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THE OFFSHORE SEDIMENTS OF LAKE WINNIPEG

by

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ERRATA

p. 8, column 1, line 54	The reference should be to Brunskill and Schindler et al. 1979, Figs. 4-9.
p. 9, column 1, line 2	...kurtosis values of 0-14 (graphic kurtosis range = 0.6 to 2.4).
p. 12, column 1, reference 9	Should be: Brunskill, G. J., D. W. Schindler, S. E. M. Elliott, and P. Campbell. 1979. The attenuation of light in Lake Winnipeg. Can. Fish. Mar. Serv. MS Rep. 1522: v + 79 p.

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ABSTRACT

Brunskill, G. J. and B. W. Graham. 1979. The off-shore sediments of Lake Winnipeg. Can. Fish. Mar. Serv. MS Rep. 1540: v + 75 p.

Samples of surface sediments of Lake Winnipeg were taken with dredges at 50 stations, and 1 to 2 m cores were taken at 13 stations. Suspended and bottom sediments of the Red River were also obtained. Over 70% of off-shore sediment samples were silty clays or clayey silts. Coarser sediments near shore were not adequately sampled. The major minerals in sediment samples were quartz, feldspars, dolomite, calcite, illite, the montmorillonite group, and chlorite and kaolinite. Water content varied from 27% to 80%. Inorganic carbon (C_i, dolomite and calcite) varied from 83 to 3500 μmoles C_i/g, and organic carbon (C_o) varied from 166 to 3920 μmoles C_o/g. Total phosphorus (ΣP) in sediment samples varied little (13 to 27 μmoles P/g) throughout the lake, whereas total nitrogen (ΣN) varied over a wider range (<7 to 286 μmoles N/g). Dilute acid or buffered NTA extracted 40% to 70% of ΣP in sediments, but the sediment sorbed orthophosphate from solutions at concentrations similar to those of Lake Winnipeg water. Ratios of C_o, ΣN, and ΣP in sediments were not those expected for organic matter, and it is suggested that much of the ΣN and ΣP in Lake Winnipeg sediments is inorganic. Among the major elements of the sediments, Al was most strongly correlated with the abundance of the clay fraction, Ca and Mg were correlated with C_i (likely dolomite), and Si was correlated with the large particle sizes (likely quartz and feldspars in sands and silts). Trace elements (V, Cu, Co, Cr, Ni, Be, Cd, Mo, As, Zn, Pb, Sr, Mn) in these sediment samples varied little with location or sediment depth, but small increases in Hg concentrations near the sediment surface of several cores of the south basin were noted. Major and trace element data are also given for Red River suspended sediment, and an estimate of elemental sedimentation rates is given for the south basin of Lake Winnipeg. Major element data are reported for interstitial water squeezed from dredge samples. Sulfate was usually depleted in these interstitial waters, and Ca, Mg, Na, K, Cl, and Si were usually enriched, compared to overlying lake water.

Major basins of sediment accumulation in Lake Winnipeg are designated and described. The Saskatchewan, Cannibal, Mukutawa, Berens, and Black Bear Basins in the northern part of the lake are supplied with sediments primarily from shore and island erosion. The Red River Basin is provided with sediments from the Red River and shore erosion. Sedimentation rates for the Red River Basin ranged from 150 to 1970 g m^{-2} yr^{-1} over 1969-73, and sediment accumulation rates of 0.5 and 0.9 mm yr^{-1} were estimated from sonar penetration and Red River sediment supply rates. Sedimentation rates for C_o, ΣN, ΣP were computed, and were found to lie in the low part of the range for St. Lawrence Great Lakes sedimentation rates. Moment parameters for the particle size distributions of Lake Winnipeg sediment samples were compared to St. Lawrence Great Lakes data. Lake Winnipeg sediments approach a normal distribution of particle sizes, compared to St. Lawrence Great Lakes sediments. This is because most of the sediments supplied to Lake Winnipeg are pre-sorted silts and clays derived from glacial Lake Agassiz sediments.

Key words: sediment geochemistry; particle size; cores; interstitial water; sedimentation rates; trace elements.

RESUME

Brunskill, G. J. and B. W. Graham. 1979. The off-shore sediments of Lake Winnipeg. Can. Fish. Mar. Serv. MS Rep. 1540: v + 75 p.

Dans le lac Winnipeg, des échantillons de la couche superficielle de sédiments ont été dragués à 50 stations et carottés à une longueur de 1 à 2 m à 13 stations. Ont aussi été prélevés des échantillons de sédiments et de matières en suspension dans la Red River. Plus de 70% des échantillons prélevés loin de la rive se composaient d'argile limoneuse ou de limon argileux. L'échantillonnage des sédiments plus gros situés près de la rive, n'a pas été convenablement fait. Les échantillons renfermaient surtout du quartz, du feldspath, de la dolomite, de la calcite, de l'illite, du groupe de la montmorillonite, de la chlorite et de la kaolinite. La teneur en eau a varié entre 27 et 80%. La concentration du carbone inorganique (C_i, dolomite et calcite) s'est située entre 83 et 3,500 μmoles C_i/g et celle du carbone organique (C_o) entre 166 et 3,920 μmoles C_o/g. La concentration du phosphore total (ΣP) a été sensiblement la même dans tous les sédiments du lac (13 à 27 μmoles P/g) tandis que celle de l'azote total (ΣN) a varié fortement (7 à 286 μmoles N/g). Entre 40 et 70% du ΣP a été extrait à l'acide dilué ou au NTA tamponné, mais les sédiments ont absorbé les orthophosphates qui étaient à des concentrations comparables à celles que l'on trouve dans le lac Winnipeg. Les proportions de C_o, de ΣN et de ΣP n'ont pas été ce que l'on s'attendait à trouver dans de la matière organique ce qui laisse supposer que la majeure partie de ΣN et de ΣP des sédiments du lac Winnipeg est inorganique. Parmi les principaux éléments figurent Al, attribuable sans doute à l'importance de la fraction argileuse, Ca et Mg, liés au C_i (sans doute à dolomite), et Si, en provenance des grosses particules (sans doute le quartz et le feldspath du sable et du limon). Les échantillons renfermaient des éléments à l'état de trace (V, Cu, Co, Cr, Ni, Be, Cd, Mo, As, Zn, Pb, Sr, Mn) dans des concentrations analogues en dépit de leur provenance ou de la profondeur à laquelle ils avaient été prélevés. Dans certaines carottes du bassin du sud, de légères augmentations de la concentration de Hg ont cependant été observées près de la couche superficielle des sédiments. Des données sur les éléments principaux et à l'état de trace présents dans les sédiments suspendus de la Red River sont aussi fournies, ainsi qu'une évaluation de la sédimentation de base dans le bassin du sud du lac Winnipeg. Les teneurs en éléments principaux sont celles de l'eau interstitielle des échantillons dragués et essorés. Par rapport à la couche d'eau supérieure, l'eau interstitielle renfermait moins de sulfates et plus de Ca, de Mg, de Na, de K, de Cl et de Si.

Les principals bassins d'accumulation des sédiments dans le lac Winnipeg sont recensées et décrites. Les bassins (Saskatchewan, Cannibal, Mukutaoua, Berens et Black Bear) situes dans la partie septentrionale du lac se chargent surtout de sédiments formés par l'érosion des rives et des îles. Quant au bassin Red River, les sédiments qu'elle renferme proviennent de l'érosion des rives et de cette rivière. Entre 1969 et 1973, les vitesses de sédimentation y ont varié entre 150 et 1970 g.m^{-2}.an^{-1}, et d'après des sondages et des données sur l'apport de matières par la Rouge, leur accumulation, entre 0.5 et 0.9 mm.an^{-1}. Comparativement à celle des Grands lacs du Saint Laurent, la vitesse de sédimentation de C_o, de ΣN et de ΣP est faible. Si l'on compare la répartition granulometrique des sediments dû lac Winnipeg à celle des Grands lacs, il ressort que, dans le premier, cette répartition s'approche de la normale. Cela est dû au fait que la majeure partie des sédiments, en provenance du lac Agassiz glaciaire, sont constitués d'argile et de limon déjà répartis uniformément.

Mots-cles: géochimie des sédiments; granulométrie; carottes; eau interstitielle; vitesse de sédimentation' éléments à l'état de trace.

INTRODUCTION

Early explorers passing through the Lake Winnipeg watershed occasionally commented on the muddy waters of the lake and the Red River (Ross 1856, p. 9; Palliser's Journals of 1857-1860 in Spry 1968, p. 11, 88, 94; Upham 1890, p. 18E). The deposition and resuspension of this Red River sediment load in Lake Winnipeg were observed by Upham (1890), who was also the first to study rigorously the geomorphology of the glacial lake deposits around the south basin of Lake Winnipeg. Upham (1890) gave the name Lake Agassiz to this Late Wisconsinan and Holocene body of water, the sediments of which are now found over some 518,000 km^2 of what is now Manitoba, Ontario, Saskatchewan, Minnesota, North and South Dakota (Elson 1967). Tamplin (1967) reviewed the history of Lake Agassiz research. Lake Agassiz clays and silts are now agricultural soils, and likely constitute the majority of the sediments carried to Lake Winnipeg by the Red River (and to a lesser extent, by the Winnipeg and Saskatchewan Rivers). These Lake Agassiz clays and silts appear to have been derived from Cretaceous shales and Quaternary glacial sediments to the south and west of the present Lake Winnipeg (Kushnir 1971) *via* rivers draining the Dakotas and as far west as the Rocky Mountains in Alberta (Teller 1976) during the Pleistocene. Sediment supply to the north basin of Lake Winnipeg in recent time *via* the Saskatchewan River appears to have been relatively less than the Red River sediment supply to the south basin of the lake. Upham (1890) noted that the north basin of Lake Winnipeg was relatively clear, compared to the south basin of the lake. Many early explorers commented on the trapping of Saskatchewan River sediment in Moose and Cedar Lakes (Mackenzie 1801, p. 115; Hopwood 1971, p. 85). Denis (1916, p. 123) indicated that the Saskatchewan River deposited much of its sediment load into Cedar Lake (about 80 mm/yr in some locations). Sediment supply to the north basin of Lake Winnipeg has been further decreased by the construction of numerous reservoirs on the Saskatchewan River from 1913 to the present (Report of the Saskatchewan-Nelson Basin Board, 1972). Lake Diefenbaker collects about 23 x 10^6 tonnes sediments yr^{-1}, and Tobin Reservoir collects about 15 x 10^6 tonnes yr^{-1}). Franklin (1823, p. 43) found the waters of the north shore of Lake Winnipeg rather turbid, however, and told a Cree story which accounted for the muddiness of the lake and its name (Winnipeg = muddy or dirty water in Cree).

The literature on Lake Agassiz sediments is concerned largely with beaches, outlet structures, clay stability for road and building construction, and general studies concerned with the history of that expansive and oscillating glacial lake. Much of this literature is reviewed in Mayer-Oakes (1967). We have been unable to find any references to the thickness or characteristics of Lake Agassiz sediments in the present Lake Winnipeg basin. Teller et al. (1976) have mapped the thickness of glacial sediments and bedrock topography in southern Manitoba. Kushnir (1971) speculates that some laminated clay clasts from dredged sediments from the south basin of Lake Winnipeg are subaqueous outcrops of glacial Lake Agassiz sediments, based partly on sonar reflections and clay mineralogy. The sediments carried by the Red and Assiniboine Rivers to the south basin of Lake Winnipeg are, of course, largely Lake Agassiz sediments.

