

MINERAL COMPOSITION, $^{87}\text{Sr}/^{86}\text{Sr}$ RATIOS, AND CONCENTRATIONS OF STRONTIUM AND RUBIDIUM IN LATE WISCONSIN TILL OF OHIO^{1,2}

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Abstract. Samples of Late Wisconsin till from the Powell-Union City Moraine of Ohio have bimodal grainsize distributions and concentrations of carbonate minerals, illite, and kaolinite-chlorite that are primarily the result of grinding of clasts derived from local bedrock. Quartz and feldspar have unimodal grainsize distributions that suggest their derivation from distant sources on the Precambrian Shield of Canada. The carbonate content of the silt and clay fractions ($<62.5\ \mu\text{m}$) of 13 till samples collected along the Powell-Union City Moraine increases from less than 10% in the east to about 35% in western Ohio. The change in carbonate content is compatible with bedrock lithology and a southwesterly iceflow direction. The silt and clay fractions (non-carbonate) contain $\text{Rb} = 154.7 \pm 13.5$ ppm, $\text{Sr} = 104.8 \pm 11.0$ ppm, $\text{Rb}/\text{Sr} = 1.49 \pm 0.21$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7345 \pm 0.0041$. The average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of these till samples is similar to results obtained elsewhere for strontium of the continental crust and supports previous suggestions that the average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the continental crust is 0.730 ± 0.010 . The ratio of radiogenic $^{87}\text{Sr}/^{87}\text{Rb}$ increases from about 0.0060 in the east to 0.0075 in western Ohio. The low magnitude of this ratio is due to the predominance of locally derived sediment of Paleozoic age in the silt and clay fractions of till. The westerly increase is probably the result of several factors, including: 1) Increasing age of the Precambrian component (feldspar); 2) Increasing abundance of the Precambrian component; 3) Increasing age of the local bedrock from Mississippian in the east to Silurian in western Ohio.

OHIO J. SCI. 79(4): 149, 1979

"Till is the only sediment stemming directly and solely from glacial ice . . . and . . . it holds the secrets to the action of ice at the bottom of a glacier." These eloquent words of Goldthwait (1971, p. 3) suggest the importance of till as a source of information about the geologic and climatic history of the Earth during the Pleistocene epoch. The methods used to study till and its fabric were reviewed recently by Raukas *et al* (1978) and include determinations of the abundances of selected light or heavy minerals. Studies by other investigators have contributed significantly to our understanding of ice flow patterns and of the relationships between grainsize,

abundance of minerals, and distance of transport from their sources.

Chemical composition of till in Ohio has received very little attention. Wilding *et al* (1971) reported concentrations of Ti, Zr, Fe, Ca and K and reviewed the sparse literature relevant to the mid-western area of the United States. The concentrations of both major and trace elements in till may be useful in the study of iceflow directions and bedrock compositions. For example, the clay fraction of till has been shown to be a representative sample of the bedrock over which the ice moved (Goldschmidt 1954) and the chemical composition of this fraction may be used to estimate the chemical composition of the bedrock or to distinguish among tills derived from different sources.

The elements Rb and Sr are of particular interest because ^{87}Rb is radio-

¹Manuscript received 12 September 1978 and in revised form 11 January 1979 (#78-56).

²Publication of Institute of Polar Studies, Misc. Series No. 124.

active and decays by beta emission to stable ^{87}Sr (Faure and Powell 1972, Faure 1977). The isotopic abundance of ^{87}Sr in till (conveniently expressed as the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio) depends on the age and Rb/Sr ratio of the bedrock in the path of the ice. These facts suggest that ^{87}Sr in till may be used to estimate the abundance of ^{87}Sr in the rocks in the path of the ice and to identify the provenance of Sr-bearing minerals in till.

Our study was undertaken in order to obtain information about the concentrations of Rb and Sr and about the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in late Wisconsin till in west-central Ohio. The samples were collected at intervals from the Powell-Union City Moraine of Ohio (fig. 1) in order to test the hypothesis that cer-

tain mineralogical, chemical, and isotopic parameters of the less than $62\ \mu\text{m}$ fraction of till vary regionally across Ohio. Such variations may have resulted from the movement of ice over a variety of bedrock compositions including Paleozoic sedimentary rocks of Ohio and southwestern Ontario as well as the igneous and metamorphic rocks of the Precambrian Shield of Canada.

GEOLOGY OF THE POWELL-UNION CITY MORaine

The Powell-Union City Moraine extends across Ohio from east to west for a distance of over 270 km (fig. 1); it was deposited during the last recession of the Scioto and Miami sublobes of the Erie lobe of the late Wisconsin ice sheet.

