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COMPOSITION OF TILL FROM THE CLEAR LAKE QUADRANGLE, SKAGIT AND SNOHOMISH COUNTIES, WASHINGTON

BY

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editoral standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

Seattle Washington
1981

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ABSTRACT

Lodgement till, a compact mixture of matrix (<2-mm) and clasts derived from local and regional sources, forms a veneer from 4 to more than 6 m thick over much of the Clear Lake, Washington quadrangle. Twenty-five till samples averaged about 70 percent matrix and 5 percent cobbles, and the matrix contained 46 percent silt, 44 percent sand, and 10 percent clay. The distribution of locally derived clay-size minerals like serpentine, talc, stilpnomelane, and kaolinite gives specific evidence for local ice-flow direction, while the proportion of greenstone, phyllite, and other local lithologies as clasts gives an indication of their relative resistance to crushing and provides data on regional ice flow. Certain clay minerals (smectite, chlorite, and mica) and granitic clasts are derived from regional and local bedrock and are ubiquitous in Clear Lake tills, as well as in till from the Puget lowland. Ice-flow directions suggested by drumlinoid features are generally consistent with ice-flow directions derived from mineralogic and clast data. The textural and mineralogic properties of the till help determine soil fertility and the quality of surface and ground water; and, combined with engineering data, they may be used in construction and waste-disposal planning.

INTRODUCTION

Till is typically a nonsorted, nonstratified sediment deposited directly from glacier ice and composed of rock and mineral fragments ranging in size from clay to boulders. Till usually forms compact deposits which resemble concrete, and is often called "hardpan" or "boulder-clay". In the Puget lowland north of Olympia (figure 1), till is the most common surface and near-surface material. Its physical and chemical properties help to determine soil fertility, the quality of surface water and ground water, and construction

**** Figure 1 near here ****

and waste-disposal planning. The nature of the till cover, and the composition of the clasts and matrix in the till help indicate the local flow direction of basal ice.

The Puget lobe of the Cordilleran ice advanced south to near Olympia from the Coast and Interior Ranges of British Columbia at least four times during the Quaternary Epoch (Armstrong et al, 1965), blanketing western Washington with thousands of meters of ice and depositing a till mantle over most of the area. Following the most recent advance, the Puget lobe melted back into Canada shortly before 11,000 yr BP and vegetation invaded the deglaciated terrain. Weathering, mass-wasting, and fluvial-transport processes have dominated the landscape for the past 10,000 years. This report presents selected analyses for lodgement-till samples that were collected in the Clear Lake 15' quadrangle (see figure 2) during geologic mapping of the Port Townsend 1:100,000 sheet (see Whetten, Dethier, and Carroll, 1979; 1980; Dethier,

**** Figure 2 near here ****

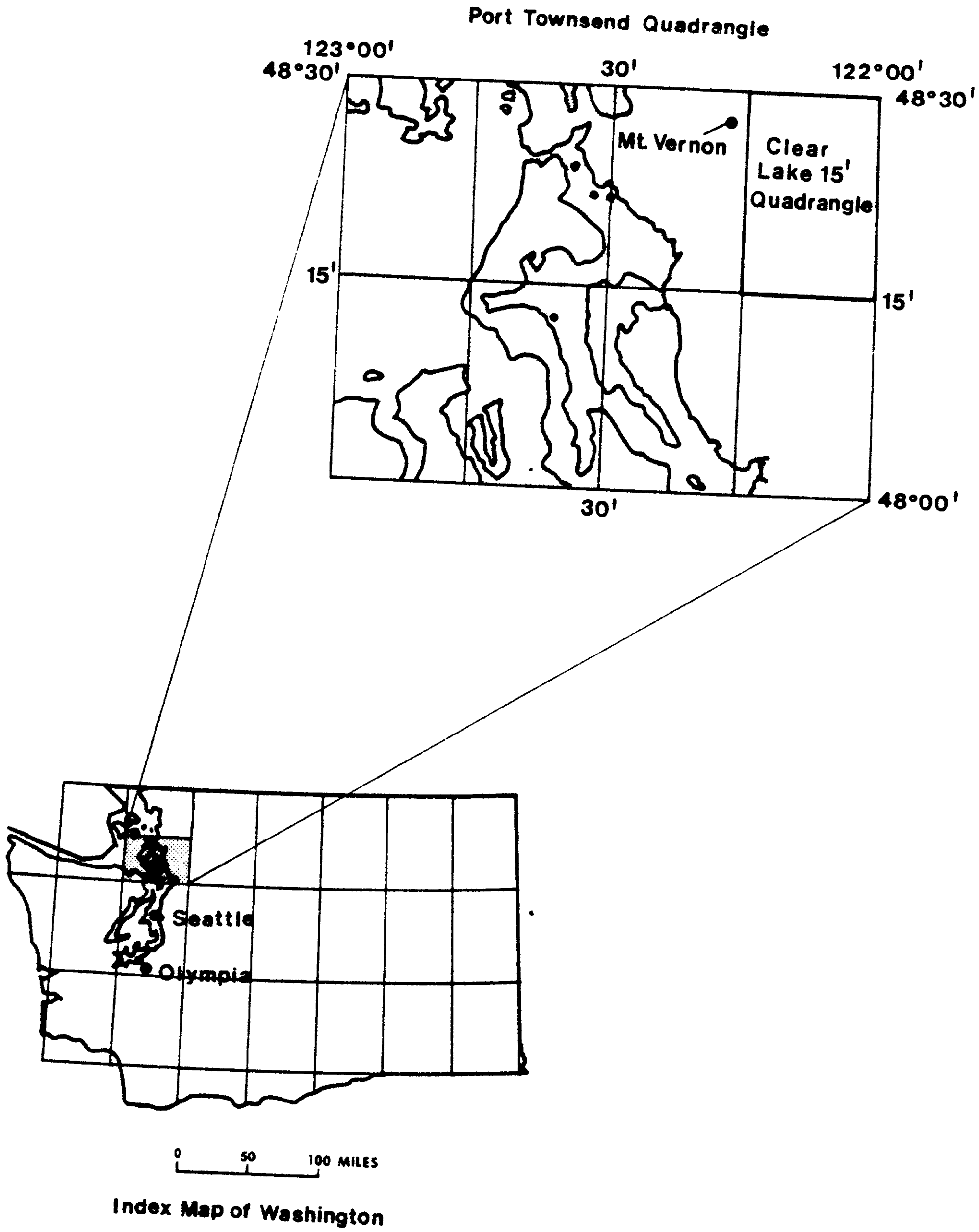


Figure 1.--Map of northwestern Washington, showing location of the Port Townsend 1:100,000 quadrangle, and the Clear Lake 15' quadrangle.

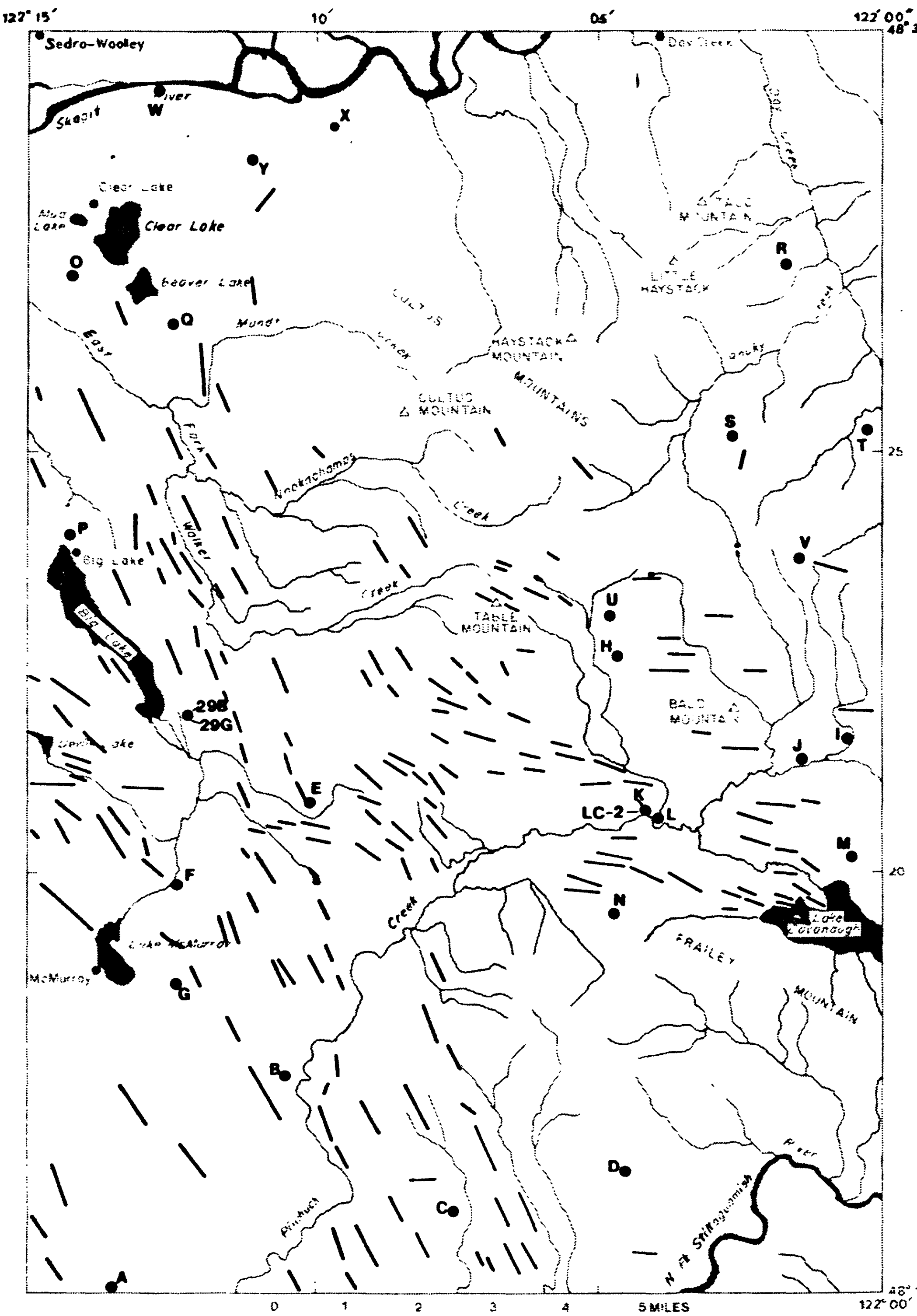


Figure 2.--Place names, sample locations, and drumlinoid features (dash), Clear Lake quadrangle, Washington.

Whetten, and Carroll, 1980, and Dethier and Whetten, 1980). Analyses provide preliminary data on the texture and composition of the most common surficial deposit in the Cascade foothills, an area experiencing rapid development from the expansion of urban and suburban areas in the Puget lowland.

ACKNOWLEDGMENTS

Tim Heironimus and Emilio "Pancho" Gonzales collected many of the till samples and aided in their analysis and Linda Reinink-Smith and Jeff Sprague performed the textural analyses and Jeff Hartley assisted in x-ray diffraction analysis.

SETTING

Location, Climate, and Topography

The Clear Lake quadrangle is located in the foothills of the North Cascade Range between the Skagit and North Fork Stillaguamish Rivers. Sedro Woolley (pop. = 3705), in the northwest portion of the sheet (figure 2), and Mount Vernon (pop. = 7921; figure 1), located 9 km west of the quadrangle, are the largest incorporated towns in the area (U.S. Bureau of the Census, 1971). Agriculture, logging, and tourism are the principal industries in the Sedro Woolley and Mount Vernon areas, but logging provides the main economic base for most of the Clear Lake quadrangle because prime agricultural land is largely confined to the extreme north and northwest portions of the map area (Ness, Buchanan, and Richins, 1960).

Climate is mild with cool, wet winters and warm, drier summers. Mean annual precipitation varies from about 1000-mm near the western border of the area, to more than 3500-mm at higher elevations in the eastern part of the map area (Drost and Lombard, 1978). About 75 percent of the precipitation falls during the winter period (October-March) and snow reaching depths of two meters or more persists for several months above an elevation of 800 m. Average annual temperature in the valley areas is about 10°C (Drost and Lombard, 1978). Drost and Lombard (1978) provide a comprehensive review of surface and ground-water resources for the northern part of the map area, which drains into the Skagit River. The Lake McMurray and Lake Cavanaugh basins drain south into the Stillaguamish River.

The Clear Lake area is hilly to mountainous, but includes floodplains at the north and south ends of the map area, and a narrow trough which runs south from Sedro Woolley. Topography in the mountainous areas is steep and rugged, and the hilly areas are dissected by deep channels cut into till or bedrock. Frederick (1980) shows that most of the natural slopes exceed 30 percent. A strong topographic "grain", marked by elongate ridges (see figure 2) and linear troughs, trends NNW in much of the map area; east-trending ridges and peat-filled troughs extend from the Devils Lake area to east of Lake Cavanaugh, reflecting structural control by the Devils Mountain fault (Whetten, 1978), and erosion by the continental ice-sheet.

With the exception of a small area near Table Mountain, all of the original old-growth forest in the area has been cut, and vegetation types largely reflect the age of the logging. Brushy vegetation of alder, maple, and willow species dominate the recent cuts, while fir, hemlock, and thick understory vegetation are common in older logged areas. More detailed discussion of the forest communities present in the Clear Lake area can be found in Franklin and Dyrness (1973).