Other studies on Lake Winnipeg sediments include Solohub and Klovan (1970), Solohub (1967), and Veldman (1969), who were concerned largely with nearshore and beach sediment movement, deposition, and particle size sorting. Wallace and Maynard (1924), Elson (1961), Ehrlich et al. (1955), Wicks (1965), Last (1974), and Teller (1976) gave chemical, mineralogical, and particle size data for Lake Agassiz sediments, which may be useful in studies of Lake Winnipeg sediments. Ward (1926) contributed an estimate of Red River sediment transport rates, particle size and chemical analyses of Red River suspended sediments, Red River bottom sediments, and Lake Winnipeg sediments near the mouth of the Red River. Bajkov (1930) briefly described and categorized surface sediments of Lake Winnipeg. There have been no synoptic chemical studies on Lake Winnipeg sediments, except for Allan and Brunskill (1977) which is part of this work.

We now give descriptive data for Lake Winnipeg sediment samples, interstitial water, and river-born sediments. Our objectives were to provide a whole lake view of Lake Winnipeg off-shore sediment texture, chemistry, and sediment supply rates, as a background for future detailed studies on selected problems.

METHODS

The CGS Bradbury (Department of Public Works, Selkirk, Manitoba) was utilized as a research vessel. Her draft of 1.8 meters prohibited sampling in many of the large, shallow water areas (5% to 10% of lake surface area) of Lake Winnipeg (Figs. 3 and 4). Sampling stations (Fig. 2, Table 1) were located with radar, radiocompass, sonar (20 khz), and ship speed from Canadian Hydrographic Service charts 6240, 6241, 6267 and 6251, which were accurate to a radius of 100 meters or better. Some stations were at sextant-located navigation buoys identified on the above navigation charts for the lake. Water and sediment samples from the Red, Assiniboine, and Winnipeg Rivers were taken from bridges near their mouths. Water and sediment samples from other rivers were taken near river mouths using small boats.

SEDIMENT SAMPLING

Surficial lake sediments from 50 stations were taken 3-12 October 1969 with Ponar grabs, Shipek, or Ekman dredges, and transferred into polyethylene containers which were stored at 4°C. Cores were taken with a weighted 2 meter Benthos gravity corer (with a core catcher in soft sediments) from 13 locations (see Table 20), and were stored in an upright position on the deck of the ship. The sediment was sealed in core tubes with overlying water while on the ship, and later stored at 4°C in a laboratory cold room. Analysis of surface sediments were done in 1969, but the cores were not extruded until early 1971. Cores were extruded with a piston, sliced into 5 cm intervals, dried and ground for storage in plastic vials. Core samples were also taken in 1975 by Dr. R. J. Allan using similar equipment, but the cores were sliced into 2 cm intervals immediately after arrival in the laboratory. Sonar transparent and sonar reflecting sediment layers were recorded on the instrument chart paper: thickness of sediment layers were read off the water depth calibrated scale. Comparison of sonar sediment thickness with core logs was not useful since sedimentation basin cores rarely penetrated more than 1 meter of sediment and cores would not penetrate the sediment in regions of sonar reflecting top sediment.

Suspended sediments in tributary rivers were taken with 10L van Dorn samplers, or with weighted 2L bottles which were allowed to fall through the water column. Bottom sediments were sampled with the above noted array of dredges. Suspended sediments in lake water were obtained by continuous-flow centrifugation of large (20-60L) volumes of surface water.

ANALYTICAL METHODS

Water content of the sediment was determined by loss of weight upon drying at 110°C, and loss on ignition was determined by heating these samples at 900°C for 4-6 hours. For most Lake Winnipeg sediment samples, loss on ignition at 900°C includes decrepitation of calcite and dolomite, as well as combustion of organic matter and loss of hydration water. Heating sediment samples in 100°C increments over the range 100° to 1000°C allowed individual estimates of organic matter, carbonate minerals, and waters of hydration (see Dean 1974). More detailed differential thermal analyses of the clay fractions from these samples and other Agassiz clays are given in Kushnir (1971) and Wicks (1965).

Particle size composition of sediments (in terms of fraction of sand (2000-50 μm), silt (50-2 μm) and clay (2 μm and smaller)) was determined by the sieve and pipette method of Jenning et al. (1922) and Robinson (1922). In a few samples, the centrifugation and settling method of Jackson (1956) was also used. We followed Folk and Ward (1957), Shepard (1954), and Carver (1971) to obtain sediment particle size graphic parameters.

Minerals in particle size fractionated and unfractionated sediments were identified by X-ray diffraction (Klug and Alexander 1954; Jackson 1956; Rex 1969) using a Philips diffractometer (PW 1010 Generator, PW 1352/10 Circuit panel, PW 1170/00 Automatic Sample Holder, AMR-3-202 Graphite Monochromator and Co or Cu radiation). Whole or fractionated sediment samples were cleaned with H_2O_2 and sonification, and pipetted onto 6 mm thick porcelain tiles for X-ray diffraction. Known mixtures of quartz, feldspar and selected clay minerals were used for calibration to estimate semi-quantitative mineralogical composition of the samples. Major elements (Si, Ca, Mg, K, Na, Fe, Al and Mn) in sediments were determined with a Perkin Elmer 403 atomic absorption spectrophotometer following the sediment dissolution technique of Suhr and Ingamells (1966). Total carbon and nitrogen were determined on dried (110°C), ground and well-mixed sediment samples with a Carlo Erba Model 1100 CHN-O analyzer (Hauser, 1973). Inorganic carbon (calcite and dolomite) was determined by the Stainton (1973) method as follows: a weighed quantity of dried ground sediment and the appropriate quantity of sulfuric acid were introduced into a glass ampoule which was then quickly sealed and autoclaved at 121°C for one hour. The liberated CO_2 was subsampled and measured on a Fisher-Hamilton gas partition chromatograph. Carbonate mineralogy was determined according to Tennant and Berger (1957) and Dean (1974). Total phosphorus was determined according to Andersen (1976). Sulfur was determined on a few samples by the University of Manitoba, Department of Earth Sciences, using a Leco Analyzer. Color of moist sediment in cores was determined by comparison with a Munsell Soil Color Chart (1954).

Interstitial water from the surface (roughly 0-20 cm) sediment samples and cores was extracted within a month of sampling by squeezing samples or sections of the core for 2 to 4 hours at room temperature, under 20-80 p.s.i., using an apparatus modified from the design of Reeburgh (1967); pH was measured with a Radiometer PHM4 (glass and calomel electrodes), conductivity with a Radiometer CDM-2c, major cations by a Perkin Elmer 403 spectrophotometer and major anions according to Stainton et al. (1974).

Trace elements and some major elements were measured by radio frequency plasma emission spectroscopy (Allan and Brunskill 1977; see Tables 14 and 15). Sediments for this analysis were refluxed with HF, HNO_3, and $HClO_4$, evaporated to dryness, and redissolved in 4% HNO_3. Mercury was determined by stannous sulphate reduction to arsine gas, complexation, and colorimetric measurement at 520 nm on a spectrophotometer.

Sediment phosphorus was extracted with 0.01 M nitrilotriacetic acid (NTA) according to Golterman's methods (Golterman 1977 and personal communication).

RESULTS

PARTICLE SIZE DATA

Sediment sampling station locations and water depth are shown in Table 1 and Fig. 2. Bathymetry of Lake Winnipeg is given in Figs. 3 and 4. Lake Winnipeg has a surface area of 23,750 km², a mean depth of 12 m, and a volume of 284 km³ (Brunskill, Elliott, and Campbell 1980). Table 2 gives particle size fractionation data for surface sediments at 50 stations in Lake Winnipeg. The sampling stations are biased toward the deeper-water localities because of the ship's draft, and therefore many of the sand-gravel-boulder sediments near shores, islands and reef localities were not sampled. Coarse sand, gravel, and boulders were commonly found or observed at stations along the east side of the north basin of the lake (Stations 21, 17), near shore or islands (12, 31, 68), and at river mouths (1, 29). These coarse sediments were often composed of dolomitic and calcitic sands, gravels, and boulders on the north, west, south, and south-eastern shores of the lake, most islands, and shallow areas. Sands, gravels, and boulders from igneous rocks of the Precambrian Shield were common on the east margin of the lake, but were also observed all around the lake margin in lesser abundance. According to Kushnir (1971), these Shield-derived coarse sediments are largely composed of quartz, feldspars, hornblende, pyroxene, muscovite, weathered biotite, sericitic and chloritic schists. The high proportion of sand at Station 39 is likely related to the proximity and easterly continuation of Long Point (part of The Pas Moraine, see Davies et al. 1962) which is composed of mostly sand and gravel. Over 70% of the sediment samples are silty clays and clayey silts (Fig. 5). This distribution of silt- and clay-sized particles throughout the lake is given in Figs. 6 and 7. These data (Table 2, Figs. 6 and 7) are not directly comparable to the particle size data of Kushnir (1971), because Kushnir used different particle size boundaries for the clay and silt fractions (i.e., Kushnir used <3.9 μm for clay size, where we used <2 μm).

MINERALOGY

Table 3 gives the proportion of carbonate minerals found in selected Lake Winnipeg surface sediment samples. In general, sediments with >5% carbonate were near river mouths or near the south, west, and north shores. Dolomite was nearly always more abundant than calcite. No aragonite was detected, although we know this mineral occurs in pelecypod and gastropod shells of the lake. Larger amounts of dolomite occur in lake sediments along the north and west shore of the lake (Stations 33, 31, 27, 60B), where Ordovician (Red River, Stony Mountain, and Stonewall Formation) dolomites, limestones, and shales outcrop as cliffs on the lake shore and as islands or reefs in the lakes (Davies et al. 1962). Surprisingly large amounts of dolomite were also found in the sediments of Traverse Bay (Stations 7 and 8), under the low ionic strength water plume of the Winnipeg River, and Kushnir (1971) claims that these carbonates were from locally derived aeolian sandy silts which were deposited after glacial Lake Agassiz finally was drained. The estimates of the proportions of calcite and dolomite in Lake Winnipeg sediments derived from incremental heating to 950°C (Dean 1974) given in Table 12 appear to overestimate dolomite, compared to the X-ray diffraction data in Table 3. With the exception of the Sturgeon Bay area (Stations 64-66), where sediments rich in abraded mollusc shells were seen, carbonate minerals appear to be allochthonous in origin, and were most abundant in the silt and sand fraction of the sediment. Carbonate minerals were also present in the suspended sediments of the Red and Assiniboine Rivers, and in Lake Winnipeg suspended sediment (Table 9) during the ice-free season.

The non-carbonate fraction of our Lake Winnipeg surface sediment samples was composed largely of quartz, feldspar, illite, montmorillonite clays, chlorite and kaolinite (Tables 4 to 8). Quartz and feldspar were most abundant in the sand and silt fractions, and the clay mineral groups montmorillonite, illite, chlorite and kaolinite (undifferentiated) were more abundant in the fine silt and clay fractions. In a few samples we attempted to differentiate chlorite from kaolinite by heating glycerated slides, and we found that kaolinite usually exceeded chlorite in abundance. Kushnir (1971) studied many of our south basin Lake Winnipeg samples in more detail, and found a very homogeneous distribution of these clay minerals in the clay particle size fraction throughout the south basin of the lake (Table 28). Based upon X-ray diffraction and differential thermal analyses, he found that the montmorillonite clays were interstratified with illite, that the illite was being transformed into an abnormal montmorillonite, and that the dominant exchangeable cation on the montmorillonite was Ca. In the clay-size fraction of the surface sediments, this complex montmorillonite group was frequently the dominant identifiable mineral (Tables 7 and 8).

The Red River is likely the main source for all of these minerals in the south basin of Lake Winnipeg (Table 9), and samples of suspended sediment from the Red and Assiniboine Rivers yield X-ray diffractograms similar to the surface sediments of the south basin. Suspended sediments in the lake waters were also mineralogically similar to Red River suspended sediments and the lake sediments.

