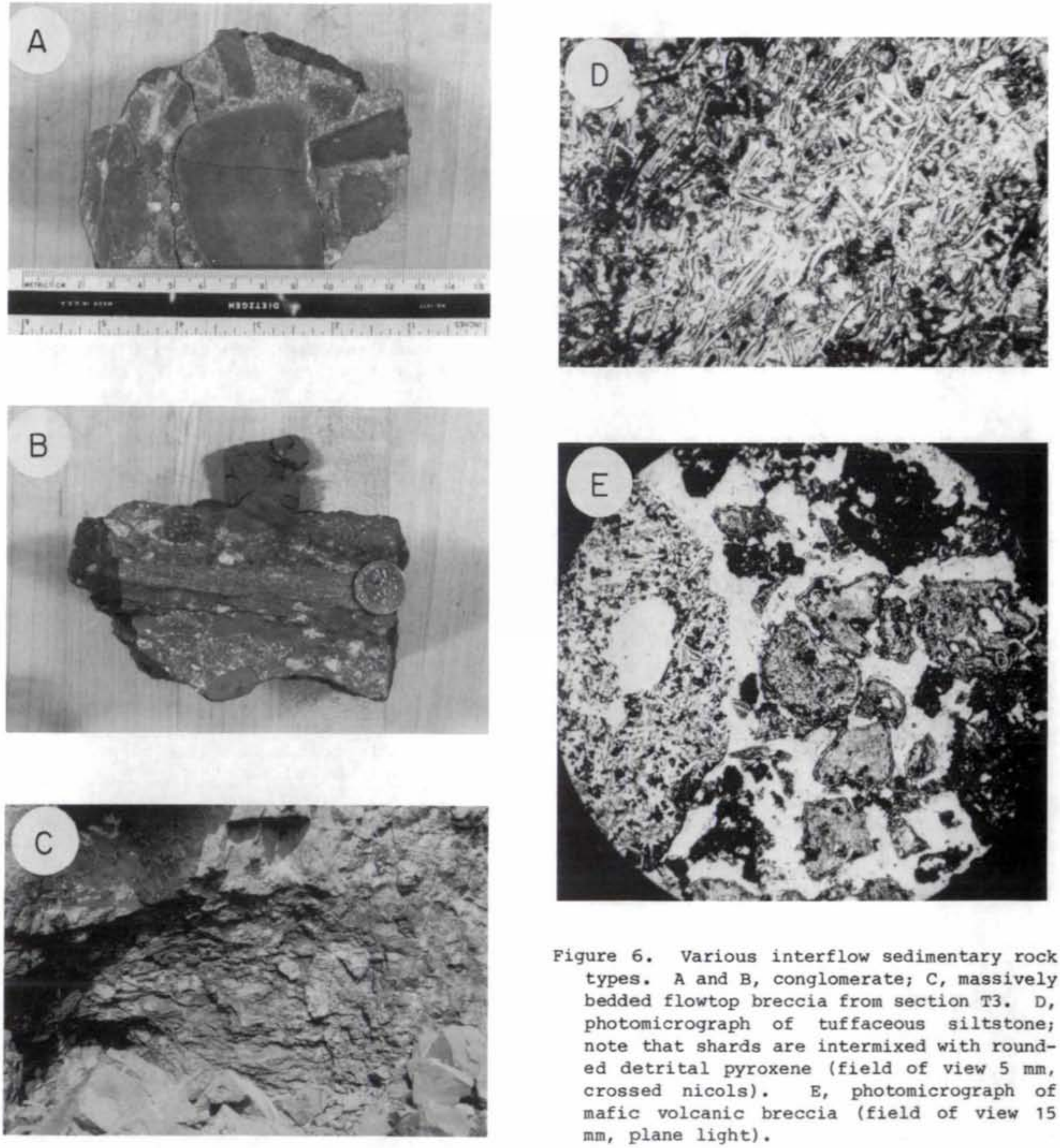

Figure 6. Various interflow sedimentary rock types. A and B, conglomerate; C, massively bedded flowtop breccia from section T3. D, photomicrograph of tuffaceous siltstone; note that shards are intermixed with rounded detrital pyroxene (field of view 5 mm, crossed nicols). E, photomicrograph of mafic volcanic breccia (field of view 15 mm, plane light).

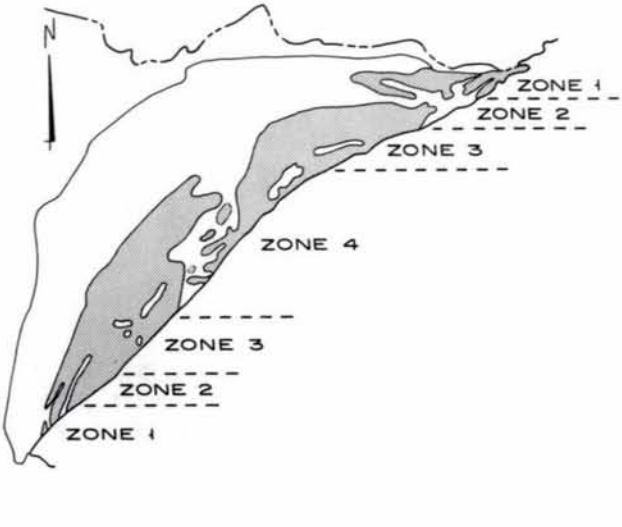

Figure 7. Map distribution of burial metamorphic minerals in interflow sedimentary rocks; zone 1, epidote-chlorite-quartz (± albite, calcite); zone 2, prehnite-epidote-quartz (± pumpellyite, copper, albite, chlorite); zone 3, laumontite-quartz (± epidote, chlorite, calcite); zone 4, laumontite-calcite (± heulandite).

rocks near Duluth and Grand Portage contain epidote, chlorite, and quartz, indicating sub-greenschist-facies metamorphism (zone 1). Successively younger sedimentary rocks contain minerals indicative of the prehenite-pumpellyite facies (zone 2) and zeolite facies (zones 3 and 4). A similar zonation of secondary minerals occurs in the volcanic rocks (Green, 1972). The presence of agate clasts in the interflow sedimentary rocks implies that an earlier metamorphic event must have occurred during which older flows were buried, metamorphosed, and then uplifted and eroded.