Geology

Bedrock geology of the North Cascade Range has been reviewed by Misch (1966; 1977) and Miller (1979); Whetten and others (1980) have reinterpreted the geology of the western North Cascades and adjacent San Juan Islands on the basis of recent mapping and dating of the bedrock units. The bedrock geology of the Clear Lake quadrangle (cf, Whetten, Dethier, and Carroll, 1980; Dethier and Whetten, 1980) and the North Cascades exposes a complex sequence of thrust-bound upper Paleozoic through Jurassic terranes which include rocks from ocean-floor, island-arc, and continental-margin settings. These rocks are metamorphosed to greenschist, and, in places, blueschist facies; associated ultramafic rocks are completely serpentinized. More gently folded Early Eocene to Oligocene terrestrial and shallow-marine sandstone and conglomerate crop out in the west and southwest portions of the Clear Lake quadrangle, and are cut by shallow felsic intrusives. Northwest-trending high-angle faults and the east-trending Devils Mountain fault zone cut the Tertiary rocks and the older metamorphic rocks. Figure 3 shows the general distribution of bedrock and till cover in the Clear Lake area. Table 1 indicates the dominant

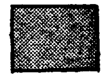
**** Figure 3 near here ****

lithologies in the bedrock units. Detailed descriptions of the bedrock units and structural relations may be found in the references cited above.

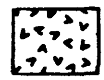
**** Table 1 near here ****

Deposits of the Fraser (late Wisconsinan) Glaciation, latest Pleistocene and early Holocene landslides, and Holocene alluvial fill dominate the surficial geology of the Clear Lake area. In other areas of northwest Washington and southern British Columbia, strong evidence exists for at least one older

EXPLANATION FOR FIGURE 3

Qvt - till cover 

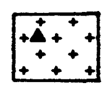
BULSON CREEK UNIT - conglomerate, lithic sandstone, and siltstone of Late Eocene to Early Oligocene age. The unit unconformably overlies or is in fault contact with Pzi, Volcanic Sandstone, Trafton, and Chuckanut units. B

TR RHYOLITE UNIT - ash-flow tuffs and flows, with minor andesite flows, and probable intrusive rhyolite of Tertiary age intruding and interbedded with Chuckanut Formation. 

CHUCKANUT FORMATION - feldspathic sandstone, siltstone, and coal of Eocene age in fault contact with Haystack and Bulson Creek units; interbedded with Tertiary rhyolite. C

VOLCANIC SANDSTONE UNIT - a tectonic mixture of medium-grain sandstone, greenstone, and minor fine-grain sandstone, siltstone, argillites, and chert; Mesozoic in age. Unit is in fault contact with Haystack, Shuksan, Trafton, and Bulson Creek units. V

HAYSTACK THRUST PLATE - a tectonic mixture of greenstone, metasedimentary rocks, and serpentinite of Jurassic age in fault contact with Tertiary and pre-Tertiary units and locally overlies rocks of the Shuksan unit. H

SP SERPENTINITE - widespread within the Haystack Thrust Plate; separates blocks of different lithologies along faults. 

SHUKSAN UNIT - composed of Darrington Phyllite and Shuksan Greenschist, protolith presumed to be Jura-Cretaceous. Unit is in fault contact with Haystack and Chuckanut units. S

TRAFTON FORMATION - a textonic mixture of chert, argillite, greenstone, and limestone, mid-Paleozoic to Jurassic. Fault contact with other units is inferred. T

PZI UNIT - mid-Paleozoic coarse-grained intrusive ranging from pyroxene gabbro to hornblende-biotite quartz diorite. Unit unconformably underlies or is faulted against Bulson Creek. Fault contacts are inferred with Trafton and Volcanic Sandstone units. 

fault or unconformity

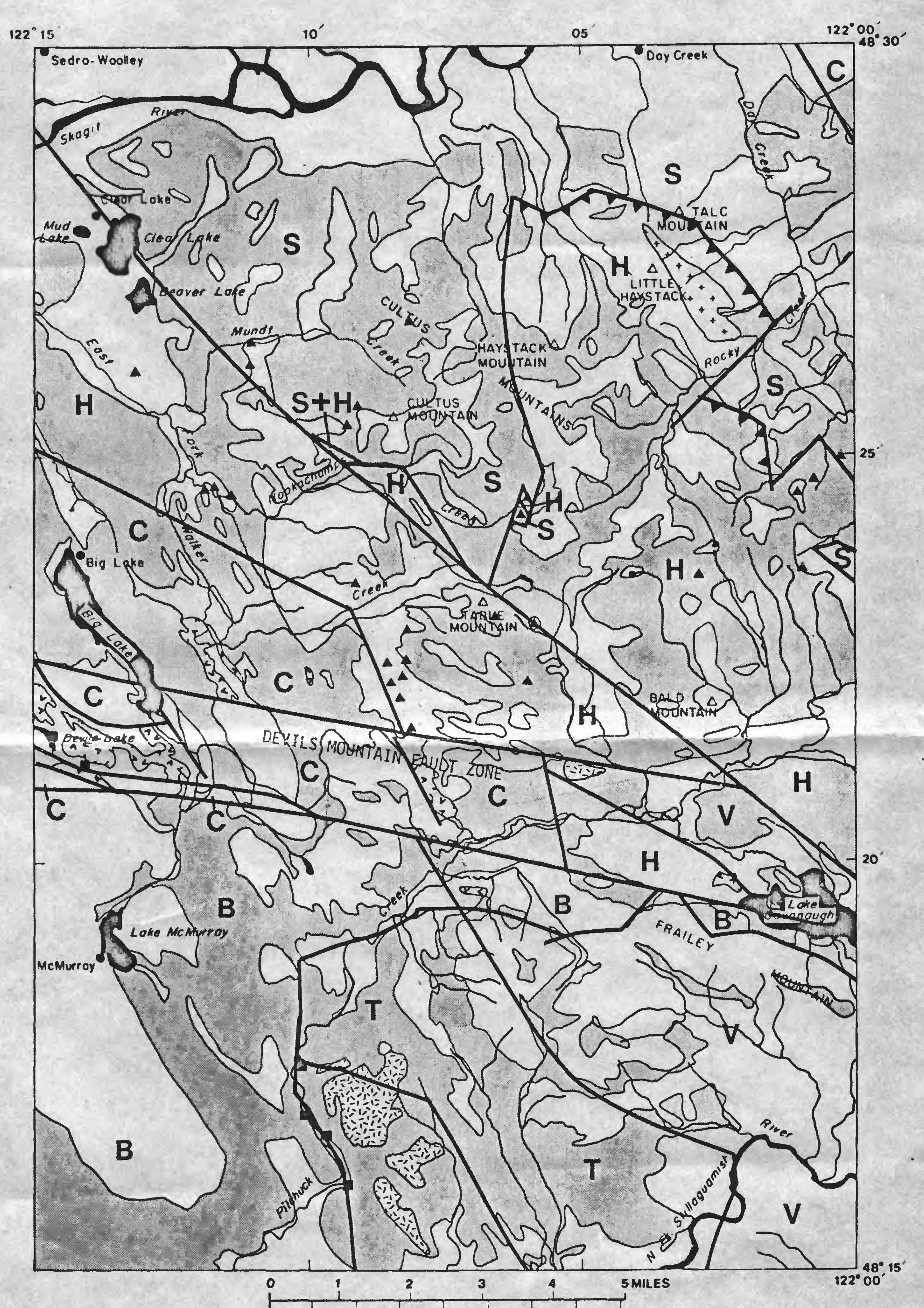


FIGURE 3.--Bedrock geology and till cover, Clear Lake quadrangle, Washington (modified from Whetten et al, 1980).

TABLE 1.--Dominant lithologies and mineralogy[1] of bedrock units in the Clear Lake quadrangle, Washington

Bedrock unit	Dominant lithologies	Mineralogy
Bulson Creek unit	conglomerate, lithic sandstone, siltstone	major: felsic volcanic fragments, quartz, calcite (replacement), clay rich sedimentary clasts minor: biotite, muscovite, kaolinite, smectite, chlorite, opaques
Tertiary Rhyolite unit	ashflow tuffs and flows, minor andesite flows	major: devitrified glass, plagioclase, quartz minor: calcite, opaques, chlorite, apatite, epidote, potash feldspar, zircon, zeolite
Chuckanut Formation	feldspathic sandstone, siltstone, coal	quartz, plagioclase, potash feldspar, lithic fragments composed of quartzite, chert, albite-quartz-muscovite schist, sericite, phyllite, altered volcanic fragments, kaolinite, smectite, chlorite
Volcanic Sandstone and Greenstone unit	medium-grain sandstone	major: felsic volcanic fragments with plagioclase phenocrysts minor: lawsonite, prehnite
	greenstone	major: plagioclase, calcite, quartz, prehnite minor: hornblende, chlorite, epidote, biotite, lawsonite
	minor fine-grain sandstone, siltstone, argillite, and chert	
Haystack unit	greenstone	pyroxene, hornblende, calcic plagioclase, albite, actinolite, chlorite, quartz, epidote, clinozoisite, sericite, lawsonite, pumpellyite, ilmenite, leucoxene, sphene, iron and titanium oxides, stilpnomelane

TABLE 1.--Dominant lithologies and mineralogy[1] of bedrock units in the Clear Lake quadrangle, Washington -- Continued

Bedrock unit	Dominant lithologies	Mineralogy
Haystack unit - continued	metasediments (slate, argillites, metagraywacke)	albite, quartz, muscovite, graphite, chlorite, actinolite, clasts and lithic fragments, stilpnomelane
	serpentinite	antigorite, minor chrysotile, talc, chlorite, tremolites, opaques, stilpnomelane
	metaplutonic, metacherts	
Shuksan unit	Darrington Phyllite	major: quartz, albite, muscovite minor: chlorite, graphite, calcite (aragonite), actinolite, opaques accessories: epidote, lawsonite, sphene
	Shuksan Greenschist	major: quartz, albite, actinolite, chlorite, epidote minor: sphene, graphite, stilpnomelane, biotite accessories: carbonate, opaques, rutile
Trafton unit	greenstone	major: plagioclase, clinopyroxene, calcite minor: opaques, chlorite, pumpellyite, prehnite
	chert, argillite, siltstone, limestone	
Coarse-Grained Intrusive unit (Pzi)	pyroxene gabbro, quartz-diorite, gneiss	major: plagioclase, hornblende, clinopyroxene, quartz minor: opaques, chlorite, epidote, pumpellyite, prehnite, biotite, lawsonite

1/ modified from Misch (1966) and Whetten et al (1980).

glaciation (Easterbrook, 1968; Alley, 1979), and deposits from at least three pre-Fraser glaciations are found in the southern Puget Sound region (Armstrong et al, 1965). There is no direct evidence for pre-Fraser glaciation in the Clear Lake quadrangle, but it is likely that some of the till layers reported in the subsurface (Drost and Lombard, 1978) were deposited by earlier glaciations. Till exposed at the surface was deposited during the Vashon Stade of the Fraser Glaciation, probably between about 18,000 and 13,500 yr BP (Alley and Chatwin, 1979). Heller (1978; 1980) estimates that at least 1500 m of ice covered the Skagit River area during the Vashon maximum and documents how the Vashon ice overrode proglacial waterlaid deposits as it flowed first east up the Skagit Valley, and then south over the Cascade foothills as the ice thickened. Ice flow in the Clear Lake area produced ridges aligned both north-south and east-west (figure 2), probably reflecting the flow of basal ice and bedrock structure. Erratic granitic boulders, derived from the Coast Range of British Columbia, are present on the highest peaks (el. 1240 m) in the Clear Lake area.

Large landslides involving bedrock and glacial materials occurred as the Vashon ice thinned over the Cultus Mountains (Whetten, Dethier, and Carroll, 1980). Glacier ice and ice-marginal streams persisted longer in the Big Lake trough, along Day Creek, and in the Skagit River valley, but were gone sometime before about 13,500 yr BP, when marine waters invaded the isostatically depressed area to a relative elevation of more than 80 m. Glaciomarine drift, a silt-rich sediment which locally resembles till (Easterbrook, 1968) was deposited at lower elevations in the northwest corner of the study area before isostatic rise of the land brought it above sea level. Fluvial sedimentation commenced in the Skagit and Stillaguamish River valleys and along smaller drainages in the latest Pleistocene, and has persisted through the Holocene epoch. Till and landslide deposits thus dominate the surficial geology of the Clear Lake quadrangle, but at lower elevations recessional outwash and glaciomarine deposits are exposed, and alluvial deposits predominate in the river valleys.

METHOD

Lodgement till samples were collected from 28 localities chosen to reflect the wide range of bedrock types which underlie the Clear Lake quadrangle (see Figure 3). Unoxidized samples were collected where possible and all samples were analyzed for texture, clast lithology, and clay mineralogy. The volume percent of matrix (<2-mm) and cobbles (>64-mm) was estimated for at least a 5 m^2 area of each exposure. 100 clasts with intermediate axes larger than 20-mm were collected on a "first-touched" basis at each exposure; lithologies were classified following Heller (1980). About one kilogram of matrix material was collected at each outcrop and quartered several times after mixing. A 100 gram subsample, to which sodium hexametaphosphate was added to promote dispersion, was ultrasonically disaggregated and wet-sieved to obtain the sand fraction. The clay fraction was separated by centrifugation, using time and speed data of Jackson (1974). The silt fraction in the matrix was determined by difference after measuring the sand and clay fractions.