ORGANIC MATTER AND NUTRIENT ELEMENT CHEMISTRY OF SURFACE SEDIMENTS

Data on water content, loss on ignition, C, N, and P for Lake Winnipeg surface sediments are given in Table 10. Water content varied from a low of 27% to almost 80%. Sediment with high water content was usually composed of silts and clays, had relatively high concentrations of organic matter, and were usually found in the deeper depositional basins shown in Figs. 25 and 26.

The loss on ignition and total carbon (ΣC) concentrations given in Table 10 are the sum of contributions by carbonate minerals, organic matter, and hydration water on clay minerals (for loss on ignition only). Since the ratio of inorganic (carbonate) carbon (C_i) to organic carbon (C_o) varies greatly, ΣC data are not directly meaningful. An independent gasometric measurement of C_i was obtained and subtracted from ΣC to estimate C_o in Lake Winnipeg sediments. Table 12 gives another estimate of the proportions of C_i and C_o in ΣC by the ignition method of Dean (1974), which agrees fairly well with Table 10. C_o varied from 166 to 3916 μmoles C_o/g of dry sediment. The lower values were associated with the largely inorganic sediments near the mouth of the Red River, and the northern and eastern margin of the north basin; higher values of C_o were obtained from sediment samples from near the mouths of rivers draining the Shield (Berens and Winnipeg) and in the narrows of the lake.

C_i varied from 83 to 3500 μmoles C_i/g (Table 10). Lower values of C_i were found in sediments from the narrows of the lake and much of the deep water areas of the north and south basin. Higher values of C_i were obtained from sediment samples from near the mouths of the Red and Winnipeg Rivers, and near the west and north shores of the lake, where dolomite and limestone cliffs occur (Baillie 1952).

Total phosphorus (ΣP) in Lake Winnipeg surface sediments varied little, from 13 to 27 μmoles P/g (Table 10). The lower values were found in sediments from stations along the northwestern shore of the north basin and at the mouth of the Winnipeg River. Higher values were found in sediments from stations along the northwestern shore of the north basin and at the mouth of the Winnipeg River. Higher values were found in sediments from the center of the north basin of the lake. The standard deviation of the mean ΣP concentration in Lake Winnipeg sediments is very small, considering the size of the lake and the differences in tributary drainages. These ΣP data in Table 10 are from acidification, combustion, and colorimetric methods described by Stainton et al. (1974) and Andersen (1976), whereas the ΣP data in Table 15 were determined by radio frequency plasma emission spectroscopy. Table 15 ΣP data show the same limited variation in concentration, but the absolute values are lower, compared to ΣP data in Table 10. Concentrations of ΣP in suspended sediments of the Red and Assiniboine Rivers (Tables 17 and 18) are well within the range of the surface sediment concentrations (Table 10), but suspended sediments in Lake Winnipeg have higher concentrations of ΣP (Table 18) than the sediments.

Experiments were done in the laboratory to determine the labile or exchangeable fraction of P in sediments from the center of the north and south basins of Lake Winnipeg (Table 11). A gentle leach with NH_4Cl released 10-12% of ΣP from these sediment samples, and dilute acid or NTA buffered to pH 7 removed 40-77% of ΣP.

These sediments sorbed orthophosphate from solutions at or above Lake Winnipeg PO_4 concentrations (see Brunskill, Schindler et al. 1980). Sorption of orthophosphate by sediments increased with increasing solution concentrations (1.6 to 9.6 μmoles/L) from 0.26 to 3 μmoles P/g sediment.

Total nitrogen (ΣN) varied considerably from <7 to 286 μmoles N/g. Minimal values were obtained from sediment samples near the mouths of the Red and Winnipeg Rivers, and from stations on the eastern and northern margins of the north basin. Higher values occurred in samples from the deep water central and western areas of the north basin, Berens River mouth, Pigeon Bay, and the Narrows.

The mole ratio $C_o:\Sigma N$ (Table 10) varied from 1.6 to 48. The extremely low $C_o:\Sigma N$ ratios of 1.6-4 are partially due to analytical difficulties with samples containing a high proportion of C_i compared to C_o, and possibly NH_4 sorbed to clay minerals (Kemp and Mudrochova 1972; Byrnes et al. 1972). $C_o:N_o$ ratios between 6 and 15 are representative of recently dead or living algae (Healey 1975), and $C_o:N_o$ ratios >15 probably represent an increasing proportion of organic matter derived from terrestrial soils. $C_o:\Sigma P$ ratios varied from 30 to 156, which is low compared to C:P ratios for other lake sediment or seston data (Brunskill et al. 1971; Schindler 1976). The mole ratio $\Sigma N:\Sigma P$ varied from 1.0 to 11.5, which is extremely low. Sewage has a N:P ratio of ≃11, and living plants have N:P of 10-40. As shown in Table 11, over 50% of sediment P cannot be extracted by acid, and likely is an allochthonous mineral form of P. There were no statistically significant linear relationships between C_o and ΣN ($r = 0.22$, $n = 44$), C_o and ΣP, ($r = 0.26$, $n = 46$), or ΣN and ΣP ($r = 0.24$, $n = 47$) for the sediment data in Table 10.

MAJOR ELEMENTS IN SURFACE SEDIMENTS

Major element composition of selected Lake Winnipeg surface sediment samples is given in Tables 13 and 14. The data in Table 13 are results of metaborate fusion and flame atomic absorption determination of the elements, whereas the data in Table 14 are from acid refluxing of sediments and determination by radio frequency plasma emission spectroscopy. The sediment analyzed by these two methods are from the same station and dredge sample, but are different subsamples. The differences between the results are likely due to the sum of subsampling, different sample preparation (fusion v.s. reflux), and different analytical determination. In most cases, we have used the data set in Table 14 because it is larger.

The most abundant elements are Si and Al, which are components of the clay fraction of the sediments, and also feldspar and quartz minerals. Al was significantly (at $\alpha = 0.05$) and linearly correlated with the abundance of clay in the sediment [$\text{Log Al} = 0.0244 + 0.2529 \text{ Log } (\% \text{ Clay})$, $r = 0.84$, $n = 26$], but Si was inversely and weakly correlated with the clay fraction [$\text{Si} = 12.9325 - 1.7352 \text{ Log } (\% \text{ Clay})$, $r = -0.45$, $n = 26$]. This latter finding implies that quartz and feldspars in the silt and sand fractions are an important control on the abundance of Si in these sediment samples.

Variations in sediment concentrations of Ca and Mg appear to be related to the abundance of carbonate minerals in these sediment samples. Ca from Table 14 was significantly related to C_i (carbonate carbon, in Table 10) according to the equation: $\text{Ca} = 0.2792 + 0.5361\, C_i$, ($r = 0.88$, $n = 50$). Since dolomite ($Ca\,Mg\,(CO_3)_2$) was the major carbonate mineral (Table 3) in most of these sediments, we might expect Ca + Mg to be even better correlated with C_i. Figure 9 confirms this, and the obtained slope of the relationship is near unity for the molar relationship. The intercept of Fig. 9 gives some indication of the proportion of Ca and Mg that may be fixed in clay minerals and plagioclase feldspars. There was no statistically significant correlation (at $\alpha = 0.05$) between Ca and % montmorillonite (Kushnir 1971; Table 28), which indicates that the relatively small carbonate fraction (Table 10) controls the variation of concentrations of Ca and Mg in these sediments, despite the much larger quantities of clay. There was an inverse correlation between Ca and log (% Clay), ($r = -0.42$, $n = 50$), which implies that $CaCO_3$ was more abundant in the silt and sand fractions of the sediment than in the clay fraction.

Na and K are most abundant in plagioclase and K-feldspar minerals, and illite (Tables 4 to 8) will likely carry some of the K. Iron, Mn and P are components of both the detrital mineral phase and the flocculent rusty-orange colored surface layer (0-1 cm) of the sediment. Fe was significantly correlated with the abundance of clay in the sediment [Log Fe = -0.7246 + 0.3792 Log (% Clay), $r = 0.75$, $n = 26$], and was also correlated with ΣP ($r = 0.89$ for south basin sample and $r = 0.83$ for north basin, $n = 21$ and 18). ΣP was not correlated with the abundance of the clay size fraction ($r = 0.31$, $n = 26$). Total sulfur determinations were done on sediments from 4 stations in the central south basin, which gave an average of 11 μmoles S g^{-1} dry weight (range = 7.2 - 13.8), and one station in the Narrows (Station 55) had 20 μmoles S g^{-1}.

Most of these major element concentrations for Lake Winnipeg surface sediments (Tables 13 and 14) were similar to concentrations in Red River suspended sediment samples (Tables 17 and 18), except for an apparent small enrichment of Si in the lake sediments compared to river sediments. The ratio Ca:Mg in Red River suspended sediments was <1 (Table 18), whereas this ratio in the lake sediments varied considerably (Table 13), and suspended lake sediments have Ca:Mg ratios >1 (Table 18). The ratio Na:K in river suspended sediments was generally <1 (Table 18), whereas lake sediments varied greatly (Table 13), and lake suspended sediment Na:K ratios were >1 (Table 18).

TRACE ELEMENTS IN SURFACE SEDIMENTS

Table 15 gives the results of analyses of Lake Winnipeg surface sediments for selected trace elements. With the exception of a few inexplicably high values (e.g. 1.34 μmoles Pb/g at Station 25) the variations in trace element concentrations were small. Sediment samples from near the mouth of the major rivers draining watersheds with agricultural and industrial activities were not detectibly enriched in trace elements (see Stations 1-4, 7 and 8, 25-27). In a following section on sediment cores, however, Hg was found to be above background levels in some cores (Table 24).

The variation of trace element concentrations is better viewed in proportion to some conservative parameter of the sediment. We chose Fe, Ti, Si, and Al as conservative elements in our work, because they are abundant in the sediment phase, relatively immobile in the well-oxygenated surface sediments, and they are unlikely to have been greatly affected by pollution sources. In Table 16 we give the average ratio of selected trace elements to conservative elements, or the slope of linear regressions of each trace element against each conservative element for 21 Lake Winnipeg sampling stations. This analysis indicates that V and Zn are more abundant, relative to Fe, Ti and Al, in south basin sediments, and that Ni, Cu, and P are more abundant, relative to Fe and Ti, in the north basin of the lake. Trace elements listed in Table 15 but not shown in Table 16 were not significantly correlated with the conservative elements used here. Some of these correlations were highly significant (see Figs. 10-16 for relationships with Ti) and can be improved by subdividing the data set into the major lake basins (south basin, narrows, and north basin). Similar relationships are shown for trace elements against Fe (Figs. 17-23) in which it appears that Ti is a better predictor of P (Fig. 16) than is Fe (Fig. 23).

Trace element concentrations in Lake Winnipeg sediments (Table 15) are similar to comparable data on Red River suspended sediments (Table 17). As and V are higher in concentration in the river sediments, and Sr and Ni are lower, compared to Lake Winnipeg sediments (Table 15).

RATES OF SUPPLY OF MAJOR AND TRACE ELEMENTS TO THE SOUTH BASIN OF LAKE WINNIPEG

The chemical data for suspended sediments from the Red River downstream from the City of Winnipeg (Tables 17 and 18) are used to estimate the composition of the mass of sediments carried to the south basin of Lake Winnipeg in a year. The samples of river suspended sediments in Tables 17 and 18 were taken during high spring discharges, when suspended sediment concentrations were relatively high (see Table 9). From this rather small data base, we calculated the annual rate of supply of major and trace elements in particulate form to the south basin of Lake Winnipeg (Table 19), utilizing complete seasonal 1969-1974 water discharge and suspended sediment concentration data from Water Survey of Canada (1969-1974).