SEDIMENTOLOGY

The general stratigraphic and sedimentological setting of selected interflow sedimentary rock units is illustrated in Figure 8. Units thinner than 2 m or composed of sand-filled flowtop breccia are not depicted.

Sedimentary Structures

Sedimentary structures are locally well preserved and abundant. The sandstone units are typically thinly laminated, although beds ranging in thickness from 1 to 10 cm occur in some of the thicker units.

Graded sequences are common and vary in scale from microscopic grading in shale and fine-grained sandstone to large-scale grading in conglomerates and some breccia. Fining-upward (normal) grading is most common; coarsening-upward (reverse) grading was rarely observed.

Ripple marks are common in sandstone and shale units. Some rippled beds are solitary; others occur in complex rippled packets that have climbing ripples or ripple-drift laminations alternating with horizontal beds. In most beds the ripples are asymmetrical and homogeneous in texture; rarely, the ripple laminae are coated by fine sand, silt, or clay. Ripple marks are typically straight, and rarely sinuous or linguloid in form. Wavelengths vary from 0.5 cm to 20 cm, with amplitudes of 0.5 cm to 2.0 cm. Ripple indices (length/height) vary from 16 to 1, but smaller indices of 5 to 8 are most common. These characteristics imply that the ripple-marked clastic rocks were deposited in medium-fast to slow streams (Harms and others, 1982).

Cross-bedding is common in the sandstone units, but is rare in the conglomeratic and shale units. Trough cross-stratification is abundant and occurs as solitary channel fillings (scour and fill structures) and as multiple wedge-shaped coalescing sets. Troughs range from less than 1 to 2.5 m in thickness, and from 0.3 to 5.0 m in width. Planar cross-stratification occurs in sets ranging in thickness from 2 cm to 2 m. Sets of cross-strata typically occur either as grouped foresets or as superposed sets with nonerosional bounding surfaces. Less commonly, cross-strata occur as solitary sets bounded above and below by horizontally stratified sandstone (top and bottom sets). Foresets generally dip 10 to 35 degrees steeper than their juxtaposed topset beds. Several foresets contain parting lineations indicative of local high-velocity currents.

Fine-grained sedimentary rocks typically have convolute or horizontal laminae, ripple marks, and local desiccation cracks; they commonly contain graded sequences of silt, fine-grained sand, and clay.

Clastic dikes occur as sediment-filled fractures that range in width from a few millimeters to 20 cm, and can be traced as far as 30 m. Detritus within the fractures is fine to medium, well-sorted sand or silt; some fractures contain lava fragments apparently dislodged from dike walls that are suspended in the clastic detritus. Most of the clastic dikes are the result of sediments that filled factures in upper lava surfaces, and these sediments have concave-up or contorted lamination. Locally, sediments were injected upward from an interflow clastic unit into the base of the overlying flow, producing sediment laminations that are parallel to dike walls.

Paleocurrent Analysis

Trough and planar cross-stratification, ripple marks, and pebble imbrications were measured wherever possible. Their orientations were rotated by the stereonet procedure of Potter and Pettijohn (1963) to offset formation dip. The corrected azimuths were combined to produce a rose diagram and vectoral mean for each outcrop (fig. 9).

In most areas, the frequency distribution of paleocurrent measurements is unimodal and fairly symmetrical about the mean. In general, the measurements in each rock unit show a high degree of central tendency, as an average of 70 percent lies within a 90-degree arc.

Except for the Duluth area, paleocurrent directions are moderately uniform along the North Shore, irrespective of stratigraphic position. In nearly all deposits, the predominant current flow appears to have been toward the present Lake Superior basin. Lines drawn normal to mean paleocurrent vectors are approximate paleocontours (fig. 9), although this paleocontour construction assumes that all deposits are about the same age, which is not the case for these rocks. However, some general comments regarding the configuration of the depocenter can be made. Sedimentation appears to have occurred in one or more slightly elongate, east-northeast-trending basins, the axis of which trended more to the east than the lakeshore. The eastward paleocurrents near Duluth imply either that this area was the southwestern terminus of the depositional basin, or that the depocenter axis trended northward near what is now Duluth.

Note that the paleocontours (fig. 9) are subparallel to the existing strike of bedrock in the northeastern and southwesternmost exposures. Near the center of the exposure belt, particularly in the Grand Marais (GM) to Illgen City (IC) area, however, the paleocontours trend more southeastward than the strike. This implies that during at least part of the deposition, the basin center lay in an area that is now offshore from the southwestern sequence.

Environments of Deposition

The interflow sedimentary rocks were deposited primarily by braided streams; fluvial-lacustrine and volcanic processes contributed lesser amounts of detritus. The presence of interbedded sandstone, conglomerate, and shale, all having cut and fill structures and irregular bedding contacts (notably in outcrops IC2, IC4, IC8, LM1, and L4; fig. 8), implies that there were frequent and extreme changes in flow conditions during deposition; these features are characteristic of braided streams (Smith, 1970; Reineck and Singh, 1973; Harms and others, 1982). Where present, shale beds are thin and lenticular (except for outcrops DY1 and GH1), and thus are the result of plugged braided-stream branches; overbank flow in a meandering stream would have produced more continuous and thicker units of fine-grained strata. This interpretation is consistent with data from previous studies, including Sandberg (1938); Grout and others (1959); Johnson and Foster (1965); and Green (1972).