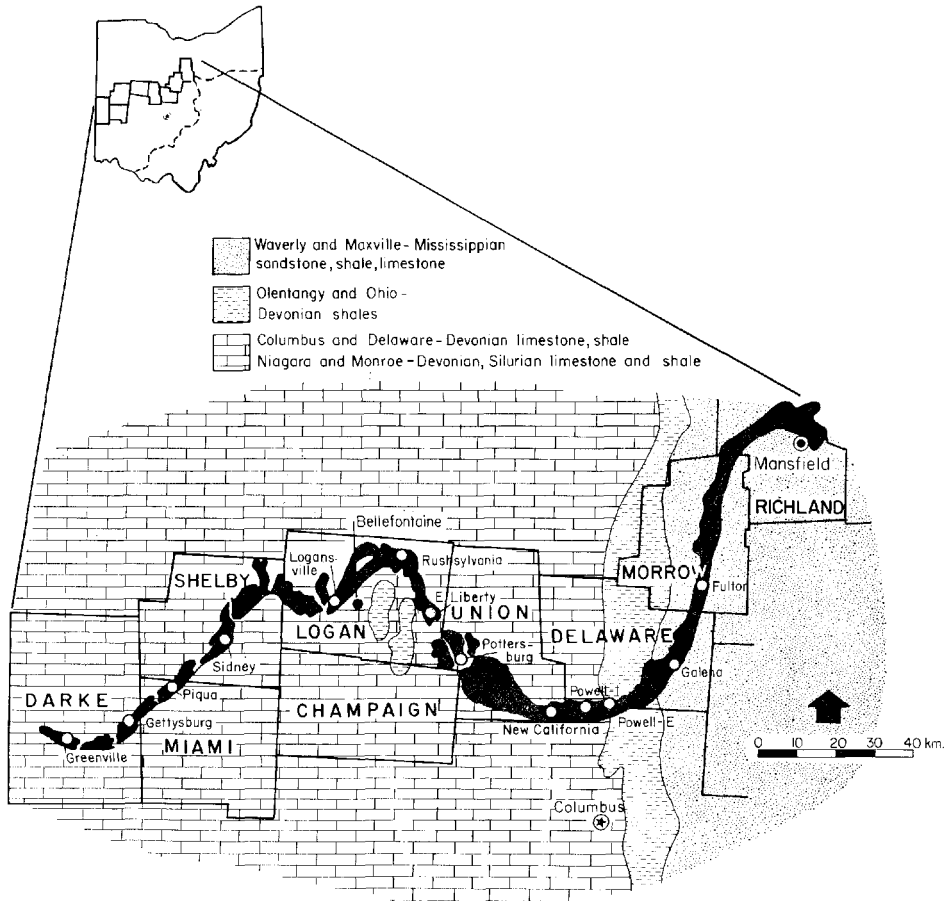


FIGURE 1. Map showing the collecting sites from the Powell-Union City Moraine and a generalized representation of the bedrock geology of central Ohio.

A carbon-14 date of $14,780 \pm 192$ years B.P. was reported for wood recovered at Liberty, Ohio (OWU-83) by Dreimanis and Goldthwait (1973). The Powell-Union City Moraine was mapped by Forsyth (1956) in Logan and Shelby Counties and is shown on the glacial map of Ohio by Goldthwait *et al* (1961). The glacial history of the Huron, Erie and Ontario lobes was summarized by Dreimanis and Goldthwait (1973) and Selby (1978) studied the glacial geology of Darke County (which includes the western extension of the Powell-Union City Moraine in Ohio).

The segment of the moraine in Shelby County is complicated by the fact that the Powell-Union City Moraine rests on the older Sidney Moraine and was subsequently covered in part by the younger Bloomer Moraine (Forsyth 1956). The samples from Logansville, Sidney and Piqua were collected from this portion of the moraine which may account for some of the anomalous results obtained for these samples. Another interesting part of the moraine is the segment associated with the bedrock exposures in the area around Bellefontaine, Ohio. The bedrock outlier in this region consists of the Delaware and Columbus limestones overlain by the Ohio and Olentangy shales of Devonian age. The presence of this bedrock knob caused the Erie lobe to split into the Scioto and Miami sublobes. The bedrock geology underlying the Powell-Union City Moraine is summarized in figure 1 which is based on the geologic map of Ohio by Bownocker (1920). The eastern part of the moraine, represented by our samples from Fulton and Galena, is underlain by sandstones and shales of Mississippian age. Farther west the moraine intersects a narrow outcrop belt of Ohio and Olentangy shales followed by carbonate rocks of Devonian and Silurian age that extend to the Ohio-Indiana border.

ANALYTICAL PROCEDURES

We collected 13 samples along the Powell-Union City Moraine from natural or man-made cuts exposing unleached till (See Appendix and fig. 1). The samples weighed about 3 kg each and were taken from a fresh surface 10 cm or more below the top of the C horizon whose depth was measured at each locality. Four

of the samples were divided into 6 size fractions to investigate the variation of mineral compositions and concentrations of Rb and Sr as a function of grainsize. The silt and clay fraction (-230 mesh, $<62.5 \mu\text{m}$) was separated by settling the coarser fractions for 100 sec in a volumetric cylinder that was 35 cm tall (Pettijohn 1975). The coarse fractions were dried and sieved into the following size ranges in order to conform with the Wentworth Scale: $+18$, $-18+35$, $-35+60$, $-60+120$ and $-120+230$, expressed in U.S. standard mesh numbers.

The carbonate content of each size fraction for the 4 samples was determined from (dried) weight loss after leaching with 2N HCl, followed by repeated washing of the residue with double-distilled water. Concentrations of quartz, feldspar, illite and kaolinite-chlorite were estimated by duplicate x-ray diffraction analyses using Cu-K-alpha radiation (Diano Corp. Model XRD-6). All samples were ground to less than 200 mesh and pressed into pellets with a boric acid backing. The quantitative determinations of mineral concentrations were made by the method of Cosgrove and Sulaiman (1973) and are based on the calibrations of Boger (1976). Peak heights were measured at $8.8^\circ 2\theta$ for illite, $12.5^\circ 2\theta$ for kaolinite-chlorite and at $26.7^\circ 2\theta$ for quartz. The abundance of feldspar was estimated from the area under the peak between $27.4^\circ 2\theta$ and $28.8^\circ 2\theta$. The reproducibilities calculated from duplicate analyses of each sample are $\pm 2.0\%$ for quartz, $\pm 1.94\%$ for feldspar, $\pm 0.85\%$ for illite and $\pm 0.45\%$ for kaolinite-chlorite and errors are expressed in units of concentration.