The annual supply of each element was divided by the area of the 8 m contour (our estimate of the zone of fine sediment accumulation) of the south basin of Lake Winnipeg (see Fig. 3, and Brunskill, Elliott and Campbell 1980) to estimate an average sediment supply rate for each element. This elemental rate of supply is an estimate because only the Red River supply is considered, and supply from the Winnipeg River, other small rivers, nearshore and shore erosion is not estimated. Although annual discharge of the Winnipeg River is 4 to 10 times greater than the discharge of the Red River, its annual suspended sediment mass is usually less, due to its largely Precambrian Shield watershed (Brunskill, Elliott and Campbell 1980). During high discharge years (1969, 1974), the Red River transports nearly an order of magnitude more sediment ($\approx 3 \times 10^6$ tonnes yr^{-1}) than the Winnipeg River, but in low discharge years (1973) the two rivers transport nearly equal amounts of suspended sediment ($\approx 0.2 \times 10^6$ tonnes yr^{-1}). The large range for the estimated sediment supply rates is due to variations in annual discharge of water and suspended sediments. If this sediment has an average density of 2.5 tonnes m^{-3} the sedimentation rate of 1170 gm^{-2} yr^{-1} is equivalent to about 1 mm yr^{-1} in the area of the 8 m contour of the south basin of the lake. This sedimentation is primarily comprised of clay and silt particles which contain the major elements Si, Al, Mg, Ca, K, Fe, Na, and Ti, in order of abundance. Among the trace elements, sediment supply rates of Zn, Sr, Cr, and V are an order of magnitude greater than other trace elements (Table 19). Much of the coarse sediment near the mouth of the Red River is transported by bedload movement, and is not represented in this calculation.

CORES OF LAKE WINNIPEG SEDIMENTS

Location and general description of 14 cores of Lake Winnipeg sediments are given in Table 20. Despite the long storage time, many of the vertically-stored cores still had lake water over the sediment surface, and had about the same % H_2O in the surface 15 cm as the dredged samples (see Table 10). Maximum water content in surface sediments was 70-75%, whereas 25-50% water was found below 90 cm sediment core depth, or in association with silty sands in cores from Traverse Bay (Station 8) and Pigeon Bay (52). Many of the core bottom sediments were composed of conchoidally fractured or granular clay, which fell apart on the extrusion trough, as if the sediments were dry, yet these clays were 30-50% water.

Data for inorganic (C_i) and organic (C_o) carbon, ΣN, and ΣP in 5 cm intervals for these cores are given in Table 21. Data for the surface 0-20 cm of the core samples can be compared to data from the dredged sediment samples in Table 10. Although some of the data in Table 10 and 21 are similar, some show great differences, which seem likely to be due to sample location and sediment variation. C_i (as dolomite or calcite, see Table 3) was highest in Traverse Bay (Station 8) and lowest in the central north basin (Station 35) and narrows (Stations 54, 14) of the lake. Intermediate values were found in sediments from near the mouth of the Red and Saskatchewan Rivers (Stations 4 and 25). C_i variation with depth was small in most cores, but a two- to five-fold variation occurred in the cores from the narrows (Stations 14 and 54) and at the center of the north basin (Stations 35-2).

C_o in the core profiles showed little geographic variation throughout the lake (with exception of Station 59 core, which seems aberrantly low), and about a three-fold variation occurred with depth. Cores in the narrows (Stations 15 and 54) and Traverse Bay (Station 8) indicated a decrease in C_o with depth. ΣN was generally higher in sediments from the center of the north basin (Station 35) and the northern narrows (Station 54). Variation with depth for ΣN was usually less than two-fold, with only slight indications of a decrease with depth. The variation of P was small (two-fold) throughout the lake, and there was no trend in ΣP concentration with depth. The highest average ΣP concentration occurred off the mouth of the Saskatchewan River (Station 25). $C_o:\Sigma N$, $C_o:\Sigma P$ and $\Sigma N:\Sigma P$ were less variable than the same data from dredged surface sediments (Table 10), but still very low values occurred. The often chaotic variation with depth seems to be imposed on a slight decrease in these ratios with increasing depth.

Major element chemistry for selected Lake Winnipeg cores is given in Table 22. These data are in general agreement with similar data for dredged sediments (Tables 13 and 14). Ca and Mg are high in Traverse Bay core (8), and are nearly equimolar, reflecting their association as dolomite (see Table 3). Little variation with core depth occurred for Ca and Mg, except in cores from the mouth of the Red and Winnipeg Rivers (Stations 04 and 08), where these elements increased with core depth. There was little variation of Na and Al with depth. Fe was low in sediments from the Traverse Bay core (08), and high in cores from the north basin and central south basin. Fe tended to decrease in concentration with sediment depth at core stations 08 and 61, but opposite trends were also evident (Table 22). Mn increased with sediment depth at core stations 04 and 25, and decreased with depth at stations 08 and 35. Ti varied little throughout the lake and with sediment depth. As in Table 21, ΣP varied little throughout the lake and with sediment depth.

Trace element data for Lake Winnipeg cores are given in Tables 23 and 24, which are in reasonable agreement with the dredged sediment data in Table 15. The variation of Cd, Co, Ni, Sr, Cr, and Zn in core samples throughout the lake and with sediment depth was less than a factor of three. Lead varied four-fold in these samples, but no pattern could be discerned. Beryllium and Cu were found in lower concentrations in Traverse Bay (08), and higher values were found in the central north and south basin cores. Vanadium was found in lower concentrations in Traverse Bay (Station 08), and higher values were found in the south basin (Stations 04, 10, 57, 59, 61). Arsenic was higher in concentration in the central south basin (Stations 10, 61, 57, 59) and northern narrows (Station 54) compared to other cores. The variation of the Mo values seems chaotic. Because the variation in element concentrations is small, the few trends with depth are likely not meaningful without more detailed sampling. Another set of cores were taken in 1975 by R. J. Allan and staff (see Fig. 24 for core locations, and Table 24), which were sampled at 2 cm intervals. As and Mo show concentrations and depth profiles similar to those in Table 23. The concentrations of Hg in the sediments at the top of these cores are about two to three-fold greater than at the bottom of the cores (Table 24, cores 1, 3-5, 8 and 9 in Fig. 24).

INTERSTITIAL WATER OF SURFACE SEDIMENTS

Interstitial water from 4°C stored dredged surface sediments was squeezed from homogenized subsamples on the ship or in the laboratory at room temperatures within 2 months of sample collection. The data are given in Table 25, where interstitial water element concentrations are compared to concentrations of the element in lake water (usually from 1 m water depth, see Brunskill, Campbell and Elliott 1979). In most cases, concentrations of Ca, Mg, Na, K, Cl, and Si were greater in interstitial water than in overlying water. Si was 5-10 fold enriched in interstitial water, compared to lake water. Na was found in very high concentration in interstitial water from Station 31 in the northwest sector of the north basin.

DISCUSSION

SEDIMENTATION BASINS AND SEDIMENT SOURCES

Based upon bathymetry (Figs. 3 and 4), sediment particle size (Figs. 6, 7, 8), qualitative interpretation of sonar penetration into sediments, and textural stratigraphy of cores, we designate the major basins of fine sediment accumulation in Lake Winnipeg (Figs. 25 and 26). The large, northerly Saskatchewan Basin receives sediment from the Saskatchewan River, and shore and island erosion of the north and northwesterly shores of this part of the lake (Fig. 26, see also Back 1836, p. 60). Sonar profiles from the center of the Saskatchewan Basin to the north, west or to the east revealed a gradual transition from a 4-15 m thickness of sonar-transparent sediment overlying a more dense sonar-reflecting layer (the center of the sedimentation basin), to a thin, irregular or absent sonar-transparent sediment overlying irregular ("spiky" or "stepped") sonar-reflecting sediment or bedrock (nearshore and off shore areas of erosion of sediment transport). Surface sediments of the central and northern regions of the Saskatchewan Basin are clayey silts, whereas the southern part of the Saskatchewan Basin has largely silty sediments (see Figs. 6 and 7). The boundaries of the Saskatchewan and other basins proposed here are approximate, and require verification by increased sample coverage.

The Saskatchewan Basin is separated from the smaller Cannibal and Mukutawa Basins by a chain of sand and gravel islands (Georges, Little Georges, Big Sandy, Little Sandy, Cannibal Islands, see Hydrographic Chart 6241, or Fig. 25), shallow areas, and a slight sandy rise between Long Point and this island-shallows barrier (Fig. 8). The delineation of the Cannibal and Mukutawa Basins is based on sonar records and bathymetry alone. The major source of sediment to these basins must be island and shore erosion because there are no large rivers in this area. Sonar-transparent sediment thins gradually to the north, east and west of the Cannibal Basin. The Mukutawa Basin may reveal a curious sediment texture when it is more extensively sampled, as sediments to the east (Stations 19 and 20) are bedrock, gravels and sands, with fragments of a compact (sometimes laminated and/or vesicular) silty clay. The vesicular (honeycomb) silty clay samples often had adult beetles in the cavities, but it is unlikely that they formed the hole, because hole diameters varied from 1 mm to over 1 cm. Sonar profiles east and north of the Mukutawa Basin showed a very "spiky" bottom with little and irregular amounts of sonar transparent sediment. We interpret this condition to represent areas of sediment erosion and transport, and little recent sediment accumulation. George's Island sediments (Station 17, see Table 2) are mostly sand and silts, and are probably transported to both basins. The Mukutawa and Popular Rivers may contribute some sediment to the Mukutawa Basin, but the watershed is well-forested Precambrian Shield, and their water discharges are small.

The Berens Basin (Fig. 25) is supplied with sediment largely from erosion of Reindeer, Georges, and Berens Island, and possibly from shallow water sediments in Sturgeon Bay (Figs. 25 and 26). No large, sediment laden rivers enter the lake in this region. Sonar transects to the northeast, east, and southeast of the Berens Basin thin out abruptly to a hard, spiky, or stepped sonar-reflecting sediment which was either sand and gravel, or a hard, compact, often laminated and vesiculate, silty clay and clay (Stations 50, 50B, 50C, 50D). The 98% clay sediment samples from Station 50D (see Table 2, Fig. 7) are an example of this latter sediment, and it is probably a Lake Agassiz deposit being eroded and transported into the Berens Basin. Berens Basin surface sediments are largely silty clays (Figs. 6 and 7).

The Black Bear Basin (Fig. 26) probably receives most of its sediment from shore and nearshore erosion to the east, and island and shallow-water sediment erosion from the west. Sonar profiles within this basin indicate a variety of sediment types, from silty sand sonar-reflecting sediment, to sonar-transparent clayey silts with relatively high amounts of organic matter (Figs. 6 and 7, Table 10, Stations 15, 52, 53, 54, 55; and Table 2). Spiky, irregular sonar profiles occurred when approaching the east shore, indicating bedrock, coarse glacial till, or erosional surfaces. Black Bear Basin sediments, and most of the narrows south to Hecla and Black Island, are probably subjected to some sorting due to currents generated by wind-generated seiches and storm surges (Einarsson and Lowe 1968; Hamblin 1976; Kenney 1979). Based on bathymetry alone, sediments of the Black Bear Basin may be transported into the Berens Basin via the narrow channel between Berens Island and Berens River. Other small depositional basins occur in the narrows (such as in Washow (Humbug) Bay, to the west of Station 14), but most of the deeper areas of the narrows south of the Black Bear Basin are areas of erosion by wind-generated currents. Stations 13, 13B, and 13C have hard, sonar-reflecting sediments, gravels, or sediments that could not be sampled with our equipment (see Kushnir 1971; Table 3, Station 713). Net suspended sediment transport should be from south to north, from the south basin to the north basin.