In a study that compares characteristics of recent braided stream deposits with Silurian sedimentary rocks in the Appalachians, Smith (1970) concluded that horizontal strata predominate, clast size is coarser, and slope and current velocities are greater in proximal regions of braided streams. Smith found that, in the downstream direction, the proportion of planar cross-stratification increases at the expense of horizontal strata, and that grain size decreases.

The 16 measured sections along the North Shore (fig. 8) indicate that horizontally stratified conglomeratic rocks are typical in outcrops between Illgen City and Lutsen (sections IC2, IC4, IC8, LM1, and L4; figs. 10 and 11). Smith's data imply that these rocks were deposited by relatively fast streams on moderately steep slopes. Sedimentary rocks to the southwest (sections D4 to CD4) and northeast (sections DY2 to MI2) contain a variety of lithologies and strata types. Although no obvious trend can be distinguished for these rocks, the abundance of cross-stratified, ripple-marked sandstone and shale implies deposition on more gentle slopes by slower currents. Thus it appears that deposition of younger (stratigraphically higher) interflow sedimentary rocks (sections IC to L) occurred near an uplifted area and on an irregular topographic surface, whereas the lower sediments were deposited farther away.

Parts of sections GH1 and DY1 contain rock types and sedimentary structures indicative of deposition in a fluvial-lacustrine environment formed by either local subsidence or damming of water by thick flows down the paleoslope. Nearly 30 percent of both sections consists of thinly bedded, graded layers of fine-grained sand, silt, and clay which contain both symmetrical and asymmetrical ripple marks. The bimodal paleocurrent distribution indicates variable current directions that might be expected where streams periodically flowed into ponded water. These fine-grained clastics are grayish brown, in contrast to the ubiquitous reddish-brown color in other interflow sedimentary rocks, and thus reducing conditions may have been present locally.

The pyroclastic rocks contain few internal sedimentary structures. The tuffaceous units

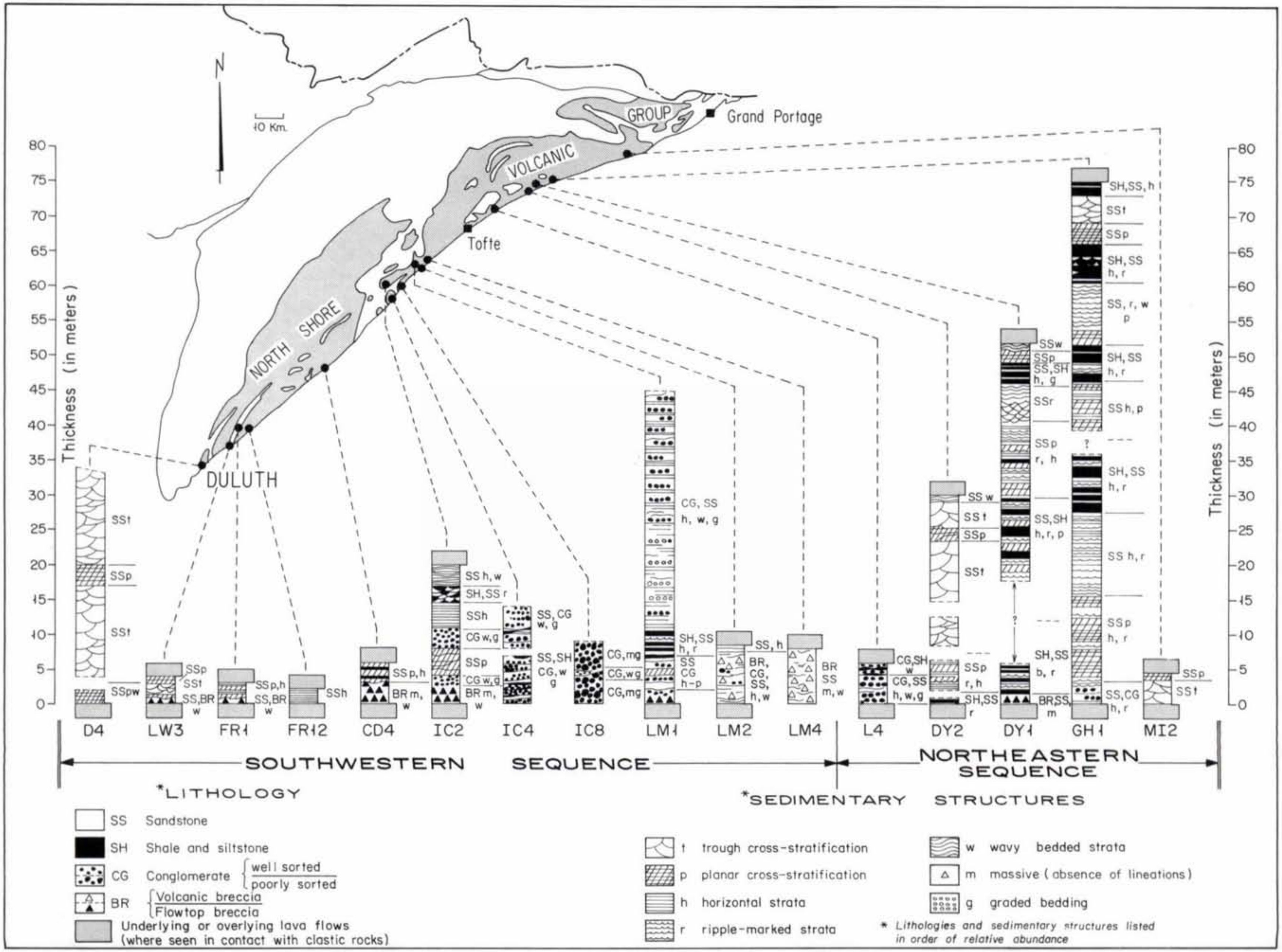

Figure 8. Generalized stratigraphy of selected rock units in the North Shore Volcanic Group.