Concentrations of Rb and Sr were determined by X-ray fluorescence using a Mo-target x-ray tube and LiF (220) diffracting crystal (Diano Corp., Model XRD-6). Ground samples (<200 mesh) were compressed into pellets and a calibration was established using the rock standards of the U.S. Geological Survey (G-2, W-1, AGV-1, BCR-1, GSP-1) and the Rb and Sr concentrations noted by Flanagan (1973). Matrix corrections were made for all standards and unknowns by means of the Mo-K-alpha Compton-scattered peak (Reynolds 1963). The reproducibility of the results, calculated from duplicate analyses of all samples, is ± 1.2 ppm for Sr and ± 5.8 ppm for Rb.

The isotopic composition of Sr was measured in the less than $62.5 \mu\text{m}$ fractions of the samples collected along the Powell-Union City Moraine. The samples (0.5 g) were dissolved in Teflon dishes using 15 ml reagent-grade HF and 3 ml distilled H_2SO_4 . Sr was separated from the solutions by cation exchange chromatography using AG 50W-X8 resin (Bio-Rad Laboratories) and purified 2N HCl as eluant. The analyses were performed on a single-filament (Ta), solid-source mass spectrometer (Nuclide Corp., Model 6-60-S). All measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were corrected for isotope fractionation to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. The Eimer and Amend SrCO_3 standard was analyzed (4x) and yielded an average $^{87}\text{Sr}/^{86}\text{Sr} = 0.70772 \pm 0.00022$ (1 SD). This value is in satisfactory agreement with results obtained by other investigators.

RESULTS AND DISCUSSION

Analysis of Size Fractions

Four samples collected at Powell (E), Pottersburg, East Liberty and Rushsylvania (fig. 1) were divided into 6 size fractions which were analyzed separately. The results for each size range were averaged (fig. 2). The silt and clay fraction (-230 mesh, $<62.5 \mu\text{m}$) was strongly dominant over the coarser fractions and amounted to 75.2% of the till samples on the average. The coarsest fraction ($+18$ mesh, $>1000 \mu\text{m}$) was next in abundance with 11.7%, suggesting a bimodal grainsize distribution for these till samples.

The highest concentration of carbonate minerals (48.4%) occurred in the coarse sand fraction ($-18+35$ mesh, 500 to

$1000 \mu\text{m}$). The carbonate content of the finer fractions decreased systematically with decreasing grain size, but rose again to 28.6% in the silt and clay fraction. The apparent bimodal distribution of the carbonate content of till was also reported by Smeck *et al* (1968), and probably is the result of grinding of carbonate clasts derived from the local bedrock by the movement of the ice. Dreimanis and Vagners (1971) demonstrated that such bimodal distributions are typical of mineral and rock components of till and that the abundance of the coarse mode decreases with increasing distance from the source, whereas the abundance of the component in the fine fraction increases. Our finding of a high abundance of carbonate grains in the coarse fraction of till suggests that they are derived from local bedrock sources.

The distribution of Rb (non-carbonate) was slightly bimodal and mirrored the grainsize distribution. High concentrations (164.2 ppm) occurred in the clay and silt fractions and in the coarse fraction (138.6 ppm). The lowest concentration of Rb (119.5 ppm) was in the fine sand fraction ($-60+120$ mesh, 125 to $250 \mu\text{m}$). Strontium, on the other hand, was strongly concentrated in the $+60-120$ mesh fraction in which its average concentration was 144.4 ppm. A comparison of the Rb and Sr contents (fig. 2) suggests a strong negative correlation between these two elements. Accordingly, the Rb/Sr ratios vary by almost a factor of 2 from 0.83 in the $-60+120$ mesh fraction (non-carbonate) to 1.48 in the clay and silt fraction. The negative correlation between concentrations of Rb and Sr suggests that they reside in different minerals whose mechanical properties caused them to be concentrated in different size fractions.

The mineral compositions of the size fractions (non-carbonate) (fig. 3) confirmed such a relationship. The abundances of clay minerals (illite and kaolinite-chlorite) correlated positively with the concentrations of Rb, whereas feldspar correlated well with the Sr concentrations. These results (fig. 4) indicate that the Rb in till resided primarily in the clay mineral illite, whereas Sr was carried by feldspar. The effect of

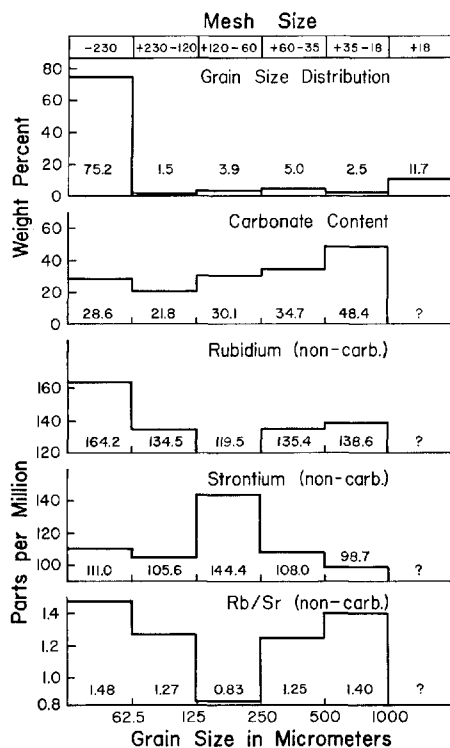


FIGURE 2. Average analytical data for size fractions of four till samples from the Powell-Union City Moraine collected at Powell E, Pottersburg, East Liberty and Rushsylvania, Ohio. The carbonate content and Rb and Sr concentrations of the $+1000 \mu\text{m}$ fractions ($+18$ mesh) were not determined. The numbers within each histogram are numerical values of the relevant parameter for each size range.