The Red River Basin (Fig. 26) is supplied with sediment from the Red River (see Table 19), shore erosion (Veldman 1969), and to a lesser extent, the Winnipeg River. Kushnir (1971, Fig. 11) delineated two basins in this area, based upon clay content. Large amounts of sediments are also deposited in the Red River Delta (Netley Marsh) and off the mouth of the Red River. Sonar transects in the Red River Basin showed an apparent thickness of 7-8 m of sonar-transparent sediments (60-80% clay, see Fig. 7) in the center of the Basin, to essentially zero thickness (sand and gravel) in the nearshore zones to the north, east, and west. At nearshore stations 12, 58, 62, 60B, and 9, we found either sands and gravels, or a compact, laminated and/or vesicular silty clay (Figs. 6, 7, 8; Table 2; see also Kushnir 1971). Veldman (1969) describes south basin shore erosion and littoral sand transport, and Solohub (1967) and Solohub and Klovan (1970) studied the usefulness of computed sediment particle size parameters as indicators of deposition environments in a Grand Beach lagoon, bay-mouth bar, and nearshore zone of the southeast shore of Lake Winnipeg. These latter authors found that graphic and moment parameters of grain size distributions failed to identify known environments of deposition (beach, aeolian dunes, channels, deltas, off-beach deepwater, reef, and lagoon), whereas factor analyses (Klovan 1966) did sort the samples into different types and energies of deposition.

With some exceptions, most of the lake bottom outside the depositional basins named here (Figs. 25 and 26) are areas of sediment erosion and transport. Much of the eastern margin of the lake bottom has sediments characteristic of old glacial lake sediments which are now being eroded and transported into the deeper basins. With exception of the southeast shore of the south basin, the east shoreline and terrestrial watershed of the lake is of igneous bedrock and does not appear to be contributing large amounts of sediment to the lake basins. The more erodible northern, western, and southern margins of the lake, however, are likely contributing a fairly large amount of sediment to the lake basin. If most of the Saskatchewan River's sediment load is deposited in Cedar and Moose Lakes (and recently the Grand Rapids Reservoir), which are part of the Saskatchewan River Delta (see Franklin 1823, p. 46-47; Mackenzie 1801, p. 115; Hopwood 1971, p. 85; and Denis 1916, p. 123), then much of the inorganic sedimentation in the Saskatchewan, Cannibal, and Mukutawa Basins must be derived from shore and island erosion. In the north basin, wind fetch is >200 km, wind velocities reach 30 km/hr, and we observed >1 m waves. Under these conditions, and by comparison to shore erosion studies at South Indian Lake (Newbury et al. 1978), erosion on the north shore of the north basin could be 10-20 m^3 of fine sediment per meter of shoreline. We estimate that sedimentation rates of 140 to 2200 g m^{-2} yr^{-1} could occur over the area of the 16 m depth contour from erosion of the northern and western exposed shorelines of the north basin (based on the data and methods of Newbury et al. 1978, and Kachugin 1966). The northern and western margins of the north basin of Lake Winnipeg were often very turbid, from the shoreline out to 8-10 km offshore, in contrast to the relatively clear water in the center of the basin (see Figs. 4-9 in Brunskill, Schindler, et al. 1980). Considerable shore erosion in the south basin has been observed by Veldman (1969), but the dominant sediment source for the Red River Basin is likely the Red River (Table 19). The effect of the wind in controlling the path of the sediment-laden Red River plume was often observed on the ship and from the air. Strong on-shore winds also resuspended shallow water sediments and/or transported fine sediments into deeper waters (Sheng and Lick 1979).

IMPLICATION OF PARTICLE SIZE ANALYSES

Dickas (1970), Upchurch (1970), Sly (1977), and many others have successfully used grain size analysis of sediments to deduce the mode and energy of deposition. Solohub and Klovan (1970) found that the graphic and moment parameters (see Table 26) of sediment particle size distributions were not useful in distinguishing known environments of deposition in their study area (a lagoon and beach area near Grand Beach, on the east shore of the south basin of Lake Winnipeg). We also found that these parameters for the whole of Lake Winnipeg (Table 27) were of limited use in interpreting the energy associated with sediment transportation or deposition, at least in our set of samples. The inclusion of more samples of coarse sediments from nearshore environments might improve the range of these computed parameters, and facilitate more general comparisons. Our sediment samples ranged from about 2 mm sands to very fine clays, whereas many beaches, shorelines and sublittoral zones of Lake Winnipeg (which we did not sample) are composed of sorted and unsorted pebbles, cobbles, and boulders. Therefore, the following comments about particle size distributions and computed graphic measurements are relevant to offshore sediment areas only.

Mean particle size ranged from 3.7 to 10.8 ϕ with a south basin average of 8.13 ϕ, and the narrows and north basin averaged 7.5 ϕ. The standard deviation of $\bar{X}_\phi$ was moderate to low (0.8-1.5) for the clay sediment samples, quite variable for the silty sediments (≈2), and moderate for the sands (1.5-2) (see Fig. 27). Although the scatter at 6-7 ϕ (in Fig. 27) is great, the line indicated is similar to the shape of the same plot for Lake Erie and Ontario (Thomas et al. 1976; Thomas et al. 1972), except that our range of ϕ is restricted (>3 ϕ). Similar values of standard deviation were found in Lake Winnipeg, compared to the Erie and Ontario data. Figure 27 is interpreted as evidence for better sorting of the clays and sands, and lesser sorting of some of the silty sediments. The data were segregated into the major areas of the lake (south basin, narrows, north basin), and the same trend was observed as in Fig. 27.

Figure 28 shows the relationship between skewness of the sediment particle size distributions and mean particle size for 50 Lake Winnipeg sediment samples. Clayey sediments tended to be negatively skewed, and sandy sediments were positively skewed. This suggests that the greatly variable silt fraction of the sediments (Fig. 6) is present in both the sandy (near shore) and clayey (deeper) sediment zones. The trend of the data in Fig. 28 is similar to data plots for the St. Lawrence Great Lakes (Thomas et al. 1976; Thomas et al. 1972; Thomas et al. 1973; Sly 1977; Thomas and Jaquet 1975) but the values of skewness are closer to zero for the Lake Winnipeg sediments. Maximum positive values of skewness were for sandy sediments from near the mouth of the Red River (Station 1), near Hecla Island (12), near Georges Island (17), and near Eagle Island (31). Maximum negative values of skewness were found in clayey sediments from the center of the Red River Basin (Stations 59, 59B, 60, 60B), the Berens Basin (48, 64), the western margin of the Saskatchewan Basin (25), and the northern part of the Black Bear Basin (52) (see Figs. 25 and 26).

The distribution of particle sizes in Lake Winnipeg sediments showed a slight trend toward graphic leptokurtosis, and most values were near +1 (Table 27, Fig. 29) over the range 3-12 ϕ. Moment kurtosis of Lake Erie and Ontario sediments varied from -2 to +20 (Thomas et al. 1972, 1976), whereas Lake Winnipeg samples gave moment kurtosis values of 0 to 14. The relationship of graphic kurtosis to skewness is shown in Fig. 30, which indicates that the Lake Winnipeg offshore sediment sample particle size distribution is closer to the normal distribution curve (Carver 1971) than sediments of the St. Lawrence Great Lakes (cf. Thomas et al. 1972, 1976). The three samples with anomalously high values of kurtosis in Figs. 29 and 30 are from Station 12 (near Hecla Island, a source of uniform sands), Station 01 (mouth of the Red River, likely bedload sands) and Station 31 (near the NW shore of the north basin, having limestone and dolomite cliffs). Sediment particle size distributions with larger standard deviations had generally lower values of kurtosis, compared to sediments having lower standard deviations (Fig. 31).

The significance of the results of the calculation of the four graphic parameters of Lake Winnipeg sediment particle size distributions is not immediately obvious. In comparison to the St. Lawrence Great Lakes sediment data (Thomas et al. 1972, 1973; Damiani and Thomas 1974), Western Lake Geneva (Vernet et al. 1972), and Lake Chad (Mothersill 1975), the Lake Winnipeg sediments appear to have small values of skewness and leptokurtosis. This implies bimodal populations of coarse silt and fine clay, with a deficiency of fine silt-sized particles. Yet the standard deviations about mean of the samples are similar to the above cited data, which would be interpreted as an indication of poor sorting in a lower energy environment. Due to Lake Winnipeg's shallowness ($\bar{Z}$ = 12 m), large surface area (A_0 = 23,745 km) and fetch, and exposure to strong prairie winds, the entire lake bottom is likely subjected to rather energetic water movements resulting from seiches, wind-driven current, and river plumes (Hamblin 1976; Einarsson and Lowe 1968). We propose that the apparent low sorting (high standard deviation about $\bar{X}_\phi$) of Lake Winnipeg sediments is due to the lack of a low energy (deep) sedimentation basin to act as a reservoir for the sorted sediments. There is likely more than adequate energy to sort sediment particle sizes, but there is an inadequate gradient of depth to allow the products of sorting to be segregated. Despite this high standard deviation, the sediments still approach a normal distribution of particle sizes. This seems likely due to a similarity of source materials, i.e. the surrounding glacial Lake Agassiz sediments. Last (1974) and Teller (1976) indicate that offshore Lake Agassiz sediment, south of Lake Winnipeg, averages 79% clay, 20% silt, and 1% sand, with the proportions of silt and sand increasing with proximity to glacial lake deltas, beaches, and glacial moraines and eskers. Wallace and Maynard (1924), Johnston (1934), Elson (1961, 1967), Wicks (1965), Smith et al. (1967), Last (1974) and Teller (1976) describe these fertile and erodible Agassiz sediments, glacial deposits and soils.

REACTIVITY OF THE SEDIMENTS

Kushnir (1971) and Wicks (1965) describe in detail the mineralogy of glacial Lake Agassiz sediments in the Red River watershed and in the present Lake Winnipeg. Much of the clay fraction of both these sediments was shown to be montmorillonite and a randomly interstratified, dioctahedral illite-montmorillonite (Table 28). The illite appears to be in transition to a montmorillonite structure, and the montmorillonite group of clays has Ca as the dominant exchangeable cation in the lake sediment (Kushnir 1971), whereas the watershed Agassiz sediments carry Ca or Mg as exchangeable cations. Suspended and bottom illitic clays in Lake Winnipeg are thus likely to take up Ca from lake or interstitial water. Computation of the appropriate ion activity products (according to Garrels and Christ 1965) indicates that the detrital dolomite and calcite should be dissolving in lake water and interstitial water (Brunskill, Campbell and Elliott 1979). Table 3 indicates that carbonate minerals were abundant near their source (rivers, island or shore erosion), but most deeper water sediments had little or undetectible amounts of carbonate minerals. Either the carbonates (probably mostly in the silt and sand sizes) are not transported to the major depositional basins (Figs. 26 and 27) or they are dissolved in these deeper sediments. Waters of the Winnipeg River are greatly undersaturated with respect to calcite and dolomite, and the relatively large amounts of these minerals in Traverse Bay surface sediments should be dissolving. The presence of carbonate minerals in Traverse Bay sediments under dilute water suggests that the rate of supply of carbonate minerals is greater than the rate of dissolution. In the higher ionic strength waters of Lake Manitoba, sedimentary calcite may be authigenic, according to Last (1979).

Lake Winnipeg bottom sediments (and likely suspended sediments) appear to act as a sink for phosphorus (Table 11), and about 50% of ΣP in the sediment is labile (leachable by dilute acid). ΣP may be sorbed or precipitated with the relatively abundant exchangable Ca of the sediment similar to soil reactions studied by Racz and Soper (1967). With increasing concentrations of P in solution, the sediment sorbed more P from the solution. Similar results were obtained by Harter (1968) for a eutrophic lake sediment in Connecticut. The sediment did not appear to be saturated with sorbed P, according to these experiments. Despite both sediment and algal uptake of P from the lake water, molybdate-reactive phosphorus remained in high concentration (0.5-3 µmoles TDP/L) throughout most of the lake waters (Brunskill, Schindler et al. 1980). In the unlikely event that P supply to Lake Winnipeg were greatly decreased, these sediments could act as a source of P to the extent of perhaps 10% of ΣP in clay-rich sediments (NH_4Cl extract in Table 11). Numerous studies on the movement and binding of P in Red River Valley soils (Racz and Soper 1967; Lewis and Racz 1969; and references therein) have been done, and they indicate that P is firmly and inorganically bound with Ca, Al, and Fe in soil profiles.