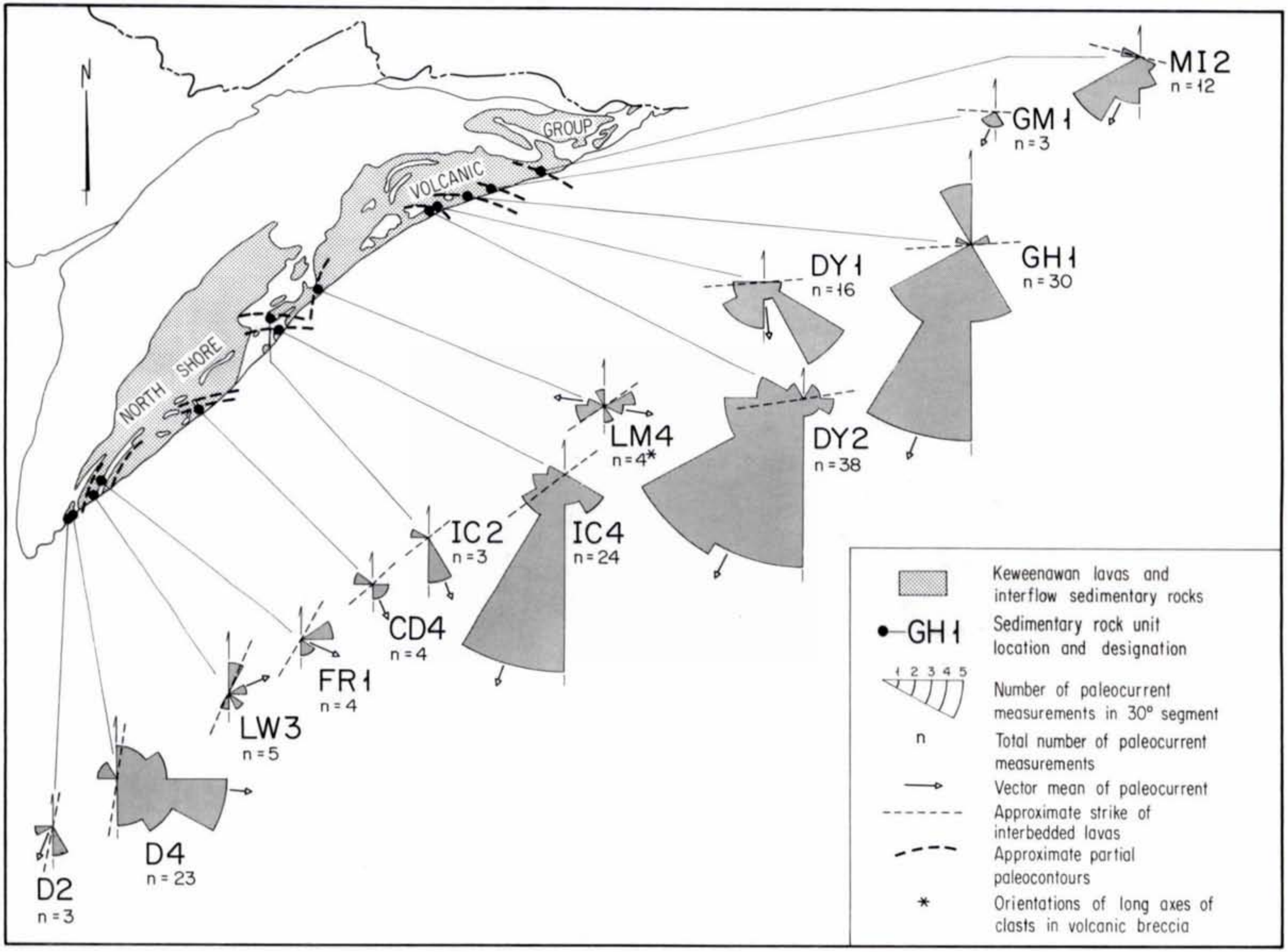

Figure 9. Paleocurrent distribution for the interflow sedimentary rocks. Data include cross-stratification, ripple marks, and pebble imbrications.

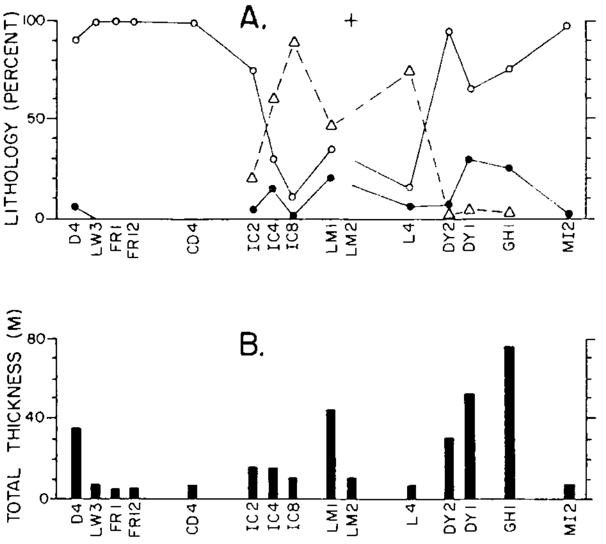

Figure 10. Variations in lithology and thickness of the interflow sedimentary rocks. A, percentage of lithology in each unit; ●, siltstone and shale; o, sandstone; ▲ , conglomerate; +, volcanic breccia. B, unit thickness.