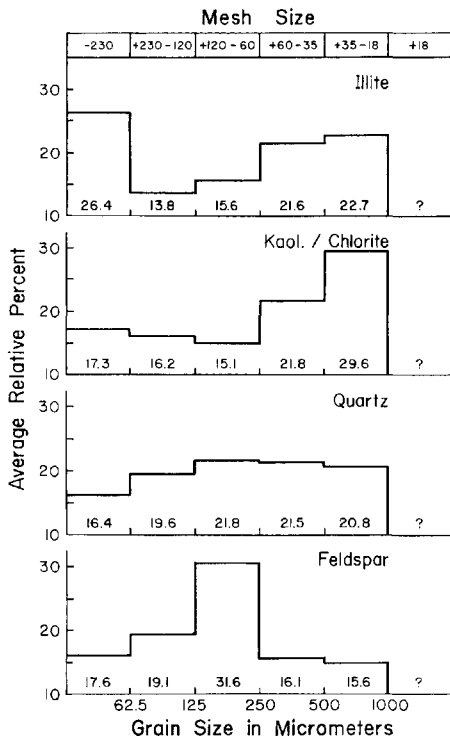


FIGURE 3. Average abundance of minerals in different size fractions (non-carbonate) of four till samples from the Powell-Union City Moraine collected at Powell E, Pottersburg, East Liberty and Rushsylvania, Ohio. The abundances are expressed as percentages of the total for each size fraction. For example, 26.4% of the illite in all size fractions finer than 18 mesh ($<100 \mu\text{m}$) is in the -230 mesh ($<62.5 \mu\text{m}$) fraction. These results indicate that illite is concentrated in the -230 mesh fraction, kaolinite/chlorite in the -18+35 mesh fraction, and quartz and feldspar in the -60+120 mesh fraction.

grainsize on the mineral composition of till fractions (non-carbonate) is shown by the data in figure 3. Illite had a distinctly bimodal distribution, but was most abundant in the clay and silt fractions, as expected. The high illite content of the coarse fraction was the result of grinding of shale fragments from the local bedrock and was released by the solution of the carbonate fraction. Kaolinite-chlorite appeared to be most abundant in the coarse fractions and presumably were predominantly of local origin. Quartz was concentrated in the fine to medium grade sand (-35+120

mesh), consistent with the conclusions of Dreimanis and Vagners (1969, 1971). Feldspar was strongly concentrated in the fine sand fraction (-60+120) which may be its "terminal grade" as defined by Dreimanis and Vagners. The unimodal distributions of quartz and feldspar suggested that these minerals were derived from distant sources on the Precambrian Shield of Canada and that the local bedrock, composed of Paleozoic carbonates, was not a significant source of either quartz or feldspar in the till included in this study.

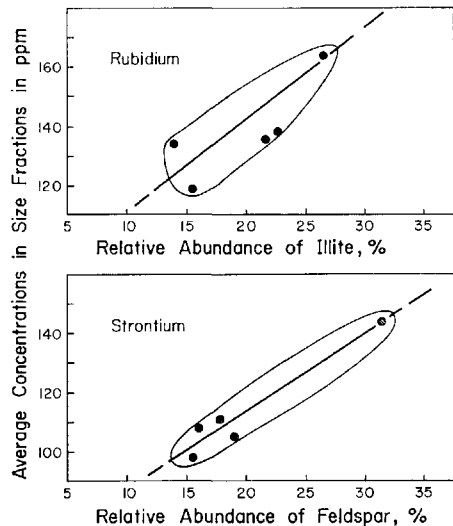


FIGURE 4. Average concentration of Rb and Sr in different size fractions of four till samples from the Powell-Union City Moraine, Ohio, collected at Powell E, Pottersburg, East Liberty, and Rushsylvania. The concentrations of Rb and Sr are from figure 2. The abundances of illite and feldspar are from figure 3.

Regional Variations Along Powell-Union City Moraine

The analysis of size fractions of till from 4 selected localities along the Powell-Union City Moraine indicated that the clay and silt fraction was not only the most abundant, but was also more homogeneous in mineralogical composition and in the concentrations of Rb and Sr than the coarser fractions. This fraction is considered most representative of the till as a whole and was selected for that reason to investigate the regional varia-

tion of certain mineralogical, chemical and isotopic parameters of late Wisconsin till along an east to west traverse across Ohio. Such regional differences in the composition of till should occur because of the influence of local bedrock in Ohio (fig. 1) and because of differences in the abundance and provenance of its Precambrian component. The relevant data are presented in table 1 and in figure 5 and a preliminary interpretation of these data was presented by Taylor and Faure (1978).

The abundances of illite and feldspar (non-carbonate) also varied systematically along the strike of the moraine (fig. 5). Illite decreased from east to west whereas feldspar increased slightly. The decrease in the abundance of illite may have been due to the prevalence of carbonate rocks west of the exposures of the Ohio and Olentangy shales and the resulting decrease in locally-derived shale clasts. The variation in the feldspar content must be attributed to distant sources on the Precambrian Shield of

TABLE 1

Analytical data for less than 62.5 μm fractions of till from Powell-Union City Moraine.