The proportions of organic carbon (C_0), total nitrogen (ΣN) and phosphorus (ΣP) in Lake Winnipeg sediments are not those expected for degradation products of terrestrial and aquatic biota (Table 10). The variation of C_0, ΣN, ΣP with sediment depth in the core samples (Table 21) does not show the usual decrease with depth attributed to diagensis of organic matter (e.g. see Kemp (1971)). We propose that many of the very low C_0:N ratios are due to sorption of NH_4 and other N species on the abundant clay fraction of the sediment. In the south basin of Lake Winnipeg, all sediment samples with low C_o:N ratios were from the center of the Red River Basin (where the sediment is 60-80% clay, see Fig. 7), whereas C_o:N ratios >10 were usually found within 10 km from shore. This relationship was completely reversed in the north basin of the lake, however, as all low C_o:N sediment samples were from nearshore areas, and C_o:N ratios >30 were found in the sediments of the Saskatchewan Basin. Kemp and Mudrochova (1972) found that a fraction of ΣN in Lake Ontario sediments was exchangeable and fixed NH_4, and that illite (see Table 28) was the clay mineral likely to immobilize NH_4 (Stevenson and Dhariwal 1959). In a similar manner, much (≈50%) of the Lake Winnipeg sediment P appears to be in a tightly bound, possibly crystalline form (Table 11). C_o:ΣP and ΣN:ΣP ratios for sediment samples depend largely upon variations in concentrations of C_o and ΣN, because ΣP is relatively uniform throughout the lake. There is insufficient C_o and ΣN for the P concentration of these sediments, relative to the composition of plant material (where C:P ≈85-260, N:P ≈10-40). Williams et al. (1976) partitioned Lake Erie sediment phosphorus into allochthonous apatite-P (in nearshore silts), nonapatite inorganic-P, and organic-P (in deep water clays).

SEDIMENTATION RATES AND ELEMENTAL SEDIMENT SUPPLY RATES

Our estimate of sedimentation rate (Table 19) for the Red River Basin (Fig. 26) is in the same range as estimated basin sedimentation rates for Lakes Erie and Ontario (Table 29). It seems likely that the Red River Basin sedimentation rate is at least twice the values given in Tables 19 and 29, since lake shore erosion, atmospheric (Teller 1972) and Winnipeg River contributions are not represented. If post-Agassiz or early Lake Winnipeg sedimentation began about 8000 years B.P. (Teller 1976; Teller and Fenton 1979), and if the sonar-transparent Red River Basin sediment thickness of 7-8 m represent this period of the lake's history (see also Kushnir 1971), then the average sedimentation rate in this basin would be 1.0 mm yr^{-1}. The southern and western lobes of the Saskatchewan Basin (Fig. 25) had sonar-transparent sediment depths of 12-15 m, which represents about 1.5 mm yr^{-1} accumulation rate.

Ringrose (1975, and personal communication) provided evidence indicating that the south basin of present-day Lake Winnipeg was dry during 7000-8000 yrs B.P., just before the final draining of Lake Agassiz to the north. Our Shipek sediment samples from nearshore stations along the northeastern shore of the south basin (Station 9, 6.4 m water depth, see Fig. 2) were compact, laminated, and sometimes vesicular silty clays and sandy clays. Some of the larger holes or tubes (1-10 mm in diameter) in the hard sediment were occupied by living adult beetles and fine organic matter. These samples could represent desiccated Lake Agassiz sediments with fossil root casts from terrestrial vegetation. Similar compact vesicular silty clays were found at Stations 50, 50B, 50C, and 19, along the eastern margin of the north basin, ranging in water depth from 5 to 16 m (Fig. 2) which would indicate a very low water stage for the north basin during this time. In any case Ringrose's (1975) hypothesis suggests that Lake Agassiz and post-Agassiz aquatic sedimentation may not have been continuous in the present Lake Winnipeg basin. Last and Teller (1979a, b) and Last (1979) interpret episodes of lake desiccation from sediment cores of adjacent Lake Manitoba, and they have radiocarbon dates of 9500, 8500, and 4500 yrs B.P. for these events. Their description of desiccated "marker horizon" (low % water) sediments is similar to our observations of "conchoidally fractured" or granular clay found at the bottom of most of our cores (Table 20). In Lake Winnipeg cores, this relatively dry sediment occurred at sediment depths of 50 to 110 cm in the south basin, narrows, and north basin, and represents sediments deposited 600 to 1200 yrs B.P. based on our speculative, indirect sediment chronology (1000-2000 g m^{-2} yr^{-1}) mentioned above. In the Lake Manitoba cores, the top-most horizon of desiccated sediment occurs at 3 m sediment depth, and ^{14}C sedimentation rates are 100-750 g m^{-2} yr^{-1} (Last and Teller 1979).

Ward (1926) gave an estimate of annual suspended sediment transport via the Red River to the south basin of Lake Winnipeg. Based on records from 1916 to 1926, he estimated that about 1.712 x 10^{12} g yr^{-1} of sediment was added to the south basin. If this sediment mass was deposited over the area of the 8 m contour in the south basin, it would be 986 g m^{-2} yr^{-1}, which is within the range of the 1969-73 data in Table 19. Ward (1926) also analyzed suspended and bottom sediments from the Red River in the City of Winnipeg and 4 miles off the mouth of the Red River in Lake Winnipeg. His major element data for these samples are in fair agreement with our data in Tables 17 and 18. A comparison of our 1969 data and Ward's particle size data for Red River and Lake Winnipeg sediments (Table 31) indicates that the river sediments in 1969 had more clay, and the 1969 Lake Winnipeg Station 4 has less clay and more sand, compared to the 1926 data. This change is consistent with the aggradation and procession of the Red River Delta. The Red River Delta is being slowly drowned because of the slow (≈15 cm/100 yrs, see Penner 1974; Johnston 1946) increase in elevation of land at the lake's outlet. This process is significant over geologic time, but probably would not affect sediment distributions over 50 years time.

Lake Winnipeg elemental sediment supply rates (Table 30) were usually on the lower side of ranges of sedimentation rates for Lakes Erie and Ontario, usually greater than the sedimentation rates of Lakes Superior and Huron, and surprisingly comparable to rates for California coastal sedimentation basins. We found a small increase in Hg concentration in surface sediments (relative to older sediments) from the Red River Basin, the mouth of the Red River, and Traverse Bay near the mouth of the Winnipeg River (Table 24). Armstrong and Hamilton (1973) found high (5-35 µmoles Hg/g dry weight) concentrations of Hg in bottom and suspended sediments of Clay Lake and the Wabigoon River system (downstream from a chlor-alkali plant at Dryden, Ontario). These waters are tributary to the Winnipeg River and Lake Winnipeg, and are a likely source for the higher Hg concentrations observed in Traverse Bay sediments. Derksen (1973) found slightly elevated Hg concentrations in waters and fish from the Assiniboine and Souris Rivers, which are tributary to the Red River and the Red River Basin. It is also known that municipal sewage is a source of Hg (van Loon 1974; F.A.J. Armstrong, personal communication), so it would appear that the City of Winnipeg and the Assiniboine River are also sources for the higher Hg values observed in surface samples of Red River Basin cores (Table 24). Industrial and municipal sources of Hg are also known on the Saskatchewan River (Wobeser et al. 1970, Uthe et al. 1973; Patterson and Nursall 1975), but we have no Hg data for the sediments of the north basin of Lake Winnipeg.

Hg concentrations began to increase in the top 14-22 cm of sediment cores from the Red River Basin (Table 24). If the sedimentation rate for this basin is ≈1 mm yr^{-1} (see above), then this depth of increasing Hg concentration is associated with 100-200 year old sediments. Perhaps this represents sediment mixing of technologically derived Hg into pre-settlement age sediments. Wolery and Walters (1974) used sediment depth of Hg increase to calculate sedimentation rates for western Lake Erie, based upon a known history of chlor-alkali industrial activity beginning in 1939. Thomas (1972) and Kemp et al. (1974) studied the distribution of Hg in pollen dated Lake Ontario cores. They found that sedimentary Hg profiles were in general agreement with industrial history, which indicates that initial Hg additions to the lake began in 1900. Some interstitial water samples did not show great enrichments of major ions or depletion of SO_4, relative to overlying lake water (Table 25), and for these stations, relatively complete mixing between surface sediments and lake water probably occurs. We plan to measure ^{210}Pb and ^{137}Cs on some of these cores, which will give us independent estimates of sediment mixing depth and sedimentation rates.

Brunskill (1973) gave a nutrient budget for Lake Winnipeg for 1969, and he reported the fraction of river supplied N and P which was retained in the lake (input - outflow) as 60% and 25%, respectively. If this mass of nutrient elements annually retained in the whole lake was sedimented into the Red River Basin (the 8 m contour in the south basin, Figs. 3 and 26) and the Saskatchewan, Cannibal, Mukutawa, and Berens Basins (the 16 m contour in the north basin, Figs. 4 and 25), the sediment supply rates would be 291 μmoles N m^{-2} yr^{-1} and 4.6 μmoles P m^{-2} yr^{-1}. This rough estimation indicates that N and P sediment supply rates in the Black Bear Basin, Berens Basin, Cannibal Basin, Mukutawa Basin, and Saskatchewan Basin (see Figs. 25 and 26) must be much less than in the Red River Basin (Table 30).

Allan and Brunskill (1977) discussed the variation of trace element concentrations in Lake Winnipeg sediments, based on some of the data given here in Tables 15-17. The enrichment of V (relative to Fe and Ti) in south basin sediments was thought to be related to small amounts of hydrocarbons and humic organic material in Cretaceous and Agassiz sediments of the Red River Valley, according to these authors. Although concentrations of some trace elements (Zn, Cr, V) were rather high compared to other lake sediment data, the co-variation of most of these trace elements with conservative elements (Fe, Ti, Al) (see Table 16) seems to indicate a relatively natural rate of supply of these elements. Linear correlation matrices of data in Tables 2, 10, 15, 27 showed that the abundance of C_O was not correlated with any of the trace elements determined, but that Cu, Zn, V, As and P were positively correlated with mean particle size (ϕ). Lacking individual sedimentation rates for each core, it is not feasible to identify sites of accelerated trace element deposition from Table 23. In most cases (with exception of Hg and Pb), there is little difference between trace element concentrations at core tops and bottoms. This is in marked contrast to the results of many sediment core studies on the St. Lawrence Great Lakes (Kemp and Thomas 1976a, b; Kemp et al. 1976; Kemp et al. 1978; Kemp and Dell 1976; Lineback and Gross 1972; Frye and Shrimp 1973; Walters et al. 1974; and others referenced therein) which demonstrate authropogenic enrichments of many trace elements in the surface 0-10 cm of deep sediments.

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Table 1. Longitude, latitude and maximum depth of water at Lake Winnipeg sediment stations, October 3-12, 1969. See also Fig. 2.