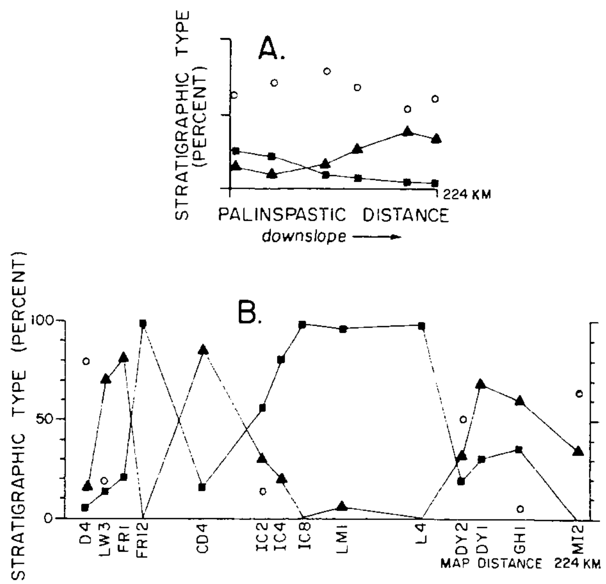

Figure 11. Distribution of principal stratification types. A, expected (after Smith, 1970). B, observed in the North Shore Volcanic Group; o, trough cross-stratification; ▲, planar cross-stratification; ■, horizontal stratification.

typically are horizontally stratified and appear to have formed from airborne ash settling onto the flows. In some of the tuffaceous sandstone deposits, the ash was probably reworked by flowing water which added minor epiclastic detritus. Breccia units typically contain matrix-supported, subrounded blocks having a subparallel orientation. Bedding within the matrix material is generally contorted except where thin lenses of well-sorted sandstone are intercalated. These characteristics and the composition of the breccias imply a laharic origin.

PROVENANCE

The interflow sedimentary rocks generally contain small amounts of quartz but high percentages of chemically unstable minerals and clasts. The typically fine-grained, well-sorted, subrounded to subangular character of the compositionally immature sandstones implies a somewhat distant source terrane upon which only minor weathering occurred. The coarse-grained clastic rocks may indicate areas of local uplift, and glass shards and other pyroclastic particles indicate local explosive volcanism.

This study demonstrates that the interflow sedimentary rocks are composed almost entirely of detritus derived from lava flows of the North Shore Volcanic Group. Comparison of plagioclase and augite grain sizes in sediments (table 2 gives some indication) with their crystal sizes in lavas (Konda and Green, 1974) reveals that both constituents could have been derived from the volcanic rocks. However, the possibility exists that some of these clasts were eroded from Keweenawan intrusions, especially during later phases of sedimentary deposition when these intrusions may have been unroofed by erosion. Although the presence of an unconformity between reversely polarized lavas and younger lavas cannot be conclusively demonstrated, it is possible that the older reversed flows were buried, mineralized, and uplifted to provide the agate-rich detritus in the younger, normally polarized sequences.

Variations in the abundance of intraformational detritus, including most quartz, feldspar, volcanic rock fragments, and agate (see table 2; fig. 4), largely appear to reflect differences in lava composition. The amount of plagioclase and mafic volcanic clasts decreases irregularly from the lowermost sedimentary rocks near Duluth to the uppermost rocks near Tofte. Nearly the opposite trend is shown for the amount of K-feldspar and felsic volcanic clasts. Several thick rhyolite flows exposed between Illgen City (IC) and Grand Marais (GM) may have provided felsic detritus to produce these trends. The quartz percentage shows no clear-cut trend; however, unit quartz is moderately abundant in interflows from Duluth to Knife River (KR) and in most interflows in the northeastern sequence

(L-GP). If unit quartz was derived primarily from Keweenawan felsic rocks, its trend should mirror that of felsic volcanic clasts. This is the case for the quartz-rich interflow clastic rocks in the northeastern sequence. However, unit quartz is also abundant (>7 percent) near Duluth (D), Lakewood (LW), and French River (FR), yet interflows in this area do not contain a high felsic clast content. Therefore, the unit quartz in these lower level rocks may have been derived in part from quartz-rich pre-Keweenawan rocks.

Keweenawan rocks probably provided most heavy minerals including pyroxene, apatite, magnetite, and rare altered olivine; however, no significant trend in their relative abundance is seen.

Detritus that presumably was derived from pre-Keweenawan rocks makes up less than 1 percent of the clastic rocks. It includes: (1) polycrystalline quartz possibly derived from granitic rocks; (2) iron-rich chert which may have been eroded from lower Proterozoic or Archean iron-formations; (3) some phyllitic fragments presumably from lower Proterozoic metasedimentary rocks; and (4) microcline from pre-Keweenawan granite. These indicators of possible pre-Keweenawan source terrane are most abundant in the sedimentary rocks in the southwestern sequence, and are moderately abundant throughout the clastic rocks in the northeast. In rocks of the southwestern sequence, paleocurrents flowed from the west and northwest. Thus, older rocks on the fringes of the watershed probably were uplifted during early sedimentary deposition, and may have been mantled by lava flows during later deposition.

STRUCTURAL DATA

Clastic dikes in the Keweenawan lavas are generally the result of sediment that filled cooling fractures in lava surfaces. Such fractures should have random strike directions and are not, therefore, expected to reflect broad, tensional tectonic patterns. However, the orientation of some clastic dikes may have been affected by regional stress patterns as basins and uplifts developed on the Keweenawan terrane.

To examine the possible influence of tectonic stress on dike directions, stereonet plots of clastic dike contacts (plotted as poles) were made for six segments of the North Shore (fig. 12). Preferred orientations are inferred to represent local tectonic extension, although dikes oriented perpendicular to the lakeshore (i.e., northwest-trending dikes) were probably intersected more frequently and may dominate the measurements for that reason.

Most of the clastic dikes strike to the northwest or west. Northeast-trending clastic dikes are present throughout the area, but dominate only the segments near Duluth and Little Marais. The northeastward trend near Little Marais is subparallel to the orientation of intrusive rocks of the Beaver Bay Complex and associated faults that lie several kilometers to the southwest. This implies that the area adjacent to the intrusions may have been tectonically active before intrusion occurred. In addition, the area from Little Marais (LM) to Lutsen (L) is interpreted from sedimentological data as having had moderately high relief and possible intermittent uplift during sedimentary deposition. Because the northeast trend of dikes near Duluth (LW) is subparallel to the Endion sill and Lester River diabase sill, this area also may have been a zone of tectonic extension during deposition and volcanism.