The clay fraction (<2-μm) was suctioned through a porous ceramic tile to obtain an oriented mount for x-ray diffraction (XRD) analysis. Each sample was x-rayed untreated, ethylene-glycol solvated, heated to 300 and 500°C, and DMSO-treated to identify kaolinite (Abdel-Kader, Jackson, and Lee, 1978). Additional treatments, including K-saturation and analysis of the fine clay fraction, were performed on a limited number of samples. All XRD analyses were done with a G.E. XRD-5 using Ni filtered Cu radiation and a scanning rate of $2^{\circ}2\theta$/min.

Field estimates of the matrix and cobble percentages are probably accurate within 20 percent, but the estimated variation in large outcrops was as great as 30 percent. We did not test "within-outcrop" variability of clast lithologies, but Heller (1978) reports that it was less than 15 percent at sites he examined immediately north of the Clear Lake area. Pevear (written communication, 1980) reports that textural analyses of different splits of a single matrix sample give a precision of better than 10 percent; matrix textures are more variable at an exposure, but probably show less variation than cobble percentages (see, for instance, May and Dreimanis, 1976). It should be noted that many of the lithologic classifications overlap, for instance, phyllite and fine dark metamorphics, and that assignment of clasts to local or regional bedrock units is often difficult. Field and laboratory data are summarized in the following section, and are listed in Appendices A through D.

DATA

Roadcut and gravel-pit exposures, and subsurface records indicate that lodgement till forms a discontinuous mantle 4 to 10 m thick in the Clear Lake area; thicknesses commonly exceed 10 m along deeply incised stream channels. Most till is nonstratified, generally nonsorted, but includes gravel lenses, and is oxidized to depths of 75 to 120-cm. Thick exposures may display crude, disrupted stratification, low-angle thrust faults, and contorted silt and sand lenses, particularly near contacts with underlying sorted sediments. Thick sections of ablation till are not common in the field area and were not sampled. Abalation till generally forms an oxidized, thin (<1.5 m), discontinuous layer which appears to be less compact, better-sorted, and more sand-rich than lodgement till. Till rich in ultramafic clasts is partly cemented by carbonates, and is completely cemented near the contact with ultramafic bedrock. No till fabrics were measured, but exposures rich in phyllite and other elongate clasts display an apparent near-horizontal fabric oriented south to southeast. Soil horizonation is weakly developed and disturbed by logging in most places so that the organic horizon directly overlies a truncated incipient B-horizon. Unoxidized till is grey and compact, and is often separated from the oxidized layer by a sheeted zone as much as 30-cm thick and subparallel to the surface topography. The oxidized soil zone may include ablation till, colluvial debris, and sorted and nonsorted materials deposited during or after ice recession.

Texture

The tills sampled in the Clear Lake quadrangle are gravelly silt-rich sands, and the matrix generally includes 5 to 15 percent clay. Field estimates and laboratory analyses of till textures are listed in Appendices A and B. Figures 4 and 5 show field estimates of percent matrix (<2-mm) and percent cobbles (>64-mm) for 25 samples. The Clear Lake sample sites average about 70 percent matrix, and about 5 percent cobbles; about 25 percent of the clasts are between 2 and 64-mm in diameter. While the largest erratics noted near the sample sites generally had intermediate axes of about 3 m, greenstone boulders in the northern half of the quadrangle are commonly larger than 5 m, and intermediate diameters as large as 15 m have been noted.

**** Figures 4 and 5 near here ****

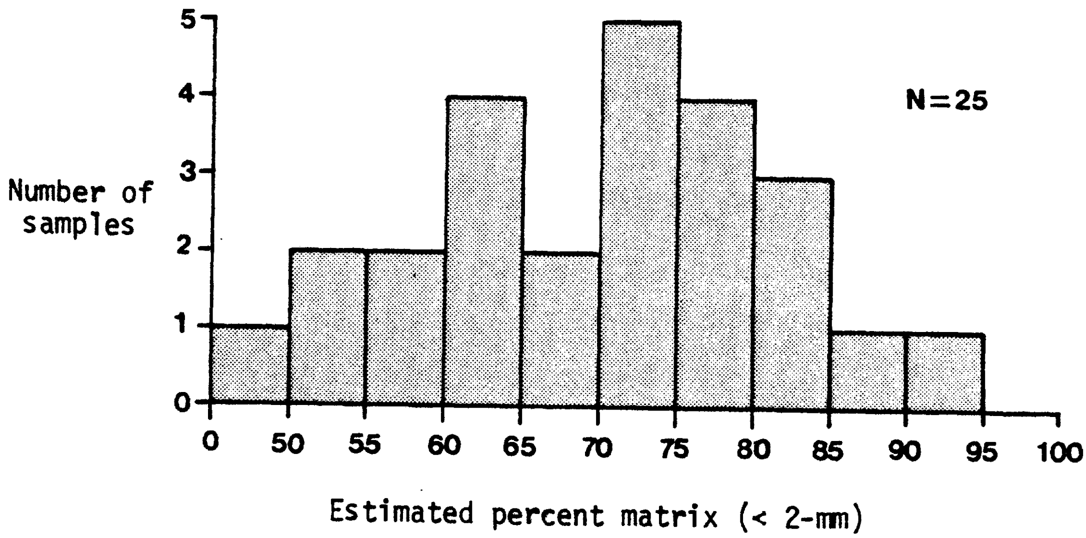


Figure 4.--Estimated percent matrix in 25 till exposures in the Clear Lake quadrangle, Washington.

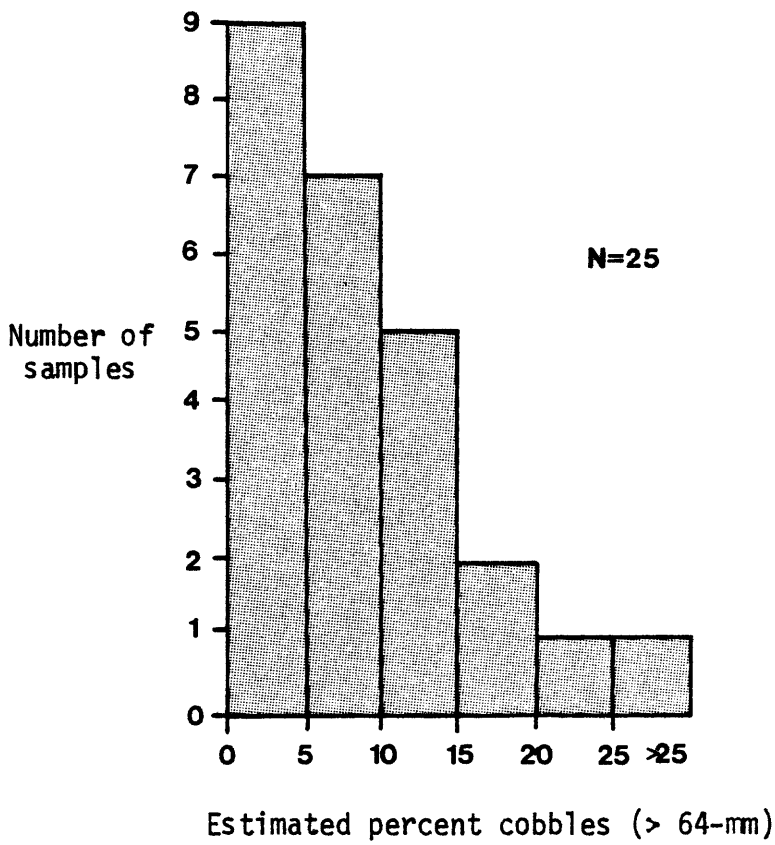


Figure 5.--Estimated percent cobbles in 25 till exposures in the Clear Lake quadrangle, Washington.

Laboratory textural analyses for the matrix (<2-mm) fraction of 28 samples are plotted in figure 6. From 80 to more than 90 percent of each sample is sand and silt. Textural data for individual samples are listed in Appendix B.

**** Figure 6 near here ****

Till sample "O" contains an unusually high percent of silt and clay, and field relationships suggest that it may be glaciomarine drift (Easterbrook, 1968), or till reworked by marine waters. Till sample "X" is rich in sand and was collected less than one kilometer south of the Skagit River valley. The other till samples fall within a narrow field on the triangular diagram. The fraction of clay in each sample is unrelated to the percent of matrix, but silt and sand percentages each show significant correlations (figure 7). Although the data show considerable scatter as the matrix percent increases, the silt fraction increases and the sand fraction decreases.

**** Figure 7 near here ****

Mineralogy of the clay-sized fraction

The predominant minerals in the clay fraction of Clear Lake tills are chlorite, smectite, mica, kaolinite, and minor amphibole (table 2). Significant amounts of talc, serpentine, and stilpnomelane are present in samples collected in the northeast part of the study area. Mixed layer chlorite-vermiculite and chlorite-smectite are present in most oxidized samples.

**** Table 2 near here ****

Figure 8 shows typical patterns for three of the samples. Sample "O" is from the northwest portion of the Clear Lake area and shows a pattern common in till and glaciomarine samples from the Puget lowland (Pevear, written communication,

**** Figure 8 near here ****

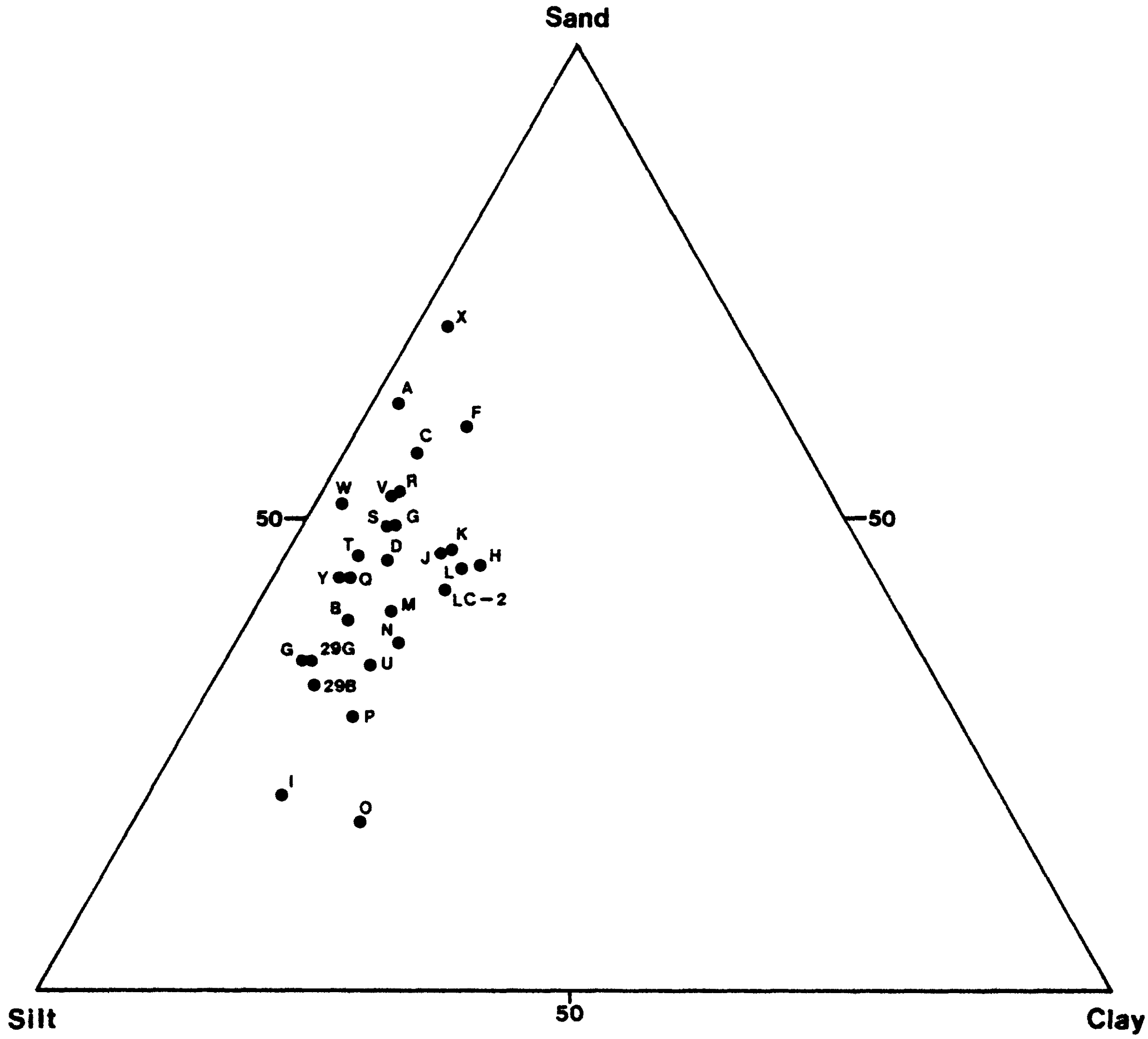


Figure 6.--Triangular plot of clay-silt-sand percent in the matrix (< 2-mm) of 28 till samples from the Clear Lake quadrangle, Washington.