Locality	% Carbonate by Weight	Rb (ppm)	Non-carbonate Sr (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$
Fulton	8.1	148.1	86.3	0.7354
Galena	13.7	157.9	90.0	0.7414
Powell E	21.3	150.5	101.4	0.7288
Powell	14.0	153.0	92.0	0.7375
New California	21.5	172.9	95.4	0.7380
Pottersburg	30.0	177.9	107.5	0.7354
East Liberty	30.0	164.3	116.6	0.7365
Rushsylvania	33.2	164.2	118.5	—
Logansville	16.5	143.8	108.3	0.7289
Sidney	24.7	161.5	104.5	0.7348
Piqua	18.7	128.7	111.4	0.7292
Gettysburg	36.8	139.9	117.4	—
Greenville	33.3	150.6	113.1	0.7334

The carbonate content of the clay and silt fraction increased fairly smoothly from 8.1% at Fulton on the eastern end of the moraine to about 33.2% at Rushsylvania (fig. 1). The samples from Logansville, Sidney and Piqua had anomalously low carbonate contents ranging from 16.5% to 24.7%. However, the samples collected at Gettysburg and Greenville to the west appeared to continue the westerly increases in the carbonate content. This pattern implied that the ice moved from areas underlain by Mississippian sandstones in northeastern Ohio toward areas underlain by Devonian and Silurian carbonate rocks in central and southwestern Ohio. The variation of the carbonate content of till was therefore entirely compatible with the pronounced westerly component of the iceflow direction of the Erie lobe of late Wisconsin age (Goldthwait *et al* 1961, Dreimanis and Goldthwait 1973).

Canada because this mineral does not occur in appreciable concentrations in the bedrock of Ohio. The concentrations of kaolinite-chlorite were less than those of illite but varied similarly. The abundance of quartz varied locally, but showed no regional pattern.

The concentrations of Rb and Sr in the clay and silt fractions (non-carbonate) varied as expected in accordance with their respective mineral hosts (fig. 4). The concentrations of Rb ranged from 129 to 178 ppm (av. 154.7 ± 13.5 ppm). Strontium varied from 86.3 to 118.5 ppm and had an average of 104.8 ± 11.0 (mean \pm SD). The Rb/Sr ratios ranged from 1.16 to 1.81 and had a mean of 1.49 ± 0.21 . In view of the fact that these data apply to the most abundant and homogeneous fraction of till, the average Rb and Sr concentrations were probably representative not only of the whole till, but also of the sedimentary, igneous and meta-

morphic rocks that were overridden by the ice sheet. The average Rb content of till (carbonate free) was in good agreement with the average Rb concentration of shale for which Turekian and Wede-

pohl (1961) reported 140 ppm. Their Sr content for shale is 300 ppm which was much higher than that of till, presumably because of the carbonate content of the shale. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the clay