The orientations of the clastic dikes are consistent with some structural observations in the Duluth Complex and related rocks. On the basis of lineaments and displaced contacts predominantly in Keweenawan intrusive rocks, Weiblen and Morey (1980) define three general fault trends--north-northeast, north-northwest, and west-northwest (fig. 12). Mudrey (1976) defined a regional joint system (N. 53° E., N. 14° W.) which he attributed to northwest-oriented extension during deposition and emplacement of the normally polarized rocks. Many of the clastic dike orientations trend more to the west than the predominant northeast and northwest trends, notably in the FR, KR, TH, and T-L segments. Two explanations for this are possible: (1) the west-northwest-trending orientations may represent a statistical domination of dikes that are perpendicular to the corridor of exposure, or (2) the segments containing west-northwest-trending dikes are distal from zones of tectonic extension. The latter explanation appears more reasonable as these segments are distal from existing intrusions.

TECTONISM-SEDIMENTATION MODEL

Paleocurrent data indicate that sedimentary deposition occurred in a slightly elongate, east-northeast-trending basin. During at least some of this deposition, the basin appears to have had two morphologically different sub-basins which were the result of different relative rates of subsidence, and which very generally correspond to the northeastern and southwestern sequences. The intervening area from Silver Bay to Lutsen appears to have experienced intermittent uplift, explosive volcanism, and faulting. Evidence from both this study and previous workers for the two-part basin model is given below:

(1) The dip of lavas in portions of the southwestern sequence, which decreases slightly from older to younger deposits, suggests that basin subsidence was concurrent with de-

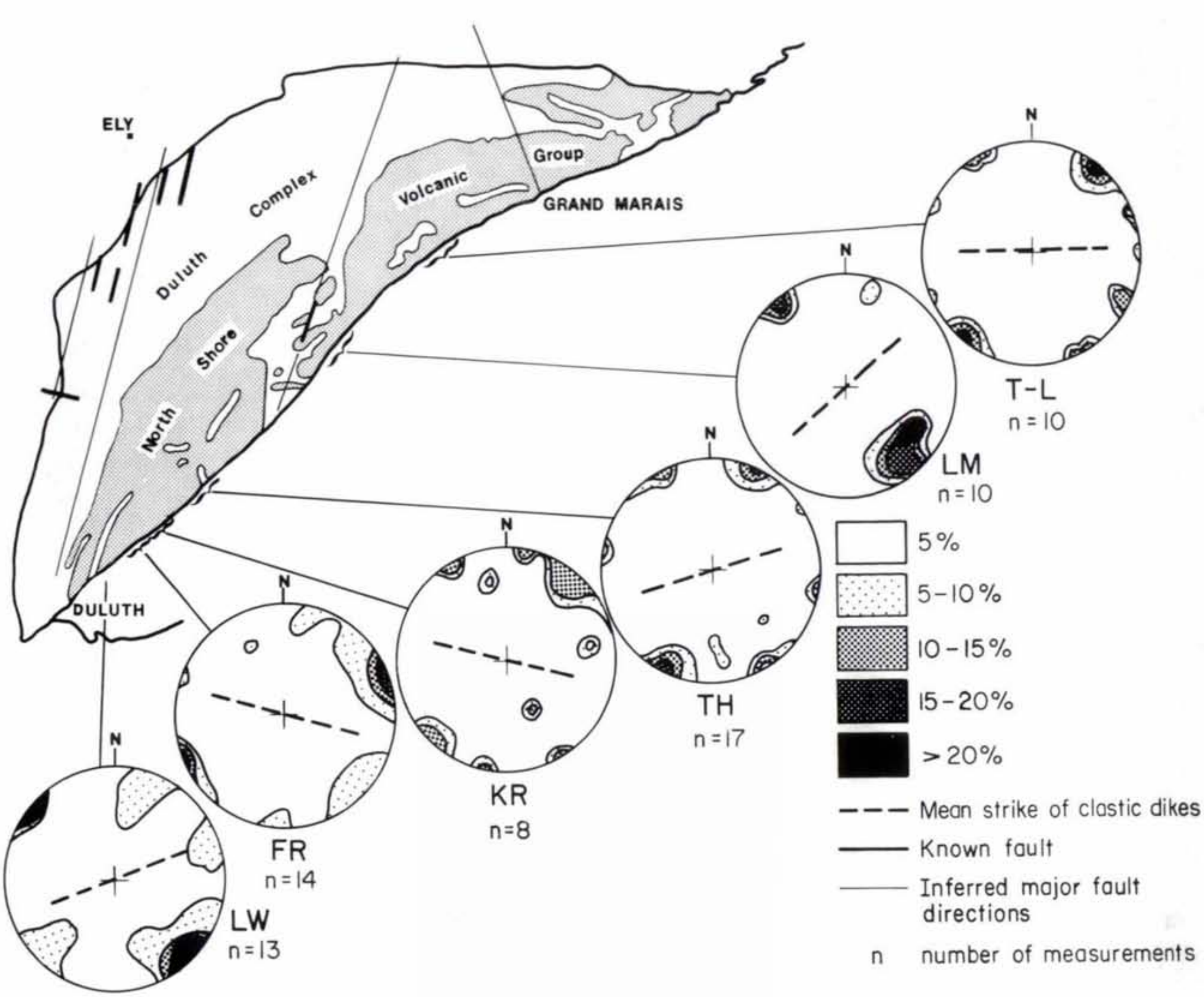

Figure 12. Structure diagram based on contoured stereonet projections of poles to clastic dikes (this study) and inferred fault trends (Weiblen and Morey, 1980).

position (Green, 1972). No appreciable change in dip was observed in the northeastern sequence, and so its deposition may have occurred on a relatively flat terrane whose subsidence occurred largely after deposition was complete.