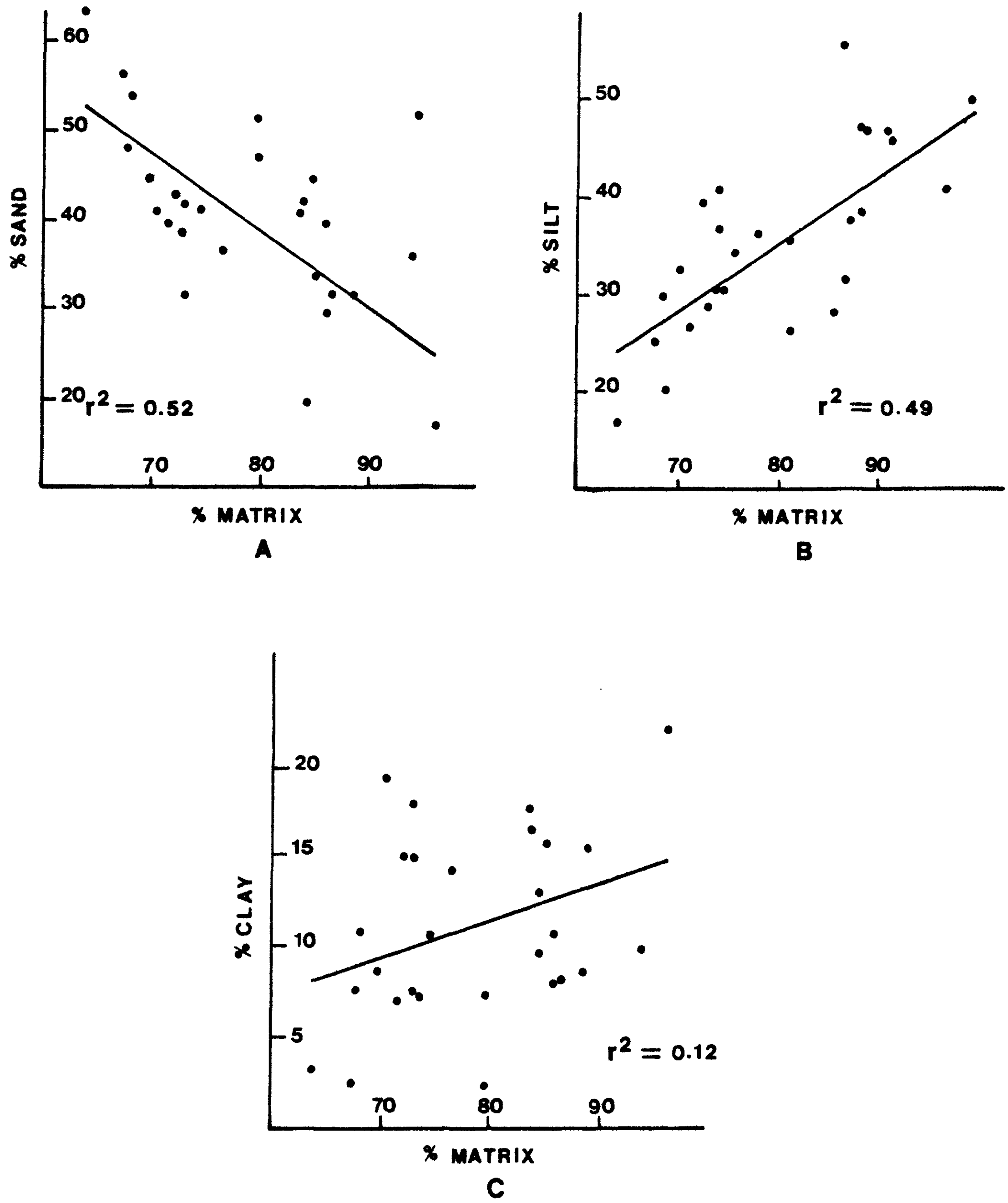


Figure 7.--Relationship between percent matrix (laboratory) and (A) percent sand, (B) percent silt, and (C) percent clay in 28 till samples from the Clear Lake quadrangle, Washington. The variance explained by the regression line is given as r^2.

TABLE 2.--Frequency of major (M=>25%), minor (m=10-25%), and trace (t=<10%) minerals[1] in the clay fraction of 28 samples from the Clear Lake quadrangle, Washington.

	M	m	t
Chlorite	22	4	1
Smectite	15	8	4
Kaolinite	9	12	2
Mica	6	15	7
Chlorite-Vermiculite	3	8	5
Serpentine	3	6	3
Talc	1	7	13
Amphibole	0	3	21
Quartz	0	3	14
Feldspar	0	0	13
Stilpnomelane	0	0	11

1/ These data were obtained by making visual estimates of peak intensities on the diffraction patterns.

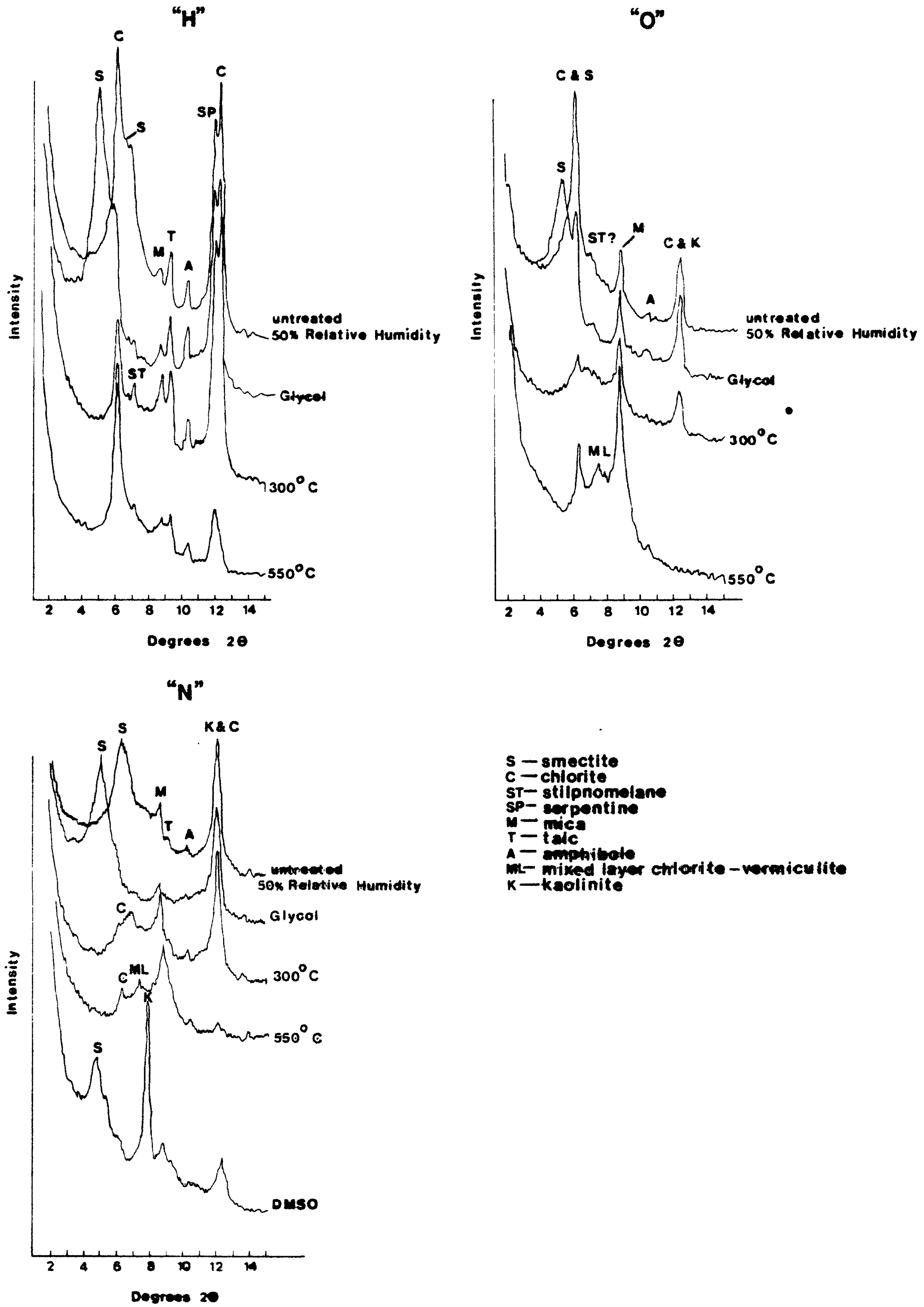


Figure 8.--Typical x-ray diffractograms for till sample from the lowland ("O"), upland ("H"), and the southwest portions ("N") of the Clear Lake quadrangle, Washington.

1980; Hepp, 1972; Heller, 1980). The major minerals in this untreated sample are mica, chlorite, and smectite, but after heating to 550°C, the sample developed a mixed layer mica-chlorite peak near $7^{\circ}2\theta$. Prior to heating, this sample must have contained mixed layer chlorite-vermiculite, which would not be detectable in the other patterns, because both of these types of layers have the same spacing and are unaffected by glycol treatment. Only after heating do the vermiculite layers collapse to produce the characteristic mixed-layer peak near $7^{\circ}2\theta$. Sample "H" (figure 8) is characteristic of the Cascade foothills in the eastern part of the study area, and contains major amounts of serpentine, minor talc, and traces of stilpnomelene as well as chlorite, smectite, mica, and amphibole. The smectite displays a spacing near $7^{\circ}2\theta$ in the untreated sample because it is Na-saturated due to the sodium hexametaphosphate ("Calgon") used to disperse the sample and therefore has only one water layer. Note the characteristic increase in intensity of the chlorite peak at $6^{\circ}2\theta$ and the persistence of the serpentine peak after heating to 550°C. Sample "N" is characteristic of the kaolinite-rich south-central part of the study area. The major peaks are due to smectite, which expands with glycol treatment, and kaolinite, which expands to near $8^{\circ}2\theta$ (from near $12^{\circ}2\theta$ in the untreated sample) with DMSO treatment. Minor amounts of chlorite, mica, and mixed layer chlorite-vermiculite and traces of talc and amphibole are also present.

Complete clay mineralogy for each of the till samples is listed in Appendix C. Quartz and feldspar are generally present in the clay fraction of tills; however, because these minerals are also present in the porcelain plate upon which the clay is mounted, notations in table 2 and Appendix C are significant only if quartz and feldspar are absent.

The semiquantitative data shown in Appendix C were obtained by making visual estimates of peak intensities on the diffraction patterns. The strongest peaks were called major constituents, peaks of lesser intensity were attributed to minor constituents and barely perceptible peaks were ascribed to trace constituents. Actual percentages were not determined, but major constituents probably make up >25 percent of the sample, minor constituents 10-25 percent, and trace constituents <10 percent. This method can be understood by comparing the diffractograms in figure 8 with the abundance data for the same samples given in Appendix C.

Clast Lithologies

Rock types present in a sample of about 100 clasts from each of 25 till exposures are listed in Appendix 3, and are summarized in table 3. Greenstone/ greenschist, phyllite, and fine-grained dark metamorphic rocks predominate in most samples, but ultramafic rocks, rhyolite, and other lithologies are important constituents of individual samples. In general, the clasts are subangular to subround, and subspherical to subelongate (see Appendix A), but samples vary over a wide range of shapes.

**** Table 3 near here ****

The frequency of greenstone and phyllite clasts suggests the dominance of local rocks, but table 3 also demonstrates the important contribution of resistant "regional" lithologies like granite and schist. Interpretation of the distribution of clast lithologies is discussed in the following section.

TABLE 3.--Summary of clast lithologies[1] from 25 till exposures in the Clear Lake quadrangle, Washington

Rock type	Percent of all clasts
Greenstone/greenschist	31
Phyllite	15
Fine dark metamorphic	7
Vein quartz	5
Quartzite	4
Granitic	4
Ultramafic	3
Sandstone	3
Schist	3
Quartzite, brown	2
Rhyolite	2
Andesite	2
Metavolcanic	2
Argillite	2
Porphyritic andesite	2
Gabbro	2
Chert	1
Dark volcanic	1
Shale	1
Other (Diorite, gneiss, talc-schist, etc.)	8

1/ About 2500 clasts >20-mm were counted

DISCUSSION

The till samples from the Clear Lake quadrangle contain more silt than alpine tills (Mills, 1977), slightly less clay than "lowland" tills, and about 20 percent less silt than many glaciomarine samples from the northern Puget lowland (Pevear and Thorson, 1978). While these generalizations about texture are based on a limited sample, the textural data, used with data on till-bulk density (Easterbrook, 1964), strength, and permeability, help provide data to aid in analysis of waste-disposal sites, foundation strength, aggregate suitability, and other engineering applications.

The influence of local bedrock and ice-flow direction is strongly reflected by the clay mineralogy of lodgement tills in the Clear Lake quadrangle. This influence contrasts with the more regional nature of minerals and clasts found in Puget lowland till and glaciomarine drift. The occurrence of significant amounts of serpentine and talc in some till samples is somewhat unusual, and suggests that asbestiform minerals (Rohl, Langer, and Selikoff, 1977; Schreier and Taylor, 1980) may be present in these samples.