Sediment Station	Longitude (W)	Latitude (N)	Water Depth (m)
01	96°49'00"	50°23'15"	5.0
02	96 50 00	50 26 00	6.5
03	96 47 30	50 25 15	5.5
03C	96 37 15	50 27 45	5.5
03D	96 43 30	50 28 30	7.3
04	96 48 30	50 28 00	7.9
04B	96 52 30	50 29 30	7.6
05	96 38 15	50 40 45	10.8
06	96 35 30	50 45 30	10.9
07	96 22 45	50 39 00	14.0
08	96 28 30	50 44 45	8.5
10	96 34 00	50 55 15	15.5
12	96 37 45	51 06 16	11.0
14	96 38 00	51 26 30	9.5
15	96 50 00	51 44 00	26.2
17	97 38 30	52 48 30	13.0
18	97 30 00	52 40 15	16.8
21	97 51 30	53 26 15	17.0
23C	98 33 15	53 22 00	16.4
23E	98 15 00	53 16 00	17.4
23H	98 32 45	53 08 00	17.4
25	98 55 15	53 12 15	15.2
26	99 01 15	53 19 30	15.0
27	99 11 15	53 20 15	7.3
31	98 57 00	53 36 45	11.6
33	98 29 30	53 50 45	8.5
34	98 31 15	53 35 15	14.6
35	98 34 30	53 30 15	18.0
39	98 11 30	53 02 30	18.0
41	98 27 15	52 49 45	15.5
47	97 59 15	52 39 00	17.7
48	97 50 30	52 38 45	17.1
50	97 17 15	52 22 45	11.0
50D	97 23 00	52 35 15	12.8
51	97 01 15	52 21 15	4.5
52	97 08 15	52 17 15	10.4
53	97 07 45	52 07 15	9.1
54	97 02 30	52 00 00	12.5
55	96 56 15	51 51 45	11.0
56	96 43 00	51 36 30	26.0
57	96 48 30	50 52 00	11.6
59	96 44 30	50 41 30	11.0
59B	96 51 00	50 40 00	10.5
60	96 47 00	50 34 45	10.1
60B	96 57 00	50 38 00	8.5
60C	96 40 00	50 33 30	8.5
60D	96 54 15	50 36 30	9.1
61	96 48 15	50 31 30	10.1
64	97 37 45	52 14 30	16.2
68	97 25 00	52 06 15	13.4
69	97 10 45	52 00 30	11.0

Table 2. Particle size fractionation [sand (>50 µm), silt (50-2 µm), clay (<2 µm)] of Lake Winnipeg surface sediment samples (homogenized, 0-20 cm sediment depth), expressed as % of mineral fraction <2 mm in size, collected 3-12 October 1969.

Station	% Sand >50 µm	% Silt 50-2 µm	% Clay <2 µm
01	70.7	24.5	4.8
02	1.4	57.3	41.3
03	5.3	49.3	45.4
03C	1.7	67.7	30.6
03D	2.0	61.2	36.8
04	19.6	36.6	43.8
04B	0.8	51.3	47.9
05	0.4	40.5	59.1
06	4.2	59.2	36.6
07	18.3	68.4	13.3
08	0.8	49.6	49.6
10	0.9	28.1	71.0
12	76.5	14.9	8.6
14	16.2	57.1	26.7
15	30.2	52.5	17.3
17	49.4	23.7	26.9
18	3.5	69.7	26.8
21	40.7	24.1	35.2
23C	0.6	43.4	56.0
23H	4.0	81.6	14.4
28	0.5	34.1	65.4
26	2.5	69.0	28.5
27	3.7	74.3	22.0
31	79.7	16.5	3.8
33	3.5	62.3	34.2
34	3.3	65.3	31.4
35	0.5	67.6	31.9
39	39.0	36.2	24.8
41	1.0	58.4	40.6
47	0	62.9	37.1
48	1.8	26.0	72.2
50	10.3	42.1	47.6
50D	0.7	1.0	98.3
51	18.3	50.6	31.1
52	9.1	22.9	68.6
53	17.1	38.6	44.3
54	3.1	49.0	47.9
55	14.1	47.3	38.6
56	1.4	55.9	42.7
57	0.5	41.9	57.6
59	1.8	30.5	67.7
59B	0.5	18.7	80.8
60	0.6	31.1	68.3
60B	2.1	31.8	66.1
60C	0.9	45.6	53.5
60D	1.1	41.1	57.8
61	0.8	44.2	55.0
64	2.6	29.7	67.7
68	47.3	29.2	23.5
69	24.1	32.7	43.2
Red River in City of Winnipeg	3.6	44.9	51.5

Table 4. Mineralogy of the medium silt fraction (20-5 μm) of Lake Winnipeg surface (0-20 cm homogenized) sediments collected October 3-12, 1969.†

Mineral Station	Quartz	Feldspar	Illite	Chlorite plus Kaolinite	Montmorillonite
04	S*	S	S	S	S
08	M	M	S	S	-
10	S	-	S	S	S
14	M	M	S	S	S
25	M	M	M	M	-
35	L	L	M	M	-
52	M	M	S	S	-
54	L	L	S	S	S
57	M	-	S	S	S
59	S	S	M	M	M
60	S	S	S	S	M

* L = 8-20 times background trace, a large (>50%) component of the crystalline mineral phase of the sediment.

M = 5-8 times background trace

S = 2-5 times background trace, a small (<10%) component of the crystalline mineral phase.

(-) = none detected

† The method of Jackson (1958) was used. Calcite and dolomite were identified separately by X-ray diffraction on an unacidified sample.

Table 3. Quantitative X-ray diffraction carbonate mineralogy (according to Tennant and Berger, 1957) of Lake Winnipeg 0-20 cm homogenized sediments collected October 3-12, 1969.

Station	% Dolomite	% Calcite	Ratio Dolomite: Calcite	Station	% Dolomite	% Calcite	Ratio Dolomite: Calcite
01	13	11	1.2	33	10	29	0.4
02	12	7	1.7	34	8	< 1	> 8
03	8	7	1.1	35	1	< 1	> 1
03C	10	6	1.7	39	3	< 1	> 3
03D	7	6	1.2	41	4	< 1	> 4
04	5	4	1.3	47	6	< 1	> 6
04B	8	< 1	> 8	48	3	< 1	> 3
05	3	< 1	> 3	50	< 1	< 1	-
06	4	< 1	> 4	50D	< 1	< 1	-
07	19	2	9.5	51	< 1	< 1	-
08	13	< 1	>13	52	6	< 1	> 6
10	1	< 1	> 1	53	< 1	< 1	-
12	1	< 1	> 1	54	< 1	< 1	-
14	1	< 1	> 1	55	< 1	< 1	-
15	1	< 1	> 1	57	< 1	< 1	-
17	1	< 1	> 1	59	< 1	< 1	-
18	1	< 1	> 1	59B	< 1	< 1	-
21	1	< 1	> 1	60	3	< 1	> 3
23C	2	< 1	> 2	60B	15	< 1	>15
23E	1	< 1	> 1	60C	7	< 1	> 7
23H	7	< 1	> 7	60D	4	< 1	> 4
25	5	< 1	> 5	61	4	< 1	> 4
26	9	< 1	> 9	64	7	< 1	> 7
27	15	4	3.8	68	< 1	< 1	-
31	20	< 1	>20	69	< 1	< 1	-

Table 5. Mineralogy of the fine silt fraction (5-2 μm) of Lake Winnipeg surface (0-20 cm homogenized) sediments collected October 3-12, 1969.†

Mineral Station	Quartz	Feldspar	Illite	Chlorite plus Kaolinite	Montmorillonite
04	L*	-	M	M	-
08	L	M	S	S	-
10	L	M	S	S	-
14	L	L	-	S	-
25	M	S	S	S	-
35	M	M	M	M	S
52	L	M	S	S	-
54	M	M	S	S	-
57	M	S	S	S	S
59	M	S	S	S	S
60	M	S	M	M	S

* L = 8-20 times background trace

M = 5-8 times background trace

S = 2-5 times background trace

(-) = none detected

† The method of Jackson (1958) was used. Calcite and dolomite were identified separately by X-ray diffraction on an unacidified sample.

Table 6. Mineralogy of the total clay fraction (<2 μm) of Lake Winnipeg surface (0-20 homongenized) sediments collected October 3-12, 1969.

Mineral Station	Montmorillonite	Kaolinite plus Chlorite	Illite	Quartz	Feldspar
01	L	L	L	M	-
02	S	S	S	M	-
03	S	S	S	M	-
03C	L	L	L	M	-
03D	L	L	L	M	-
04	S	S	S	M	-
04B	L	L	L	M	-
05	L	L	L	M	-
06	S	S	S	M	-
07	L	L	L	M	-
08	L	L	L	M	-
10	L	M	L	M	M
12	S	S	S	M	-
14	S	S	S	M	-
15	L	L	L	M	-
17	M	S	S	M	M
18	M	M	M	M	M
21	M	S	S	M	M
23C	M	M	M	M	M
23E	-	L	L	S	S
23H	M	S	M	M	M
25	M	M	M	M	M
26	M	M	M	M	M
27	S	S	S	S	M
31	M	M	M	M	M
33	-	L	-	L	L
34	M	M	M	M	M
35	L	L	L	M	S
39	M	M	M	M	M
41	L	L	L	M	M
47	L	L	L	M	-
48	L	M	L	M	M
50	L	M	L	M	M
50D	L	M	L	M	S
51	L	L	L	-	-
52	M	M	M	M	M
53	L	L	L	L	L
54	M	M	M	M	M
55	M	M	M	S	S
57	L	L	L	L	L
59	M	M	M	S	M
59B	L	L	L	L	L
60	M	M	M	M	M
60B	S	S	S	M	M
60C	S	S	S	M	M
60D	M	M	M	M	M
61	L	L	L	L	L
64	M	M	M	M	M
68	M	M	M	M	M
69	S	S	S	S	S

* L = 8-20 times background trace

M = 5-8 times background trace

S = 2-5 times background trace

(-) = none detected

Table 9. Mineralogy of suspended sediments from rivers draining into Lake Winnipeg, and a station from the South and North Basin of Lake Winnipeg.

Location	Date	Suspended sediment mg/L	Montmorillonite	Kaolinite	Illite	Quartz	Feldspar	Dolomite	Calcite
Red River at Lockport (St. 00C)	11 May 1970	322	M*	M	M	S	S	M	M
Red River at South Perimeter Bridge (St. 00A)	27 April 1970	555	L	M	M	S	S	L	L
Assiniboine River at West Perimeter Bridge (St. 00B)	14 April 1969	High	M	M	M	M	S	M	M
Lake Winnipeg (St. 01)	3 Oct. 1969	85	S	S	S	S	-	-	L
Lake Winnipeg (St. 35)**	8 Oct. 1969	21	-	-	-	S	M	-	M

* L = 8-20 times background trace

M = 5-8 times background trace

S = 2-5 times background trace

(-) = none detected

** Very small amount of sediment sample

Table 7. Mineralogy of coarse clay fraction (2-0.2 μm) of Lake Winnipeg surface (0-20 cm homogenized) sediments collected October 3-12, 1969.†

Mineral Station	Quartz	Feldspar	Illite	Chlorite plus Kaolinite	Montmorillonite
04	M*	-	M	M	M
08	S	S	S	S	S
10	S	S	S	S	S
14	M	M	M	M	M
25	S	S	M	M	S
35	M	M	M	L	S
52	M	M	M	M	S
54	S	S	S	M	M
57	S	-	S	S	M
59	S	S	S	M	S
60	S	S	S	M	M

* L = 8-20 times background trace

M = 5-8 times background trace

S = 2-5 times background trace

(-) = none detected

† The method of Jackson (1958) was used. Calcite and dolomite were identified separately by X-ray diffraction on an unacidified sample.

Table 8. Mineralogy of medium clay fraction (0.2-0.8 μm) of Lake Winnipeg surface (0-20 cm homogenized) sediments collected October 3-12, 1969.†

Mineral Station	Quartz	Feldspar	Illite	Chlorite plus Kaolinite	Montmorillonite
04	-	-	-	-	M
14	S*	-	-	S	S
25	-	-	-	-	M
35	S	-	S	S	M
52	S	-	S	S	M
54	-	-	-	-	M
57	-	-	-	-	M
59	-	-	-	-	M
60	-	-	S	S	L

* L = 8-20 times background trace

M = 5-8 times background trace

S = 2-5 times background trace

(-) = none detected

† The method of Jackson (1958) was used. Calcite and dolomite were identified separately by X-ray diffraction on an unacidified sample.