(2) The horizontal stratification and conglomeratic character of sedimentary rocks near Little Marais (LM) and Illgen City (IC) indicates high-velocity currents and fairly steep, probably irregular slopes. Several volcanic breccias and other vent types of volcanic deposits (units LM2, LM4) and at least one fault imply that the area from Silver Bay to Lutsen was tectonically unstable during deposition. Sedimentary rocks in the remainder of the southwestern sequence (units D4 to CD4) are inferred to have been deposited in streams with low to moderate velocities. With the exception of the conglomerate near Lutsen, clastic rocks in the northeastern sequence represent relatively low energies of deposition. It appears, therefore, that most of the southwestern sequence was deposited during synchronous subsidence, and much of the northeastern sequence was deposited on a moderately flat terrain upon which local ponding occurred. The area that separates the two sequences (Silver Bay to Lutsen) may have had greater relief due to intermittent uplift and/or volcanism during at least part of the deposition of both sequences.

(3) Mean paleocurrent vectors in the northeastern sequence trend more southwest

than the bedrock dips (fig. 9). This suggests that during early deposition the basin center was in an area that is now offshore from the southwestern sequence.

(4) Weiblen and Morey (1980) suggest that the intrusions and faults in the Silver Bay area occur along a major structural discontinuity which separates Keweenawan rocks into two segments having different geophysical and geological characteristics. In addition, clastic dike orientations (fig. 12) imply that this area may have been tectonically active before intrusive igneous activity.

(5) On the basis of gravity data, White (1966) proposed the existence under western Lake Superior of two basins or troughs in which Keweenawan lavas are relatively thick, separated by a gravity low interpreted to be where lavas are thin or absent. The axis of this gravity low, which intersects the lakeshore about midway between Silver Bay and Lutsen, approximately marks the divide between the two volcanic-sedimentary sequences. Much of this area is occupied by intrusions, such as the Beaver Bay Complex, and is interpreted as having undergone intermittent uplift and explosive volcanism during sedimentary deposition.

None of the evidence listed above can be used alone to construct a depositional and tectonic model. However, collectively the evidence implies the following three-stage developmental history:

(1) During early sedimentation (fig. 13A), the southwestern portion of the basin subsided and received detritus from the volcanic rocks within the basin and to a much lesser degree from older rocks marginal to the basin. The northeastern portion subsided only gently. Some detritus may have been eroded from the metamorphosed, reversely polarized lavas. Sedimentary deposits represented in this interval are units with prefixes D, LW, FR, TH, and CD in the southwestern sequence; and GP, MI, and GM in the northeastern sequence.

(2) The area between Silver Bay (SB) and Lutsen (L) later had moderately high relief as a result of faulting, local uplift, and/or volcanism (fig. 13B). Coarse-grained alluvial deposits imply that steep slopes were present and explosive volcanism occurred locally. The northeastern portion of the basin remained relatively flat, and ponding occurred. Sedimentary outcrops prefixed by IC and LM in the southwestern sequence, and GH and DY in the northeastern sequence were deposited during this interval.

(3) During the last phase of deposition recorded in the volcanic and sedimentary rocks on the North Shore (fig. 13C), the area from Silver Bay to Lutsen probably ceased to be a focus of volcanic activity, and the entire sequence of flows and sediments subsided. Maximum subsidence may have been centered offshore of the youngest flows exposed in the Tofte-Lutsen area. The presence of conglomerate (outcrop L4) indicates that subsidence in the vicinity of these youngest flows may have been rapid. This central subsidence followed by burial and erosion would explain the decrease in dip stratigraphically upward in only the southwestern sequence (from Duluth toward Tofte) and the present structure of the North Shore Volcanic Group.

REGIONAL SEDIMENTOLOGIC AND TECTONIC RELATIONSHIPS

Sedimentary strata are interbedded with volcanic rocks in most areas of Keweenawan exposure surrounding Lake Superior (fig. 14). These interflow sedimentary rocks are immature, polymictic, fine- to coarse-grained red beds that were deposited in fluvial and lacustrine environments (Merk and Jirsa, 1982). Paleocurrent directional indicators demonstrate that streams flowed generally toward the central Lake Superior area from marginally located highlands. The highlands consisted of both Keweenawan and pre-Keweenawan rocks, and both contributed detritus to the interflow sediments. The compositional immaturity of the interflows indicates that only minor weathering occurred in the source terranes. The clast sizes, composition, and sedimentary structures suggest that the relief of the source regions was highest on the east side, moderately high on the south side, and lowest on the north and west sides of the Lake Superior area (Merk and Jirsa, 1982). Some of these source regions contain numerous Keweenawan intrusions that may have served as feeding fissures for the lavas.

The interflow sedimentary rocks represent only a part of the depositional sequence related to the Keweenawan rifting event in the Lake Superior region. Prior to volcanism (and associated sedimentation), a thin layer of quartz-rich clastics was deposited by braided streams that flowed toward what may have been the developing Lake Superior basin (Ojakangas and Morey, 1982). Once rifting began, several sub-basins developed into which lavas and sediments were deposited. The paleocurrent and lithologic data for the interflow sedimentary rocks indicate a close association of basin development with volcanism and the tectonic development of the rift. As volcanism waned and finally ceased, subsidence and sedimentary deposition within the rift zone continued, producing a thick clastic sequence and the structure of the Lake Superior syncline.