Texture

The matrix texture of lodgement till is a function of the surficial and bedrock units overridden by temperate glacial ice, abrasion of larger particles into sand, silt, and clay particles, subglacial water conditions, and weathering. Before the Fraser Glaciation, surficial deposits were thicker and finer grained in the Puget lowland than in the adjacent Cascades (Crandell et al, 1965). Bedrock rich in silt and clay-sized material is most common on the western fringe of the North Cascades. These two factors made large quantities of fine sediment in lowland areas available to the advancing Puget lobe. However, the Puget lobe overrode proglacial deposits sorted by ice-marginal streams, and ponded by glacier ice, so a wide range of textures was incorporated into the basal ice-zone.

Published granulometric analyses of tills are not common in the geologic literature of western Washington and southwestern British Columbia, though considerable data may reside in the files of private consultants. Data from mountainous zones glaciated by the Cordilleran ice are particularly sparse. In figure 9 we have compiled data for Puget lowland till, till deposited by Cascade alpine glaciers, and some "typical" till analyses from the midwest and eastern United States. The Clear Lake till contains more silt and less clay than most of the other tills, but is finer-grained than the alpine tills reported by Mills (1977).

**** Figure 9 near here ****

Textural differences among tills probably result from the texture of materials overridden by the ice--crystalline rocks by alpine ice, various lithologies by Laurentide ice--but abrasion and hydrologic effects may also be important. Matrix textures show no strong relationship to the texture of bedrock which underlies till exposures in the Clear Lake area. Regression analyses, presented in figure 7, suggest that at the base of the ice a "constant" supply of clay-size material was available to form matrix. Silt and sand are the principal components of matrix-rich till in the Clear Lake area, and both sand and silt are significantly correlated with percent matrix in a till sample, but the process responsible for these relationships is not understood. Pedogenic processes have resulted in a grain size reduction in matrix material since deposition of the till, but effects are minor. No textural "B" horizons have been reported at other sites in the western Cascades (see Bockheim, 1972).

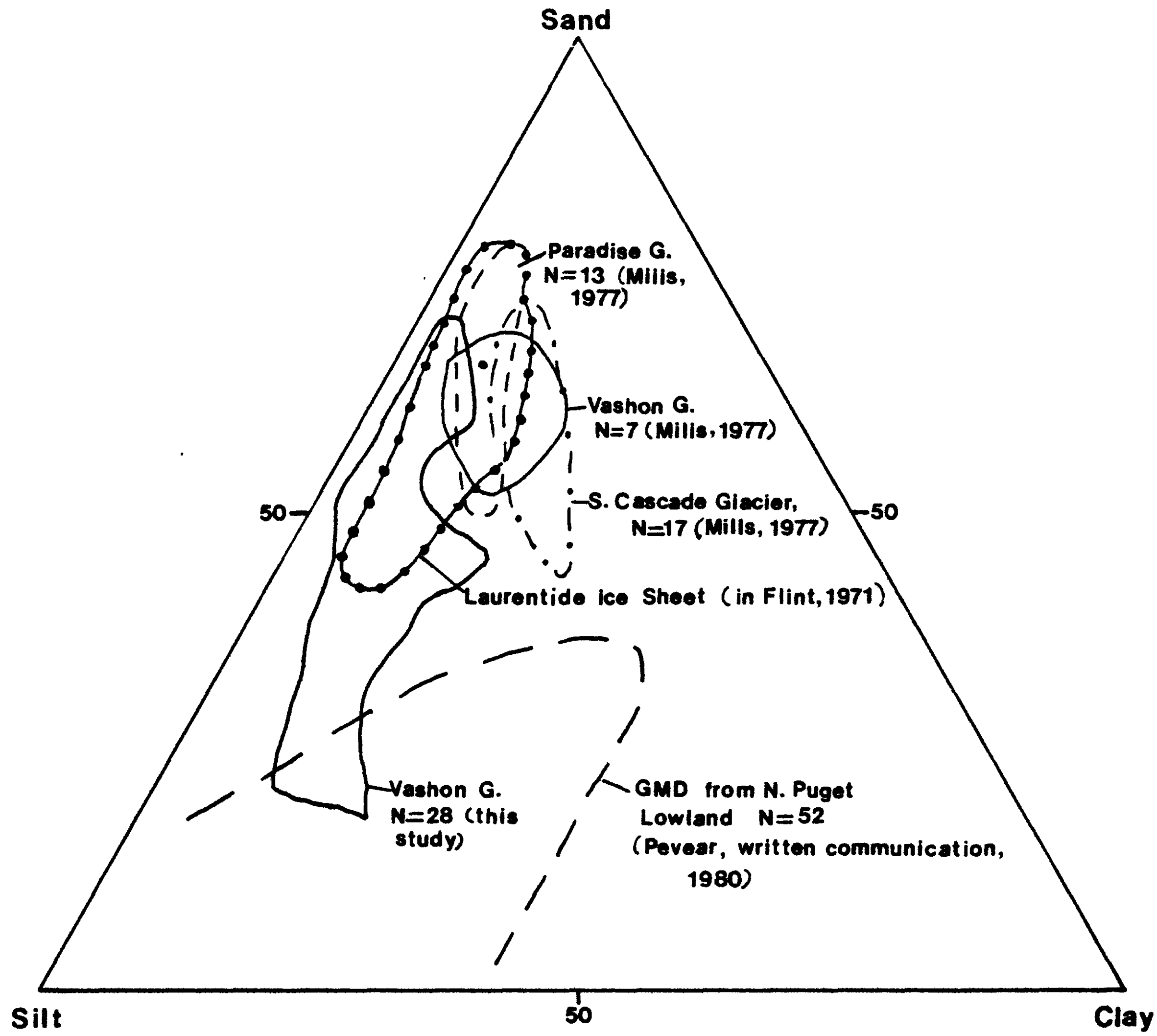


Figure 9.--Textural analyses of matrix from till deposited by Vashon ice, selected alpine glaciers, and the Laurentide ice sheet. Analyses for glaciomarine drift (GMD) deposited near floating ice in the Puget lowland are also plotted.

Lodgement till from the Clear Lake area can be distinguished from glaciomarine drift on the basis of texture (figure 9), but overlap exists, and Clear Lake samples "O" and "I" plot in the glaciomarine field. It is possible that till sample "O", collected in the northwest part of the study area, is actually glaciomarine drift, or lodgement till reworked by marine waters. Till can be distinguished from glaciomarine drift (GMD), in some cases, by geochemical criteria (Pevear and Thorson, 1978), but results are not definitive. Samples of shell-bearing glaciomarine drift from the Clear Lake quadrangle contain slightly more sodium and boron than till samples from the same area, but differences are not statistically significant. Thus the presence of shell material remains the best means of distinguishing till from GMD, but textural criteria provide useful guides in the absence of shells.

Clay Mineralogy

Clay comprises about 10 percent of the till matrix, but, with fine silt, is largely responsible for the compact nature of lodgement till, and contributes to other physical and chemical properties. Some of the clay-fraction minerals (serpentine, talc, stilpnomelane, kaolinite) present in till from the Clear Lake quadrangle are largely derived from local bedrock and provide better indicators of local bedrock composition and ice-flow direction than clasts in the till. The presence of rock units of highly varied mineralogy (Tables 1 & 4) in the Clear Lake quadrangle, each of which contributes a unique suite of minerals to the fine fraction of the tills (Table 4), allows the fine fraction to be used to deduce ice-flow directions and to differentiate lowland-type tills, containing major chlorite, smectite, and mica, from the mineralogically diverse tills of the Cascade foothills.

**** Table 4 near here ****

TABLE 4

Minerals[1] in bedrock units which contribute to the clay fraction of tills

BEDROCK UNIT	MINERALS CONTRIBUTED TO CLAY FRACTION
Bulson Creek unit	smectite, kaolinite, chlorite
Chuckanut Formation	kaolinite, smectite, mica, chlorite
Volcanic sandstone and greenstone unit	chlorite, mica, amphibole
Haystack Unit	
greenstone and metasediments	chlorite, mica, amphibole, stilpnomelane
serpentinite unit	serpentine, talc, chlorite, amphibole
Shuksan Unit	
Darrington Phyllite	mica, chlorite, stilpnomelane, amphibole
Shuksan Greenschist	chlorite, amphibole, stilpnomelane, mica

1/ Underlined minerals are particularly characteristic of or unique to a bedrock unit.

Distribution and ice-flow direction--Chlorite, smectite, mica, and minor amphibole and kaolinite are the principal clay-size minerals in till from the Puget lowland (Pevear et al, unpublished data, 1980; Hepp, 1972; Heller, 1980) and the Clear Lake area. However, many Clear Lake tills contain significant quantities of serpentine, talc, stilpnomelane, and other minerals found only in the Haystack terrane, along its faulted contacts with other lithologic units, and along the Devils Mountain fault zone. Other till samples contain major amounts of kaolinite which is derived from Tertiary sedimentary rocks (Chuckanut Formation and Bulson Creek unit of Lovseth). The Tertiary sedimentary rocks are soft and apparently do not survive transport in the ice (note the absence of sandstone and shale in the data of Table 3 and Appendix D); however, the abundance of kaolinite in many of the tills is compelling evidence that these sedimentary rocks have contributed significantly to the till matrix, since there is virtually no other source of this mineral.

Figures 10a through 10d show the distribution of selected minerals (Table 4) in the clay-size fractions of tills from the study area. Talc, serpentine, and stilpnomelane are found primarily in Haystack rocks and, to a lesser extent, along the Devils Mountain fault zone. Mica is most abundant in the Darrington Phyllite and kaolinite is unique to the Tertiary sedimentary rocks. Other minerals, abundant in the tills, are not shown in figure 10 because they are not characteristic of individual bedrock units and are present in most of the samples. These include chlorite and smectite which, with mica and minor kaolinite and amphibole, are also the minerals most common in the more homogeneous lowland tills.

**** Figures 10a through 10d near here ****

The mineralogy of the tills is strongly controlled by bedrock. All samples containing major (>25 percent) mica (figure 10a) occur in the northern

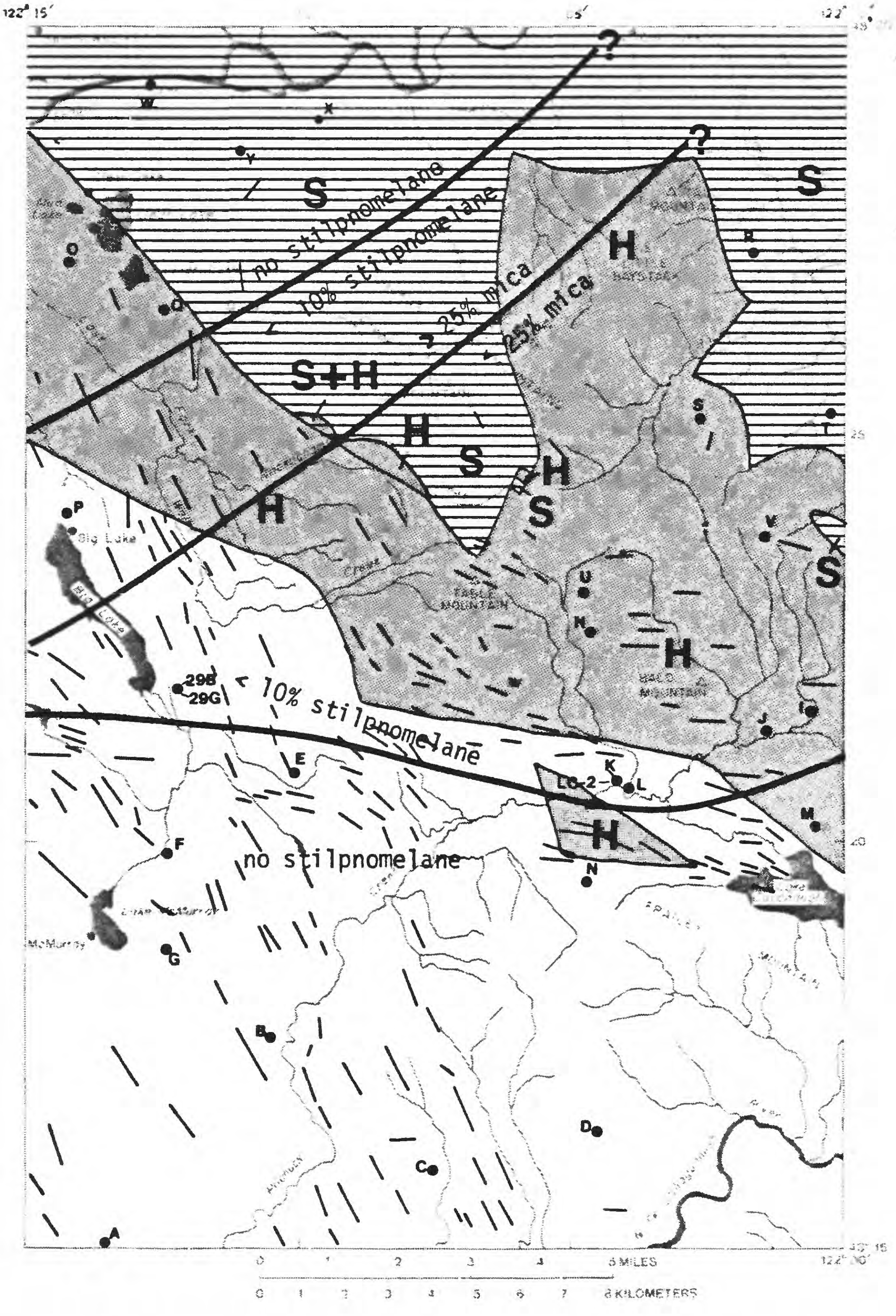


Figure 10a.--Distribution of mica and stilpnomelane in the < 2-μm fraction of till from the Clear Lake quadrangle, Washington. Haystack unit is shaded, Shuksan unit is lined.