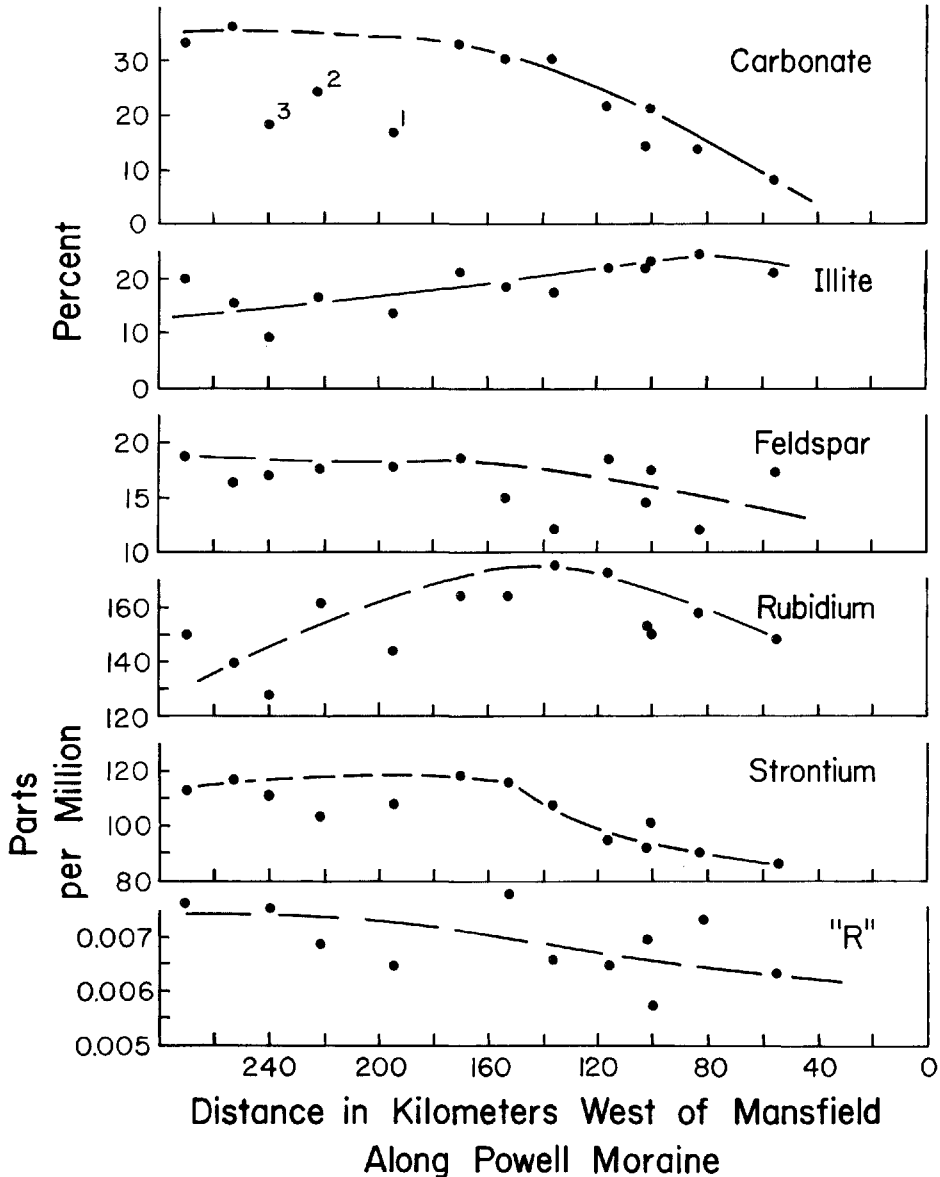


FIGURE 5. Analytical data for <62.5 micrometer fractions of till collected along the Powell-Union City Moraine, Ohio. Illite, feldspar, Rb, Sr and "R" apply to the non-carbonate fraction. R is a measure of the abundance of radiogenic ^{87}Sr which exists in minerals derived not only from the Paleozoic bedrock of Ohio but also in feldspar derived from the Precambrian Shield of Canada. Carbonate samples 1, 2 and 3 are from Logansville, Sidney and Piqua, respectively. Lines were fitted to emphasize regional trends in the data.

and silt non-carbonate fractions (table 1), ranged from 0.7288 to 0.7414 and averaged 0.7345 ± 0.0041 . In general, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of a till sample depends both on the Rb/Sr ratios and ages of its constituent mineral and rock particles. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio thus reflects not only the mineral composition of a particular till sample, but also the ages of the rocks in the source areas. Measurements of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of till can serve two useful purposes: 1) To estimate the average isotopic composition of Sr in the rocks of the continental crust; 2) To relate differences in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of till to changes in provenance of the constituent rock and mineral particles.

Interest in the average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the rocks of the continental crust arises from considerations of the chemical differentiation of the Earth and of the age and history of the crust (Moorbath 1977). The problem of estimating this parameter was originally discussed by Faure and Hurley (1963) who arrived at a value of 0.725 ± 0.005 , based on calculations for a crust having the following average properties: Rb/Sr=0.25, $(^{87}\text{Sr}/^{86}\text{Sr})_0=0.704$, age= 2×10^9 years. This estimate was supported by analyses of

mollusk shells from the Canadian Shield published by Faure *et al* (1963). Subsequently, Hart and Tilton (1966) proposed a value of 0.730 ± 0.01 for the Precambrian Shield north of Lake Superior. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the clay and silt fraction of till (non-carbonate) from Ohio confirmed the general validity of these earlier estimates. A comparison (table 2) of average $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of terrigenous sediment with marine sediment of Pleistocene to Holocene age reveals systematic differences. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of marine sediment average 0.7129, whereas those of continental sediment have a weighted mean of 0.7303. The low average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of marine sediment is due to the presence of young volcanogenic detritus (Boger and Faure 1974, Shaffer and Faure 1974), and is not representative of the isotopic composition of Sr residing in the rocks of the continental crust. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of till presented in our report are similar to those obtained by Hart and Tilton (1966) for glacial sediment in Lake Superior and support their conclusion that the average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the continental crust north of Lake Superior is within the range 0.730 ± 0.010 .

The regional variation of the $^{87}\text{Sr}/^{86}\text{Sr}$

TABLE 2
Average $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Pleistocene to Recent marine and continental sediment on a carbonate-free basis.

Sedimentary Basin (Pleistocene-Recent)	No. of Samples	Average $^{87}\text{Sr}/^{86}\text{Sr}$	Range of $^{87}\text{Sr}/^{86}\text{Sr}$	Reference*
Marine Sediment				
Atlantic Ocean	59	0.7166	0.7044 - 0.7429	1
Atlantic Ocean	16	0.7162	0.7067 - 0.7268	2
Argentine Basin	60	0.7084	0.7041 - 0.7172	3
Ross Sea	26	0.7179	0.7100 - 0.7264	4
Red Sea	29	0.70707	0.70556 - 0.70998	5
Black Sea	16	0.7147	0.7102 - 0.7306	6
Black Sea	18	0.7135	0.7077 - 0.7179	7
Weighted Average	224	0.7129	0.7041 - 0.7429	
Continental Sediment				
LaPlata Estuary	11	0.7192	0.7100 - 0.7304	3
Lake Superior	10	0.7397	0.7377 - 0.7419	8
Paleozoic Shale	2	0.7215	0.7204 - 0.7226	9
N. America Composite Till, Ohio	11	0.7345	0.7288 - 0.7414	10
Weighted Average	34	0.7303	0.7100 - 0.7419	

* 1. Dasch (1969) 2. Murthy and Beiser (1968) 3. Biscaye and Dasch (1971) 4. Shaffer and Faure (1976) 5. Boger and Faure (1976) 6. Nardone and Faure (1978) 7. Cooper *et al* (1974) 8. Hart and Tilton (1966) 9. Faure and Hurley (1963) 10. This study.

ratio of till in the Powell-Union City Moraine can be discussed most effectively by means of a parameter R which is defined as:

$$R = \frac{{}^{87}\text{Sr}/{}^{86}\text{Sr} - 0.704}{{}^{87}\text{Rb}/{}^{86}\text{Sr}}$$

This parameter removes the effect of the variable Rb/Sr ratio of the sediment on its ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ ratio and reflects only its age relative to an arbitrary, but reasonable, initial ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ ratio of 0.704. Values of R were calculated for each sample using the data in table 1 and are plotted in figure 5. In spite of considerable scatter in the value of R along the strike of the moraine, a general increase from east to west is indicated. Such a trend may result from one or several of the following causes: 1) The age of sediment (primarily feldspar) derived from the Precambrian Shield of Canada increases along the moraine from east to west due to a change in provenance from the Grenville to the Superior Province; 2) The abundance of the Precambrian component in the till relative to locally-derived non-carbonate sediment increases without a change in its age; 3) The age of the non-carbonate component derived from local bedrock increases from Mississippian in eastern Ohio to Silurian in central and western Ohio.