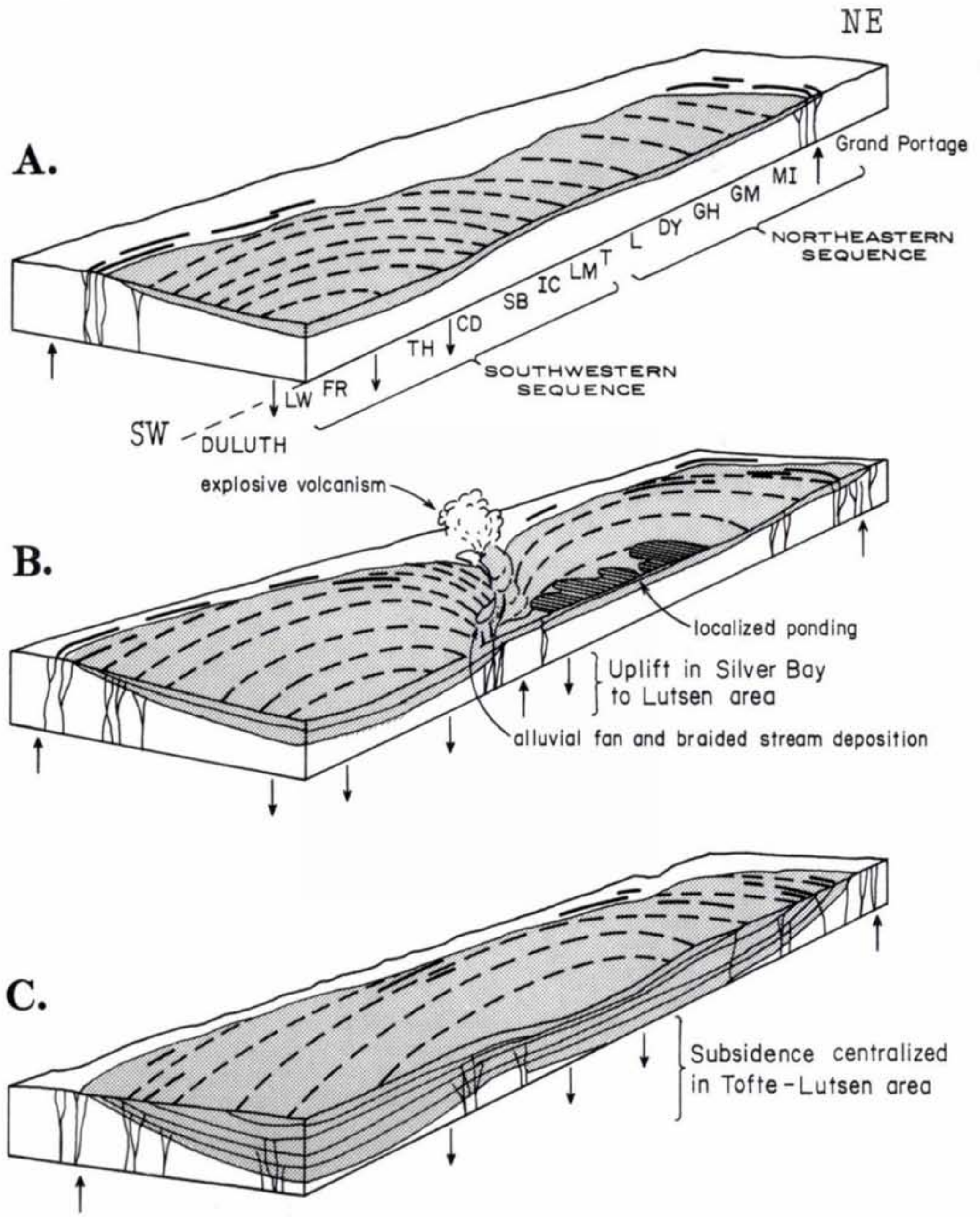

Figure 13. Proposed three-stage depositional and tectonic model for sedimentary rocks in the North Shore Volcanic Group; dashed lines, inferred form lines of basin; stipple, lavas and sediments; white, pre-Keweenawan rocks; see Figure 3 for key to locations.

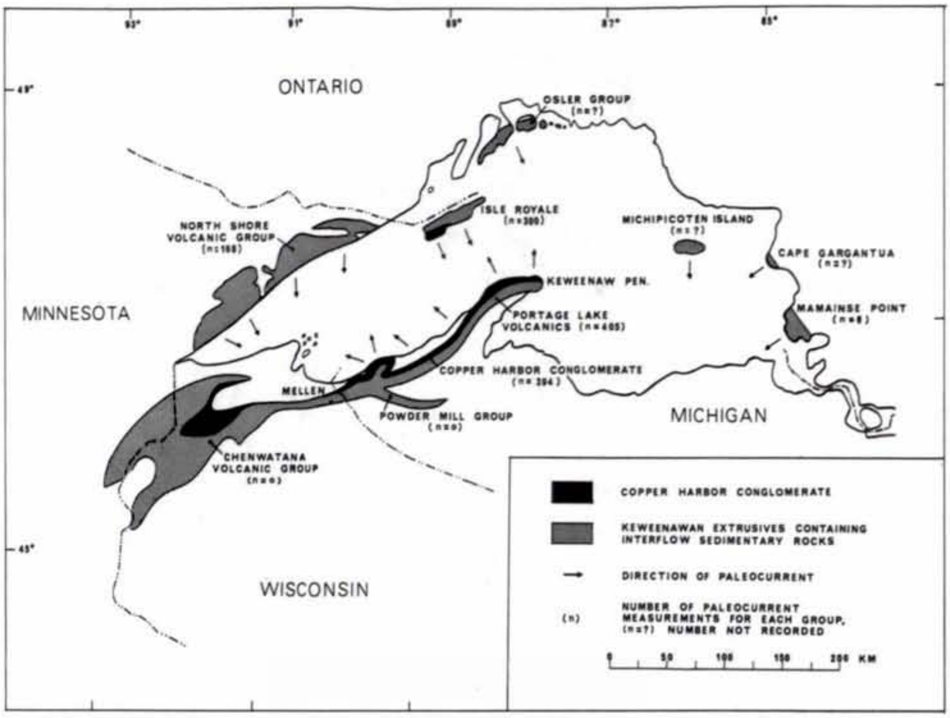

Figure 14. Distribution of Keweenawan extrusive rocks in the Lake Superior region that contain interflow sedimentary strata (from Merk and Jirsa, 1982).

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