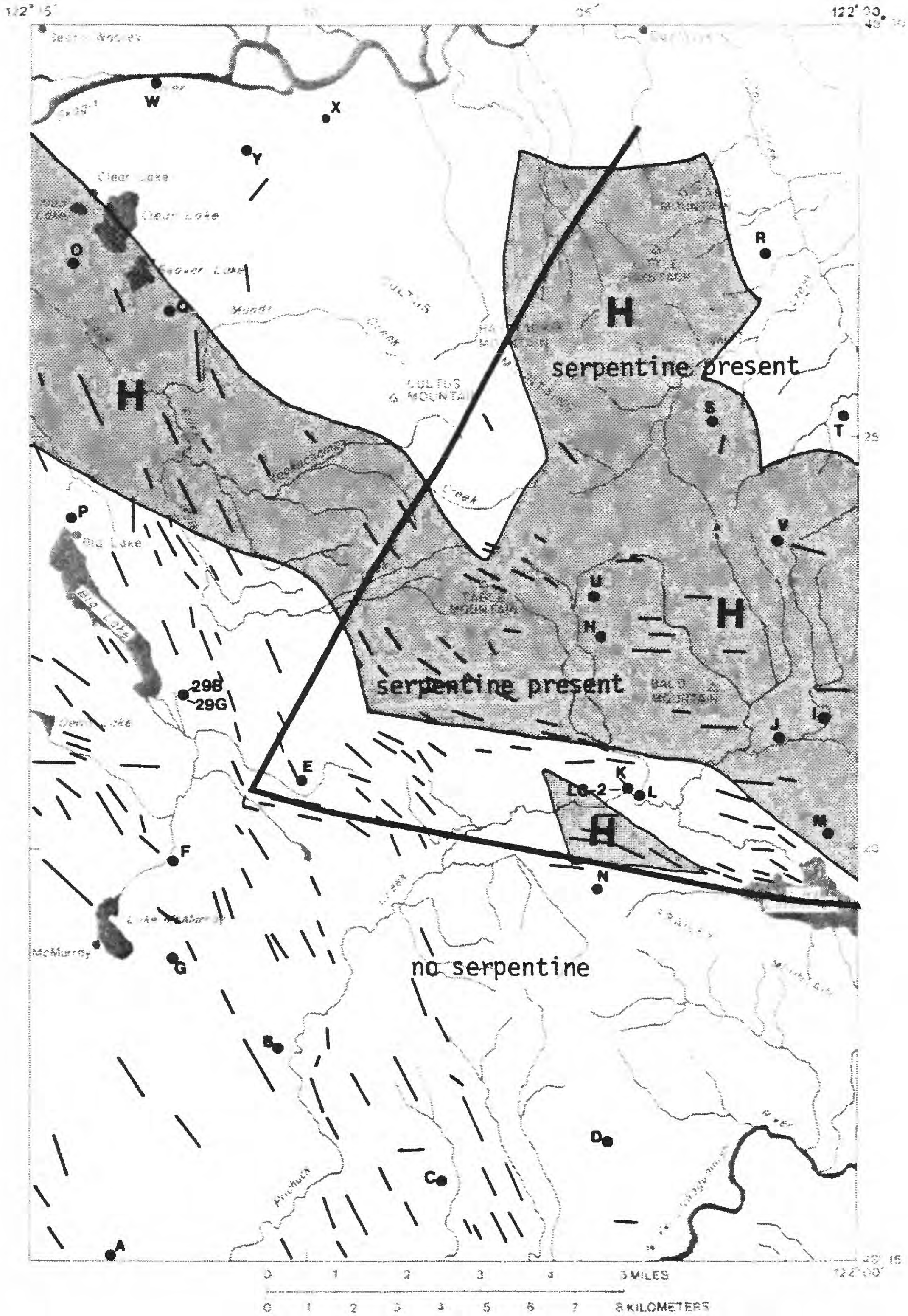


Figure 10b.--Distribution of serpentine in the < 2-μm fraction of till from the Clear Lake quadrangle, Washington. Haystack unit is shaded.

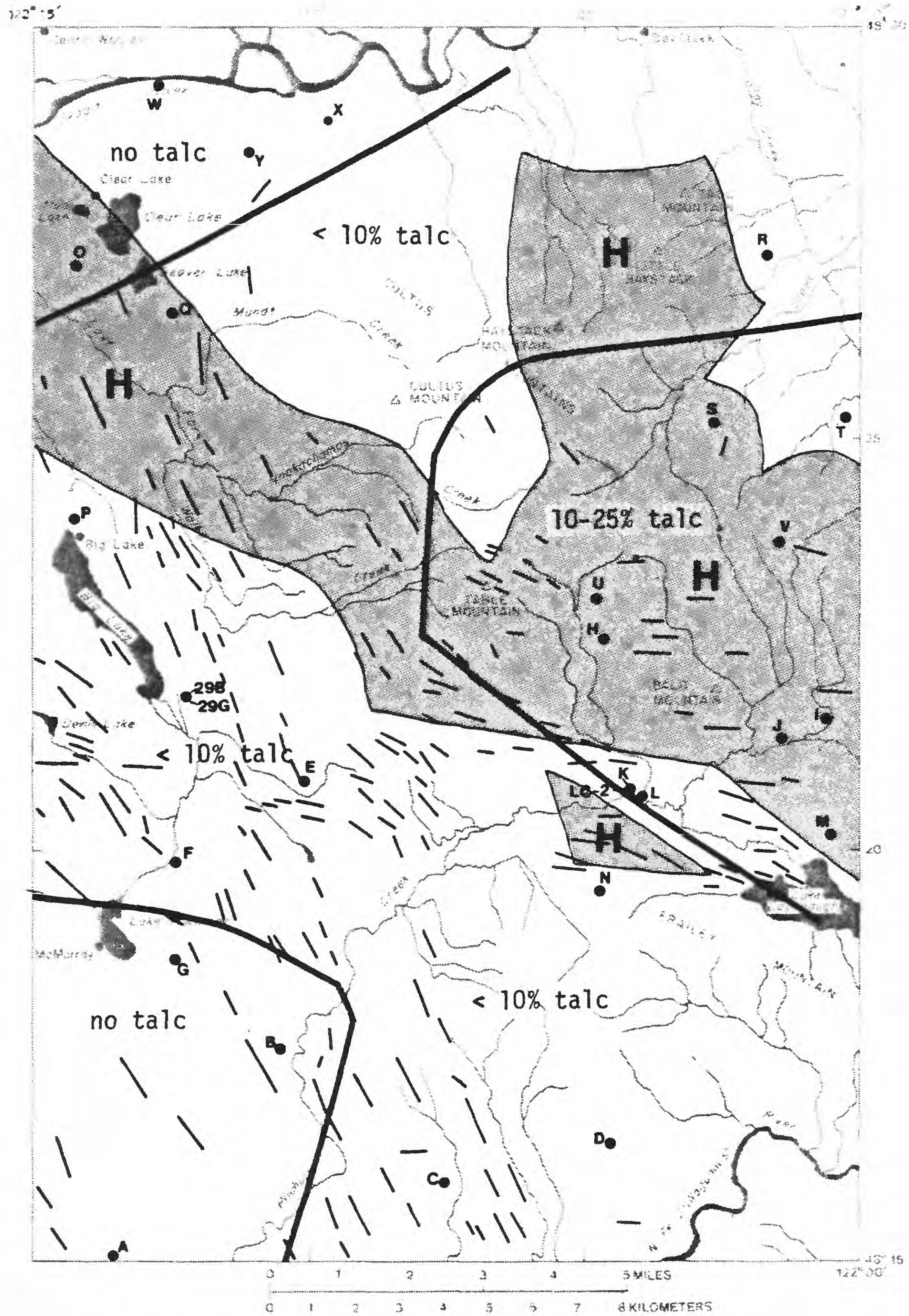


Figure 10c.--Distribution of talc in the < 2-µm fraction of till from the Clear Lake quadrangle, Washington. Haystack unit is shaded.

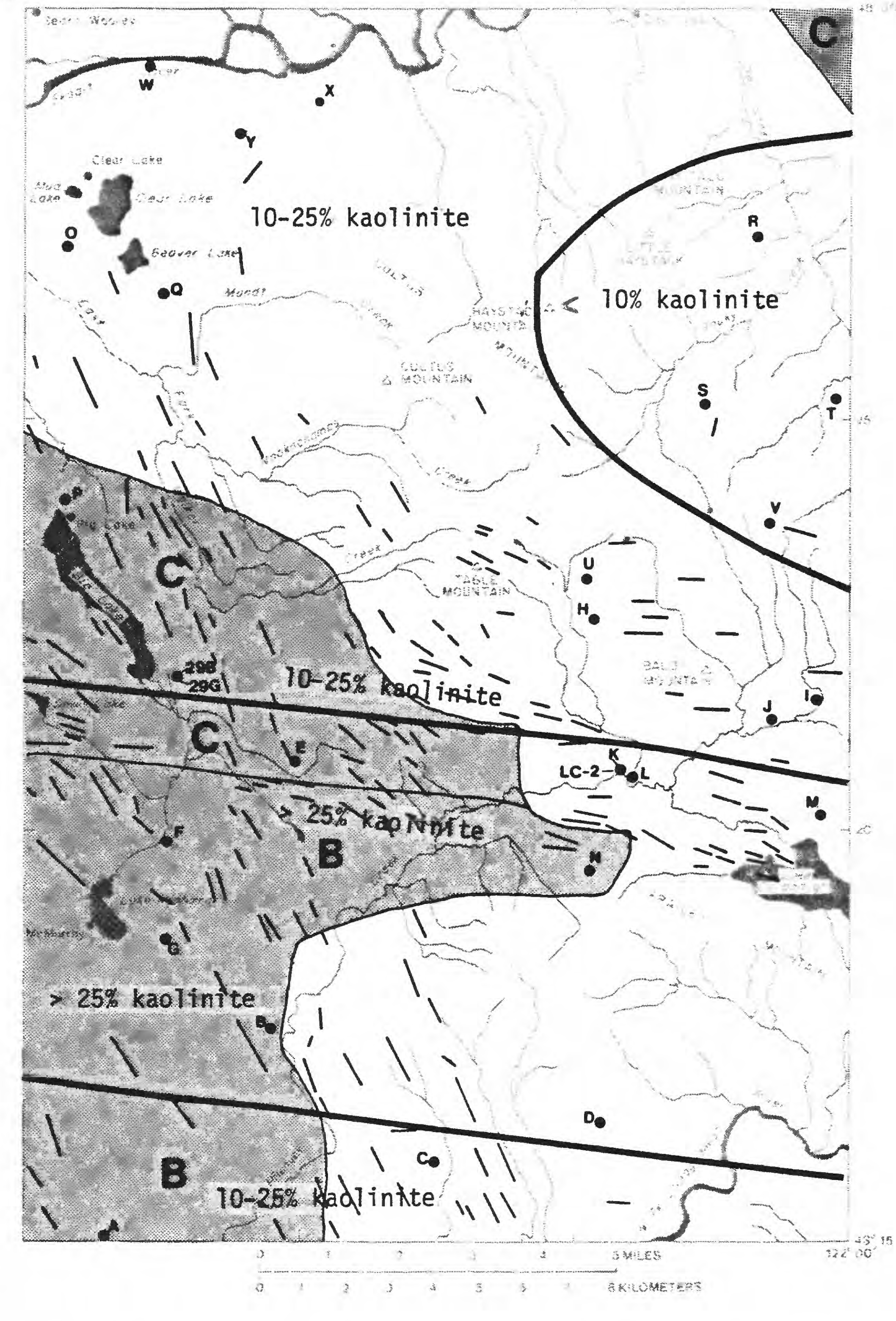


Figure 10d.--Distribution of kaolinite in the < 2-μm fraction of till from the Clear Lake quadrangle, Washington. Tertiary sediments (Bulson Creek unit and Chuckanut Formation) are shaded.

part of the quadrangle, an area underlain chiefly by mica-rich Darrington Phyllite. Serpentine, talc, and stilpnomelane (figures 10b, c, and a) are clearly abundant only on or near areas underlain by Haystack rocks in the eastern part of the area. In fact, these minerals are undetectable in most of the tills outside the Haystack area. Major kaolinite (figure 10d) defines a band extending east across the lower one-half of the quadrangle. This area contains many outcrops of Tertiary sedimentary rocks of the Chuckanut Formation and Bulson Creek unit, both of which are rich in kaolinite in this area. Local bedrock is thus a significant source for the fine fraction of the tills, and most till samples reflect this local influence as well as regional contributions.