The predominance of sediment derived from local bedrock was strongly suggested by the grainsize distribution and carbonate content of the till discussed above. Additional evidence was obtained from the numerical values of R which ranged from about 0.0060 at the eastern end of the moraine to about 0.0075 in western Ohio. These values are transformable into dates (assuming that the decay constant of ${}^{87}\text{Rb}$ is $1.42 \times 10^{-11}\text{y}^{-1}$) of about 425 and 530 million years, respectively. The dates are within the early Paleozoic era and thereby indicate that sediment of Paleozoic age greatly dominates over Sr-bearing minerals of Precambrian age. The trend of increasing radiogenic ${}^{87}\text{Sr}$ per unit ${}^{87}\text{Rb}$ that is implied by the westerly increase of R is probably due to a combination of all three factors listed above, but the absolute value of R is determined by the

dominance of locally derived sediment of Paleozoic age.

The properties of till were remarkably systematic with regard to grainsize distribution, mineral composition and bedrock lithology in the path of the ice. These relationships result from the grinding action of ice acting on rocks and minerals of differing mechanical properties. Complete granulometric analyses combined with the determinations of the mineral composition of systematically collected till samples can provide basic information about the grinding of sediment during transport by ice and about the sources of specific rock or mineral particles in till.

Our measurements of ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ ratios in the clay-silt fractions (non-carbonate) of late Wisconsin till in Ohio are in excellent agreement with previous estimates of the isotopic composition of Sr in the rocks of the continental crust. The relatively low content of radiogenic ${}^{87}\text{Sr}$ per atom of ${}^{87}\text{Rb}$ is consistent with the conclusion that a large proportion of this size fraction is derived from the local sedimentary rocks of Paleozoic age. The results of this study lead to the conclusion that feldspars are the principal Sr-bearing silicate minerals in the late Wisconsin tills of Ohio and that these feldspars originated predominantly from the Precambrian Shield of Canada. The abundance, chemical composition and ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ ratio of feldspars may therefore provide information about the provenance of the Precambrian component in Wisconsin tills of Ohio.

Acknowledgments. We are pleased to acknowledge the helpful discussions and advice we have received from R. P. Goldthwait, S. E. White, G. W. White, and Ian Whillans. The Department of Geology and Mineralogy helped us with a small grant for the purchase of topographic maps. This paper is Contribution No. 47 of the Laboratory for Isotope Geology and Geochemistry of The Ohio State University. The research project was supported, in part, by the National Science Foundation through Grant DPP76-11871-A01.

LITERATURE CITED

- Biscaye, P. E. and E. J. Dasch. 1971. The rubidium, strontium, strontium-isotope system in deep sea sediments: Argentine Basin. *J. Geophys. Res.* 76: 5087-5096.
- Boger, P. D. 1976. A study of the history of sedimentation in the Red Sea by means of iso-