The distribution of distinctive rock types has traditionally been used to reconstruct flowlines for continental glaciers (Flint, 1971) and clay minerals have been used to distinguish tills of different ages and source areas in the Midwest and Northeastern United States (cf., Rieck et al, 1979). The present study suggests that clay minerals may provide at least local "markers" for deposits of the Cordilleran ice in northwest Washington. Figure 10 shows that the mineralogy of tills in the mountains (Cascade Foothills) is more diverse and bedrock-controlled than that of the Puget lowland. Only in the western part of the quadrangle does the till mineralogy resemble that of the typical lowland tills. The "lowland" mineralogy (chlorite, mica, smectite) appears to extend up the valleys of the Skagit River to the north and the Stilliguamish River to the south, but in the mountains local bedrock influences dominate.

Figure 10 shows that ice movement had a strong eastward component, a fact suggested by the lineations derived from other evidence shown in figure 2. The distribution of serpentine (Figure 10b) is particularly striking. Tills which contain serpentine form an eastward trend away from the Haystack outcrops but it is absent in western and southern tills. Sample "N" was collected about one mile south of serpentine-rich till exposures (samples "K", "L", "LC-2") but contains no serpentine and is dominated by kaolinite which is abundant in the subjacent bedrock and in outcrops to the west.

Serpentinite-rich till--Cementation of Wisconsin-age till by carbonate, silica, or iron oxyhydroxides has been reviewed by Flint (1971). We report that serpentinite-rich till from the Clear Lake area is cemented by aragonite and a mineral resembling hydrotalcite ($(MgCO_3 \cdot 5Mg(OH)_2 \cdot 2Al(OH)_3 \cdot 4H_2O)$), a mineral rarely noted in Quaternary deposits. Hydrotalcite and aragonite form the principal cement in a thin (5 to 15-cm) zone where till directly overlies serpentinite, and are apparently formed by the weathering of serpentine. The pH of interstitial water flowing from these deposits is as high as 8.6, which suggests that carbonates may be presently forming in the tills. We are studying the mineralogy of the primary and secondary minerals and the chemistry of weathering solutions to aid in understanding the apparent stability of these carbonate minerals in a humid environment. Aragonite and calcite (?) cement the till matrix in a zone 0.5 to 2.0-cm thick around individual ultramafic clasts, and till may be completely cemented where ultramafic clasts predominate (for instance, localities "H" and "K" or close to ultramafic bedrock). Cementation is also found in the landslide deposits located along Rocky Creek and on the west slopes of Cultus Mountain, areas where serpentine is an important component of the bedrock. Similar carbonates and hydroxycarbonates were reported by Craw and Landis (1980) in serpentinite-rich Quarternary debris flows from New Zealand. Neither the aragonite nor the aragonite-hydrotalcite cement persists in the soil-forming horizons, but both may contribute to the impermeability of some tills at depths greater than one meter.

The presence of ultramafic rocks and serpentine minerals in the Cultus Mountains area suggests that asbestiform minerals may be present in soil and surface waters of the Clear Lake quadrangle. Many of the logging roads in the Table Mountain-Talc Mountain area are surfaced with ultramafic rocks, and bed material in Day Creek, Bear Creek, and Nookachamps Creek contains abundant clasts of serpentine. Recent work in ultramafic terranes elsewhere in the United States (Rohl, Langer, and Selikoff, 1977; Cooper et al, 1979) shows that asbestiform fibers may be present in potentially dangerous quantities in air and water samples, particularly where roads are surfaced with these materials.

Alteration of clay minerals--We have not systematically studied the effect of weathering on clay-mineral stability, but several reactions were noted in soils where serpentine is absent. Till samples described as oxidized in Appendix C exhibit a brown or tan color; unoxidized samples are generally gray. All oxidized samples show a broad x-ray peak near $12^{\circ}2\theta$ after heating to $550^{\circ}C$. This peak results from mixed-layer chlorite-vermiculite, which is seldom found in unoxidized samples. Mixed-layer chlorite-vermiculite apparently forms by weathering of chlorite, perhaps by oxidation of octahedral iron and concomittant loss of layer charge. The iron oxides which stain the oxidized till may well be derived from chlorite. Iron-rich material, amorphous to x-rays, is present in some weathered samples, and scanning electron microscope images show ferrogenous coatings on some mineral grains. These poorly crystalline or non-crystalline materials are probably iron or aluminum oxyhydroxides (Jackson, 1964). Lepidocrocite was present in one sample.

Chlorite is one of the least stable minerals under many soil-forming conditions (Jackson et al, 1948; Jackson, 1968). Thermochemical calculations based on soil and surface-water compositions typical of the Puget Sound region show trioctahedral chlorite to be among the least stable minerals (Wildrick, 1976). Destruction of chlorite proceeds by way of a mixed-layer chlorite-vermiculite phase (Johnson, 1964; Post and Janke, 1974). In the Puget Sound area, chlorite-vermiculite in soils has been described by Bockheim (1972), Schlichte (1968), Singer and Ugolini (1974), and Ugolini and Schlichte (1973). The formation of chlorite-vermiculite, iron oxides, and alumina-rich amorphous material is consistent with the alteration of primary silicates and clay minerals by dilute, acidic solutions in a highly leached environment (see Ugolini et al, 1977).

Clast Lithologies

Clasts larger than 20-mm comprise 10 to 20 percent, by weight, of most till samples from the Clear Lake quadrangle and other nearby areas (Heller, 1978; 1980). The clasts are a mixture of local rock types and regional lithologies that have survived transport of several tens to hundreds of kilometers. More than 60 percent of the clasts in Clear Lake tills (Table 3) are locally derived, and northern (regional) rocks comprise less than 10 percent of all till clasts. The occurrence of distinctive local lithologies like serpentinite and rhyolite as till clasts south of their outcrop area aids in qualitative measures of abrasion and dilution of clasts near the base of the Cordilleran ice.

The abundances in Table 3 show that rocks of local provenance dominate clasts in till from the Clear Lake quadrangle. Samples "W" and "Y" (see Appendix D), collected at the northern edge of the area, indicate (see Heller, 1980) substantial contributions from northern Washington and southern British Columbia and from Skagit River alluvium, but Darrington Phyllite dominates "Y", and is an important lithology in "W". Many of the other samples in Appendix D are rich in phyllite, greenstone and greenschist, rhyolite, and ultramafic rocks, all important lithologic types in local bedrock units (see figure 3) and suggest only minor contributions from sources to the north and east.

In figure 11 we use a modified Rose diagram to compare the relative abundance of five distinctive clast lithologies to their bedrock distribution and probable ice-flow directions in the Clear Lake quadrangle. Sample "F" was collected a few hundred meters south of a rhyolite-rich bedrock knob (figure 3),

**** Figure 11 near here ****

and contains more than 25 percent rhyolite clasts. However, samples "G" and "B", which lie less than 5 km south along the same assumed flowline contain only minor amounts of rhyolite, and sandstone, the underlying bedrock, is an important clast type. Rhyolite bedrock forms prominent knobs at various locations in the northwest and central parts of the Clear Lake quadrangle (figure 3), yet locality "F" is the only area sampled where rhyolite is an important constituent of the till. The "concentration" of a resistant rock, granite, with a primary source north of the study area, remains relatively constant in the Clear Lake area. Greenstone and greenschist have sources north of the study area (see Misch, 1966), and are the most abundant rock types in the northern part of the map area. The concentration of these rock types decreases to the south, corresponding to a decrease in their bedrock sources, abrasion of the greenschist, and dilution with other rock types. Samples "S" and "H", collected in the Cultus Mountains, are rich in greenstone, phyllite, and ultramafic clasts, rocks found north of the Devils Mountain fault zone. Field observations, and the fractured, strongly foliated nature of phyllite and serpentinite, suggest that these rocks cannot be transported as clasts for more than a few kilometers from their source. These rocks are

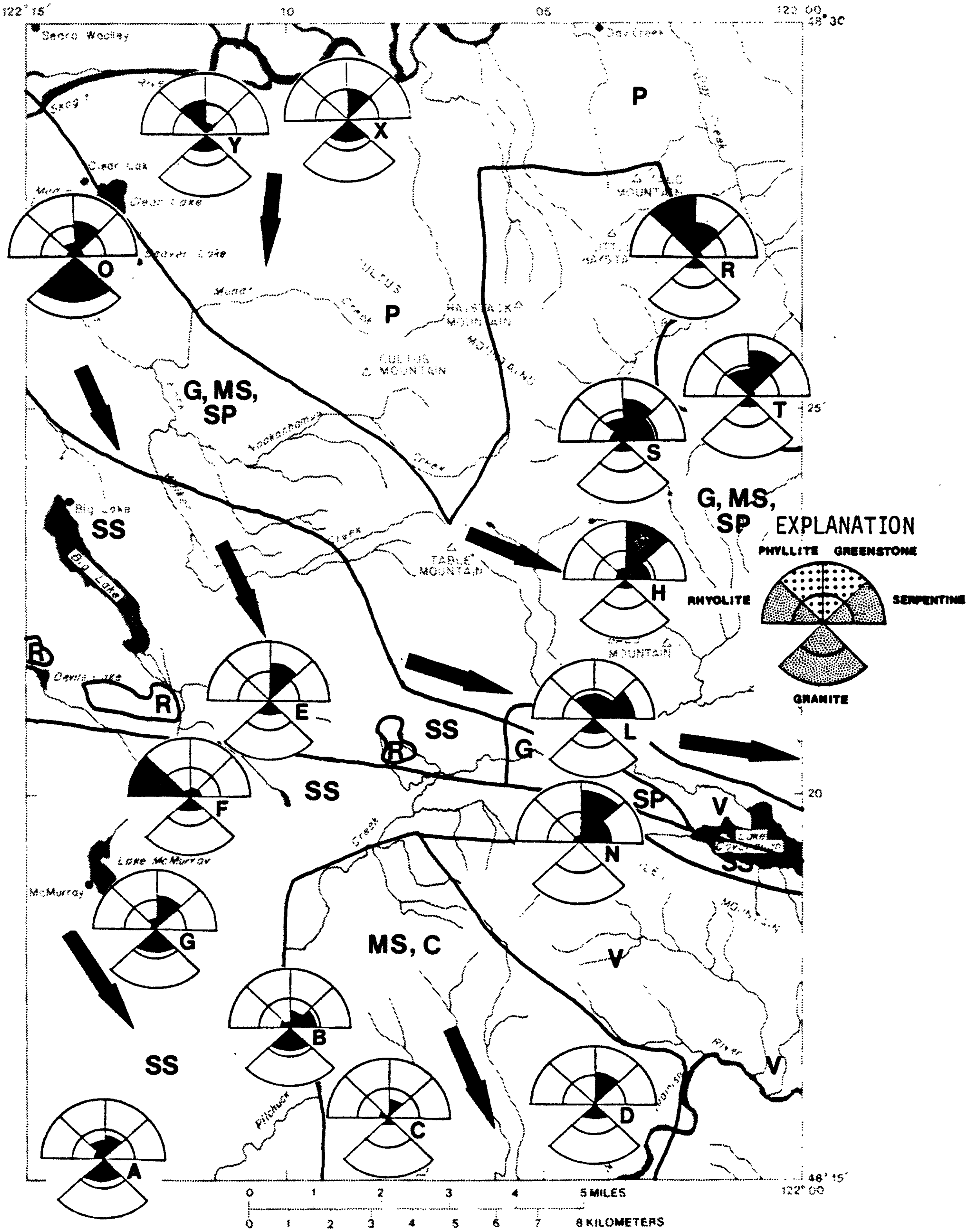


Figure 11.--Till-clast lithology (plotted on a modified Rose diagram) and simplified bedrock geology, Clear Lake quadrangle, Washington. Phyllite and greenstone plotted on a scale of 0-60 percent; other lithologies on a scale of 0-20 percent. P=phyllite, SS=sandstone and conglomerate, G=greenstone, MS=metasediments, R=rhyolite, V=metavolcanics, SP=serpentinite, C=chert.

likely to be crushed into matrix material, and eventually into clay-sized material (see figure 10), the "terminal grade" (Dreimanis and Vagners, 1971) for these foliated, clay-rich rocks. Serpentine does not persist in the clay (figure 10) or silt fraction for more than a few kilometers (D. Pevear, written communication, 1979).

The abundance of ultramafic clasts at locality "B" is striking, and suggests that serpentine may be present along a concealed NNW-striking fault shown by Dethier and Whetten (1980). Ultramafic rocks are also abundant in the Devils Mountain fault zone. Phyllite is an important component of till in the northern part of the area, and generally decreases to the south, but the pattern is complicated by the difficulty of distinguishing phyllite from "fine-grained dark metamorphic rocks", which are most abundant in the south-eastern portion of the map. Other patterns are suggested by figure 11, and by clast composition (see Appendix D), but interpretation is limited by the small sample size. However, it is apparent that serpentinite and rhyolite persist in the glacier "bedload" for a few kilometers, at most, before they are crushed to matrix-material size. Greenstone is resistant, and is probably an important clast lithology in till for tens of kilometers south of the Clear Lake area. Phyllite is a common till clast in the area, but probably disappears rapidly as it is transported beyond local source areas.

Conclusions

Lodgement till forms a veneer from 4 to 10 m thick over much of the Clear Lake quadrangle, and over most of the Puget lowland area of northwest Washington. The till is a compact mixture of matrix and clasts derived from local and northern source rocks. Twenty-five samples from the Clear Lake area averaged about 70 percent matrix and 5 percent clasts larger than 64-mm. The matrix fraction contained an average of 45.8 percent silt, 43.5 percent sand, and 10.6 percent clay, and can be distinguished from glaciomarine drift, which generally contains more silt and clay. Clay-size minerals in the matrix include serpentine, talc, stilpnomelane, and kaolinite derived from local bedrock sources, as well as chlorite, smectite, and mica from local and regional sources. Locally-derived clay-size minerals provide valuable indications of local ice-flow directions. Certain local bedrocks types, like rhyolite and serpentinite also provide distinctive "tracers" that record ice-flow directions, but clasts of these rocks are apparently crushed into matrix material within a few kilometers of their source. Other rocks, like greenstone, are more resistant and are ubiquitous as clasts in Clear Lake tills, and probably in till south of the study area. More detailed sampling would permit a better understanding of local ice-flow directions, and provide a broader statistical base for engineering applications of the data.

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APPENDIX A

Sample localities and characteristics of the gravel fraction in till from the Clear Lake quadrangle, Washington

Till Sample Localities	Percent >2-mm	Percent >64-mm	Intermediate axis of largest cobble or boulder, in mm	Roundness	Sphericity
NE¼S24T32NR4E (A)	25	7	19	rounded-subrounded	spherical
NW¼S4T32NR5E (B)	20	7	300	subrounded	subspherical
SE¼S14T32NR5E (C)	20	5	350	subrounded-subangular	subspherical-subelongate
NE¼S7T32NR6E (D)	35	15	450	rounded-subrounded	spherical-subspherical
SE¼S16T33NR5E (E)	20	1	180	subrounded	elongate
SE¼S19T33NR5E (F)	27	12	750	subrounded-subangular	subspherical
NE¼S31T33NR5E (G)	30	5	600	subrounded-subangular	spherical
NE¼S6T33NR6E (H)	40	20	1500	subangular	subspherical
SE¼S10T33NR6E (I)	15	1	180	subangular	elongate
SW¼S10T33NR6E (J)	40	10	1020	subrounded-subangular	elongate
SW¼S17T33NR6E (K)	50	3	610	subangular	subspherical
SW¼S17T33NR6E (L)	25	1	130	subangular	elongate
NE¼S22T33NR6E (M)	45	40	610	subrounded	subspherical
NE¼S30T33NR6E (N)	25	2	230	subrounded	spherical
NW¼S12T34NR4E (O)	10	1	250	subrounded	subspherical-subelongate
NW¼S25T34NR4E (P)	30	3	180	rounded-subrounded	spherical
NE¼S18T34NR5E (Q)	30	3	250	subrounded-subangular	subspherical
NW¼S10T34NR6E (R)	40	5	150	subrounded-subangular	subelongate
NW¼S21T34NR6E (S)	50	10	760	subrounded-subangular	subspherical-subelongate
NW¼S23T34NR6E (T)	45	5	250	subangular	elongate
SE¼S31T34N6E (U)	40	12	1000	subangular	subspherical
NW¼S34T34NR6E (V)	25	12	3000	subangular	subspherical-subelongate
NE¼S30T35NR5E (W)	30	6	900	rounded-subrounded	subspherical
NE¼S33T35NR5E (X)	70	15	250	subrounded	subspherical
SE¼S32T35NR5E (Y)	35	3	1500	subrounded-subangular	subelongate
NE¼S7T33NR5E (29B)	--	--	--	--	--
NE¼S7T33NR5E (29G)	--	--	--	--	--
SW¼S17T33NR6E (LC-2)	--	--	--	--	--

APPENDIX B

Granulometric analyses for 28 till samples
collected in the Clear Lake quadrangle, Washington

Sample	MATRIX			BULK SAMPLE		
	% Sand	% Silt	% Clay	% Matrix Lab	% Matrix Field[1/]	% Cobbles & Boulders Field[1/]
A	62.0	35.5	2.4	67.4	75.0	7.0
B	39.1	51.5	9.4	94.3	80.0	7.0
C	34.4	57.8	7.8	86.9	80.0	5.0
D	45.0	44.8	10.1	74.7	65.0	15.0
E	48.7	42.0	9.2	85.0	80.0	1.0
F	59.3	30.4	10.3	68.3	73.0	12.0
G	56.4	36.6	7.0	79.9	70.0	5.0
H	44.6	36.9	18.5	70.6	60.0	20.0
I	20.8	66.7	12.4	84.7	85.0	1.0
J	46.7	39.0	14.3	72.2	60.0	10.0
K	46.0	38.3	15.7	84.1	50.0	3.0
L	44.4	38.7	16.8	83.9	75.0	1.0
M	39.8	46.8	13.5	76.7	55.0	40.0
N	36.7	48.3	15.0	85.5	75.0	2.0
O	17.9	61.0	21.1	96.6	90.0	1.0
P	28.8	56.5	14.7	89.3	70.0	3.0
Q	43.3	49.1	7.6	86.3	70.0	3.0
R	52.6	40.2	7.2	67.9	60.0	5.0
S	48.8	43.0	8.2	69.8	50.0	10.0
T	45.6	47.3	7.1	73.2	55.0	5.0
U	34.2	51.5	14.3	73.2	60.0	12.0
V	52.3	40.8	6.9	73.7	75.0	12.0
W	51.5	46.2	2.3	79.9	70.0	6.0
X	69.9	27.0	3.1	63.8	30.0	15.0
Y	43.1	50.1	6.7	71.7	65.0	3.0
29B	34.2	57.5	8.2	88.9	--	--
29G	31.8	58.0	10.2	86.3	--	--
LC-2	42.1	40.8	17.1	73.0	--	--

1/Estimated

APPENDIX C

Minerals present in the clay (<2–µm) fraction of 28 till samples from the Clear Lake quadrangle, Washington

	A[1]	B[1]	C	D[2]	E	F[3]	G	H	I	J	K	L[4]	M	N	O	P	Q	R	S	T	U	V	W	X[1]	Y	DPD 29B	DPD 29G	LC-2
Chlorite	M	m	m	-	M	M	t	M	M	M	M	M	m	m	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Mica	m	m	m	m	t	m	m	t	m	t	t	t	t	m	M	M	M	m	t	m	m	m	M	M	M	m	m	m
Smectite	m	m	M	m	M	m	M	M	M	M	M	M	M	M	M	M	m	m	M	-	M	t	t	t	t	M	m	m
Chlorite-Vermiculite	-	M	m	m	M	?	M	-	m	-	-	-	m	m	m	-	t	m	t	-	-	t	-	t	-	t	-	m
Kaolinite	m	M	m	M	M	M	M	-	m	t	M	?	M	M	m	m	m	-	-	t	m	-	m	m	m	m	m	M
Serpentine	-	-	-	-	t	-	-	M	t	m	M	M	t	-	-	-	-	m	m	m	-	m	-	-	-	-	-	m
Talc	-	-	t	t	t	t	-	m	m	m	t	t	m	t	-	t	t	t	m	m	M	t	-	-	-	t	t	m
Stilpnomelane	-	-	-	-	-	-	-	t	t	t	t	-	-	-	-	t	-	t	t	t	t	-	-	-	-	t	-	t
Quartz	m	t	t	t	t	-	t	-	t	-	-	-	-	t	t	-	-	t	-	-	-	t	t	m	m	t	t	t
Feldspar	t	t	t	t	-	t	-	-	t	-	-	-	-	-	t	t	t	-	-	-	-	t	t	-	-	t	t	-
Amphibole	t	t	t	t	t	-	-	t	m	m	t	t	t	t	-	t	t	t	m	t	t	t	t	t	-	t	t	t
Oxidation	o	o	o	o	o	s	o	u	s	u	u	u	o	o	o	u	s	o	s	s	u	s	u	o	u	o	u	u

percent clay (M = >25%, m = 10-25%, t = <10%) was visually estimated from XRD peak intensities

oxidation (o = oxidized, s = slightly oxidized, u = unoxidized)

[1] poor pattern

[2] lepidocrocite

[3] peeling plate, no heat treatment

[4] not tested for kaolinite (DMSO)

APPENDIX D

Lithology of clasts from till collected at 25 locations in the Clear Lake quadrangle, Washington

SITE LOCATION / LITHOLOGY	TILL SAMPLES A	B	C	D	E	F	G	H
Rhyolite	3	2				28	1	3
Dacite		1						
Dacite porphyry			3					
Andesite	6	7		1		2	5	
Porphyritic andesite	5	5				3	2	2
Basalt	3	1				2	1	
Dark volcanic	1	1				1		
Granitic	3	5		4	3		8	2
Pink granite		1	1					
Diorite	3	2		1	1	4		
Gabbro	4	3	3		1	5	2	
Dunite		4				1		
Ultramafic		4				1		7
Quartzite	9	7		1		8	5	1
Vein Quartz	1	2	8	3	8	2	5	1
Qtzte. brown	4	5	9	1	4	2	2	
Qtzte. red			1					
Fine dark metamorphic	5	3	38	44	13	2	1	
Phyllite	17	3				3	8	10
Greenstone greenschist	25	18	18	32	38	7	35	68
Meta-breccia		2				1		
Meta-conglomerate						3	1	1
Meta-volcanic		7				3	2	2
Meta-plutonic								
Granitic with altered mafics	1	2	1			1		
Schist		1		2	7	3	4	
Talc schist								
Gneiss	3	2		1		2	1	
Amphibolite								
Chert		6	5		3	8	2	
Limestone								
Sandstone	6	3	6	1	14	5	8	1
Shale					3		3	1
Argillite								3
Conglomerate				3			1	
Felsite								
Graywacke		1	1	1	2			
Weathered		2	3	5	3	3		
Other	1		3					
Total	100	100	100	100	100	100	100	100

APPENDIX D (continued)

LITHOLOGY \ SITE LOCATION	TILL SAMPLES							
	I	J	K	L	M	N	O	P
Rhyolite		3	3			1	1	1
Dacite								
Dacite porphyry								
Andesite			1	1		1		4
Porphyritic andesite			1				6	9
Basalt								1
Dark volcanic						3	4	
Granitic	3	4	1	3	9		13	5
Pink granite					1		2	
Diorite	2			1	1			2
Gabbro	1		2	2	5	1		
Dunite								
Ultramafic	7	17	6	13	6	10	1	3
Quartzite			7	4	6	3	6	5
Vein Quartz	2	4	5		7	1	7	4
Qtzte. brown			1		1		2	4
Qtzte. red			1					
Fine dark metamorphic			1	3		7	4	1
Phyllite	17	36	36	23	16	3	10	14
Greenstone greenschist	53	17	25	26	29	47	34	29
Meta-breccia			1					
Meta-conglomerate								
Meta-volcanic	1					8		5
Meta-plutonic				1		1		
Granitic with altered mafics			1	2			1	
Schist	3	2	3	2	2	10		2
Talc schist	7					1		
Gneiss					1			
Amphibolite								
Chert				2			1	1
Limestone								
Sandstone		1	5	5	2	1	3	4
Shale	3	4		1	2	1	1	5
Argillite	1			11	11	1	2	
Conglomerate								
Felsite								
Graywacke		7			1			
Weathered							2	
Other		5						1
Total	100	100	100	100	100	100	100	100

APPENDIX D (continued)

SITE LOCATION / LITHOLOGY	TILL SAMPLES Q	R	S	T	U	V	W	X	Y
Rhyolite			3		1	3	1		
Dacite									
Dacite porphyry					1				
Andesite	3			2	2		7	4	5
Porphyritic andesite				2		5	1		
Basalt			1	1		1			1
Dark volcanic	5				11		6		
Granitic	4	1	3	2	1	4	3	6	3
Pink granite							1		1
Diorite	3	1		1	1	1	2		
Gabbro	2		1	1	1	1	4	1	
Dunite	3						1		
Ultramafic	1	1	11	1	1	2			
Quartzite	10	1		5	5	3	10		
Vein Quartz	8	6	4	3	3	7	3	7	12
Qtzte. brown	4			1		1	7	11	3
Qtzte. red	1					1		1	3
Fine dark metamorphic		2	7	6	1	1	1	28	11
Phyllite	5	50	20	24	7	17	18		33
Greenstone greenschist	16	33	42	45	34	40	26	29	11
Meta-breccia								1	1
Meta-conglomerate								2	
Meta-volcanic	1			1	2	1		1	8
Meta-plutonic	1			1				3	9
Granitic with altered mafics					2	1	1		
Schist	15	1	1		8	3	1	1	
Talc schist	6		2		6				
Gneiss	3			3	2	2	2	1	
Amphibolite					1				
Chert	3	1	1						
Limestone	2								
Sandstone		1	1			3		1	1
Shale	2			1	2				
Argillite	2				2	3	5		
Conglomerate									
Felsite					1				
Graywacke								4	
Weathered		1	1		4				
Other		2	2		1				
Total	100	100	100	100	100	100	100	100	100