- topic and geochemical methods. Unpubl. Ph.D. dissert., Dept. Geol. Mineral., Ohio State Univ., Columbus, 171 pp.
- and G. Faure 1974 Systematic variations of sialic and volcanic detritus in piston cores from the Red Sea. *Geochim. Cosmochim. Acta* 40: 731-742.
- Bownocker, J. A. 1920 Geologic map of Ohio. Division of Geological Survey, Dept. of Natural Resources, Columbus, OH.
- Cooper, J. A., E. J. Dasch and M. Kaye 1974 Isotopic and elemental geochemistry of Black Sea sediments. In: E. T. Degens and D. A. Ross (eds.) *The Black Sea—Geology, Chemistry, and Biology*, 554-565. Amer. Assoc. Petrol. Geologists, Tulsa, OK.
- Cosgrove, M. E. and A. M. A. Sulaiman 1973 A rapid method for the determination of quartz in the sedimentary rocks by x-ray diffraction incorporating mass absorption correction. *Clay Minerals* 10: 51-55.
- Dasch, E. J. 1969 Strontium isotopes in weathering profiles, deep-sea sediments, and sedimentary rocks. *Geochim. Cosmochim. Acta* 33: 1521-1552.
- Dreimanis, A. and U. J. Vagners 1969 Lithologic relation of till to bedrock. In: H. E. Wright, Jr. (ed), *Quaternary Geology and Climate*, p. 93-98. Natl. Acad. Sci. Publ. No. 1701, Washington D.C.
- and — 1971 Bimodal distribution of rock and mineral fragments in basal tills. In: R. P. Goldthwait (ed), *Till, A Symposium*, p. 237-250. Ohio State Univ. Press, Columbus, 402 pp.
- and R. P. Goldthwait 1973 Wisconsin glaciation in the Huron, Erie and Ontario lobes. *Geol. Soc. Amer., Mem.* 136, p. 71-105.
- Faure, G. 1977 *Principles of isotope geology*. Wiley and Sons, New York, 464 pp.
- and P. M. Hurley 1963 The isotopic composition of strontium in oceanic and continental basalts: Application to the origin of igneous rocks. *J. Petrology* 4: 31-50.
- , — and H. W. Fairbairn 1963 An estimate of the isotopic composition of strontium in rocks of the Precambrian Shield of North America. *J. Geophys. Res.* 68: 2323-2329.
- and J. L. Powell 1972 *Strontium isotope geology*. Springer Verlag, New York, 186 pp.
- Flanagan, F. J. 1973 1972 values for international geochemical reference samples. *Geochim. Cosmochim. Acta* 37: 1189-1200.
- Forsyth, J. L. 1956 *The Glacial Geology of Shelby and Logan Counties, Ohio*. Unpubl. Ph.D. dissert., Dept. Geol., Ohio State University, Columbus.
- Goldschmidt, V. M. 1954 *Geochemistry*. Oxford Univ. Press.
- Goldthwait, R. P. 1971 Introduction to till, today. In: R. P. Goldthwait (ed), *Till, A Symposium*, 3-26. Ohio State Univ. Press, Columbus, 402 pp.
- , G. W. White and J. L. Forsyth 1961 Glacial map of Ohio. U.S. Geol. Survey, *Miscell. Geol. Inv. Map* I-316.
- Hart, S. R. and G. R. Tilton 1966 The isotope geochemistry of strontium and lead in Lake Superior sediments and water. In: J. S. Steinhart and T. J. Smith (eds), *The Earth Beneath the Continents*, Amer. Geophys. Union Geophys. Monograph 10: 12-137.
- Moorbath, S. 1977 Ages, isotopes and evolution of Precambrian continental crust. *Chem. Geol.* 20: 151-187.
- Murthy, V. R. and E. Beiser 1968 Strontium isotopes in ocean water and marine sediments. *Geochim. Cosmochim. Acta* 32: 1121-1126.
- Nardone, C. D. and G. Faure 1978 A study of sedimentation at DSDP Site 379 A, Black Sea, based on the isotopic composition of strontium. Initial Reports of the Deep Sea Drilling Project, U.S. Printing Office, Washington D.C. 42: 607-615.
- Pettijohn, F. J. 1975 *Sedimentary rocks*, 3rd ed. Harper and Row, New York. 628 pp.
- Raukas, A., D. M. Mickelson, and A. Dreimanis 1978 Methods of till investigations in Europe and North America. *J. Sed. Pet.* 48: 285-294.
- Reynolds, R. C., Jr. 1963 Matrix corrections in trace element analysis by x-ray fluorescence: Estimation of the mass absorption coefficient by Compton scattering. *Amer. Mineral.* 48: 1133-1143.
- Selby, A. C. 1978 *Glacial geology of Darke County, Ohio*. Unpubl. M.S. thesis, Dept. Geol. Mineral., Ohio State University, Columbus.
- Shaffer, N. R. and G. Faure 1974 Regional variation of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and mineral compositions of sediment from the Ross Sea, Antarctica. *Geol. Soc. Amer. Bull.* 87: 1491-1500.
- Smeck, N. E., L. P. Wilding and N. Holowaychuk 1968 Genesis of argillic horizons in Celina and Morley soils of western Ohio. *Soil Sci. Soc. Amer. Proc.* 32: 550-556.
- Taylor, K. S. and G. Faure 1978 Use of strontium isotopes as indicators of provenance of till from the Powell Moraine, Ohio. *Abstract. Ohio J. Sci., Program and Abstract Supplement*, 78: 33.
- Wilding, L. P., L. R. Drees, N. E. Smeck, and G. F. Hall 1971 Mineral and elemental composition of Wisconsin-age till deposits in west-central Ohio. In: R. P. Goldthwait (ed), *Till, A Symposium*, 290-317. Ohio State Univ. Press, Columbus, 402 pp.

APPENDIX

Sample Locations

- Fulton:** Road cut on north side of county road 529 (elevation 1150 ft.) on property of William and Elsa LaRoche (1975) in Section 28 of Lincoln Township in Morrow County.
- Galena:** Cut along state road 61 (elevation 910 ft.) in Galena on property of Galena Shale, Tile and Brick Co. in Section 17 of Berkshire Township in Delaware County.

- Powell E:** Basement excavation (elevation 870 ft.) on property of James L. Wilcox Co. west of Jewitt Rd. in Section 15 of South Liberty Township in Delaware County.
- Powell:** South wall of embankment at the junction of Ches. & Ohio Railroad and Smoky Row Road (elevation 910 ft.) south of Powell on the property of the F. R. Schmidt Excavation Co. in Section 27 of Liberty Township in Delaware County.
- New California:** Gully of northeast tributary of Sugar Run on Mitchell-Dewitt County Road (elevation 950 ft.) about 0.75 miles west of state road 33 in Union County.
- Pottersburg:** Gully of northeast tributary of Big Darby Creek on West Darby Rd. (elevation 1072 ft.) about 70 feet west of Smokey Rd. in Union County.
- East Liberty:** Northeast bank of pond on south side of Route 347 (elevation 1140 ft.) about 0.25 miles west of East Liberty in Union County.
- Rushsylvania:** Road cut on north side of county road 50 (elevation 1210 ft.) about 0.40 miles west of state road 47 in Logan County.
- Logansville:** Excavation for telephone line on south side of state route 47 (elevation 1030 ft.) about 0.25 miles east of state route 508 in Logan County.
- Sidney:** Cut along state road 47 (elevation 1040 ft.), 3.5 miles west of interstate 75 in Shelby County.
- Piqua:** Road cut north side of state route 185 (elevation 1000 ft.) about 1.9 miles west of Moffett Rd. at Piqua airport in Miami County.
- Gettysburg:** North bank of road cut on U.S. Route 36 (elevation 1000 ft.) 0.55 miles south west of state road 721 in Darke County.
- Greenville:** Cut on south side of U.S. route 36 (elevation 1025 ft.) on property of East Zion Church in Darke County.