Table 10. Water content (H_2O), expressed as % loss of weight of wet sample after drying to 110°C; % loss on ignition (L.O.I.) is after ignition of dry sediment at 900°C; total carbon (ΣC), carbonate carbon (C_i), organic carbon (C_o), total nitrogen (ΣN), total phosphorus (ΣP) are expressed as μmoles/g dry weight, with ratios on a molal basis for sediment samples (homogenized, 0-20 cm sediment depth) from Lake Winnipeg, October 3-12, 1969.

Station	% H_2O	% L.O.I.	ΣC	C_i	C_o	ΣN	ΣP	$C_o:\Sigma N$	$C_o:\Sigma P$	$\Sigma N:\Sigma P$
01	37.5	8.0	2000	1000	1000	-	20	-	50.0	-
02	60.0	12.5	3167	1500	1667	64	25	25.9	67.0	2.6
03	59.2	14.6	2333	1500	833	57	21	14.6	39.5	2.7
03C	61.1	13.7	2583	1500	1083	57	23	19.0	47.0	2.5
03D	71.0	13.7	2167	1167	1000	86	23	11.7	43.5	3.7
04	71.0	10.8	1583	833	750	79	25	9.6	30.0	3.2
04B	70.0	13.9	2083	1333	750	107	21	7.0	35.7	5.1
05	73.5	11.9	1833	417	1416	114	23	12.4	61.7	5.0
06	68.4	12.0	1583	583	1000	93	21	10.7	47.6	4.4
07	44.5	15.1	3583	2250	1333	71	17	18.7	78.2	4.2
08	57.3	13.2	3833	1417	2416	50	21	48.4	115.2	2.4
10	76.6	12.1	1500	83	1417	93	21	15.3	67.6	4.4
12	27.3	2.7	583	-	-	< 7	22	-	-	-
14	60.9	8.8	2333	250	2083	79	24	26.5	86.7	3.3
15	66.7	11.8	2500	167	2333	114	23	20.4	101.3	5.0
17	56.8	5.2	1000	83	917	< 7	20	-	46.0	-
18	76.9	10.8	1916	167	1749	157	24	11.1	72.9	6.5
21	52.0	4.6	1167	333	834	93	20	9.0	41.5	4.7
23C	77.4	8.5	1333	167	1166	28	26	40.8	45.0	1.0
23E	78.9	8.2	1583	167	1416	136	25	10.4	56.8	5.4
23H	77.8	11.8	2666	1000	1666	157	24	10.6	69.6	6.5
25	76.7	11.5	2000	500	1500	150	24	10.0	62.5	6.3
26	71.7	11.7	2417	417	2000	93	24	21.6	83.3	3.9
27	59.8	21.2	4000	2500	1500	157	19	9.6	78.9	8.3
31	28.2	10.3	4083	3500	583	150	13	1.6	44.6	11.5
33	35.3	15.6	3750	3000	750	50	16	1.6	44.1	2.9
34	72.5	13.2	2333	1250	1083	136	23	7.9	46.9	5.9
35	79.0	8.8	1500	250	1250	150	26	8.3	48.1	5.8
39	77.8	11.6	1667	333	1334	179	24	7.5	55.4	7.5
41	78.5	10.0	2000	583	1417	164	23	8.6	61.7	7.1
47	79.7	11.8	1917	667	1250	164	24	7.6	52.1	6.8
48	75.2	9.5	1833	417	1416	150	23	9.4	61.7	6.5
50	70.9	11.2	1917	333	1584	143	23	10.1	68.7	6.2
50D	40.5	4.7	333	167	166	50	19	3.4	8.9	2.6
51	70.5	15.4	4166	250	3916	286	25	13.8	156.8	11.4
52	55.1	7.4	2417	167	2250	171	23	13.2	97.8	7.4
53	69.0	11.5	1750	167	1583	136	22	11.7	71.8	6.2
54	69.8	12.2	3250	167	3083	171	23	18.0	133.9	7.4
55	72.7	13.4	1750	167	1583	93	23	17.0	69.1	4.0
57	79.5	9.5	1333	167	1166	136	25	8.6	46.8	5.4
59	76.0	9.4	1250	83	1167	121	25	4.1	46.8	4.8
59B	74.2	11.2	1500	167	1333	143	25	9.3	53.2	5.7
60	74.8	9.2	1500	333	1167	129	27	9.1	43.3	4.8
60B	66.1	15.8	2583	1583	1000	100	19	18.3	96.3	5.3
60C	68.6	13.5	2000	667	1333	100	22	13.3	60.5	4.5
60D	71.7	13.1	1833	333	1500	129	24	11.7	62.5	5.4
61	71.6	9.6	2417	500	1917	214	23	9.0	83.4	9.3
64	74.0	10.4	2167	500	1667	164	24	10.1	69.6	6.8
68	65.9	9.3	2500	500	2000	136	19	14.7	105.3	7.2
69	65.8	12.2	2000	167	1833	121	20	15.0	91.5	6.1
$\bar{x}$, 1σ	65.7 ± 13.5	11.1 ± 3.2	2144 ± 850	732 ± 790	1412 ± 633	117 ± 52	23 ± 3	13.3 ± 8.6	65.5 ± 26.8	5.4 ± 2.2

Table 11. Results of experiments to determine the labile fraction of Lake Winnipeg sedimentary phosphorus.†

Sediment Station	Extractant Solution	Sediment Concentration	Total P (ΣP) in sediment µmoles P/g	P released from sediment		P absorbed to sediment		Final pH
				µmoles P/g	% of ΣP	µmoles P/g	% of solution P	
35	Distilled water	0.5 g/L	27 (±1.7)	1.10	4.1	-	-	6.8
	1M NH_4Cl	"	"	2.71	10.0	-	-	6.0
NORTH	0.01 N HCl	"	"	11.7	43.3	-	-	2.3
BASIN	0.01 M NTA	"	"	17.1(±0.3)	63.3(±1.1)	-	-	2.5
	0.01 M NTA *	"	"	10.9(±0.9)	40.5(±3.1)	-	-	7.0
	1.6 µM PO_4-P	"	"	-	-	0.26	8.0	6.8
	3.2 µM PO_4-P	"	"	-	-	1.23	19.0	6.8
	6.4 µM PO_4-P	"	"	-	-	2.06	16.0	6.9
	9.6 µM PO_4-P	"	"	-	-	2.97	15.3	6.8
60	Distilled water	0.5 g/L	23 (±0.1)	1.29	5.6	-	-	6.9
	1 M NH_4Cl	"	"	2.90	12.6	-	-	6.1
SOUTH	0.01 N HCl	"	"	10.2	44.3	-	-	2.2
BASIN	0.01 M NTA	"	"	18.4	80.0	-	-	2.5
	0.01 M NTA *	"	"	17.7	77.0	-	-	7.0
	1.6 µM PO_4-P	"	"	-	-	0.52	16.0	6.9
	3.2 µM PO_4-P	"	"	-	-	1.23	19.0	6.8
	6.4 µM PO_4-P	"	"	-	-	2.15(±0.23)	16.7(±1.8)	6.8
	9.6 µM PO_4-P	"	"	-	-	2.52	13.0	6.8

† Dry, homogenized surface sediment was added to the solutions listed below. The solution was stirred manually on occasion over a 68 hr period. Release or uptake of P by sediment was calculated from molybdate-reactive phosphorus measurements done on the filtered (Sartorius glass fibre) solution (minus experimental blank values). The PO_4 solution was made from KH_2PO_4. Numbers in parentheses are standard deviations for triplicate experiments.

* The solution was buffered to pH 7.

Table 12. Calculated values, according to the method of Dean (1974), for organic carbon (C_0), carbonate carbon (calcite + dolomite = C_i), and total carbon (ΣC) from ashing curves of Lake Winnipeg sediment samples collected October 3-12, 1969, and their comparison to wet chemical carbon analysis (see Methods) as percentages of whole sediment dry weight at 100°C.

Station	Location	Σ% loss on ignition at 950°C	% wt loss of total wt loss 100-500°C	% wt loss of total wt loss 550-800°C	% wt loss of total wt loss 800-950°C	Col. 1x2 % C_0	Col. 1x3 % C as Dolomite	Col. 1x4 % C as Calcite	Col. 6+7 % C_i	Col. 5+8 % C
	Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
02	South Basin	12.50	44.17	53.33	2.50	1.5(2.0)*	1.81	0.09	1.9(1.8)	3.4(3.8)
04	South Basin	10.80	74.68	21.52	3.80	2.2(0.9)	0.68	0.12	0.8(1.0)	3.0(1.9)
12	Narrows	2.70	73.21	23.21	3.58	0.5	0.17	0.03	0.2(-)	0.7
14	Narrows	8.80	88.98	7.87	3.15	2.1(2.5)	0.21	0.09	0.3(0.3)	2.4(2.8)
26	North Basin	11.70	53.85	43.96	2.19	1.7(2.4)	1.43	0.07	1.5(0.5)	3.2(2.9)
35	North Basin	8.80	81.04	13.79	5.17	1.9(1.5)	0.29	0.11	0.4(0.3)	2.3(1.8)
41	North Basin	10.00	76.92	19.23	3.85	2.1(1.7)	0.49	0.11	0.6(0.7)	2.7(2.4)
48	North Basin	9.50	82.47	14.43	3.10	2.1(1.7)	0.41	0.09	0.5(0.5)	2.6(2.2)
54	Narrows	12.20	93.01	3.50	3.49	3.1(3.7)	0.10	0.10	1.2(0.2)	3.3(3.9)
59	South Basin	9.40	88.37	8.53	3.10	2.2(1.6)	0.22	0.08	0.3(0.2)	2.5(1.8)

* In column 5, 8 and 9, the values (% dry weight) in parenthesis are from wet chemical analysis given in Table 10. Organic carbon (C_0) is from ($\Sigma C-C_i$).

Table 13. Elemental composition (in millimoles/g dry weight, 110°C) of selected surface sediment samples (homogenized, 0-20 cm sediment depth) from Lake Winnipeg. Collected October 3-12, 1969. Also given is % of total oxides that these elements represent.

Station	Si	P	Al	Ca	Mg	Na	K	Fe	Mn	% Total
01	11.95	0.02	2.12	1.04	0.64	0.51	0.36	0.34	0.01	97.27
02	10.06	0.03	4.05	1.20	1.26	0.31	0.18	0.77	0.02	101.29
04	10.88	0.03	4.05	0.66	1.04	0.27	0.15	0.85	0.02	102.68
07	9.67	0.02	3.05	1.59	1.78	0.56	0.47	0.44	0.01	97.45
08	9.74	0.02	3.63	1.16	1.49	0.47	0.55	0.66	0.01	99.15
12	13.73	0.02	2.02	0.29	0.31	0.49	0.28	0.29	0.01	101.13
14	11.31	0.02	3.73	0.44	0.54	0.73	0.43	0.63	0.01	101.09
21	10.81	0.02	3.30	0.59	0.67	0.77	0.51	0.59	0.01	97.49
23C	9.03	0.03	4.67	0.38	0.97	0.47	0.70	1.03	0.02	97.48
23E	9.03	0.03	4.67	0.39	0.96	0.48	0.71	0.97	0.02	96.97
26	9.03	0.02	4.21	0.96	1.42	0.49	0.65	0.83	0.02	98.40
33	8.25	0.02	2.97	2.67	1.47	0.50	0.67	0.66	0.01	95.83
35	9.03	0.03	4.62	0.39	0.90	0.49	0.69	0.98	0.02	96.60
39	9.25	0.02	4.04	0.83	1.05	0.45	0.70	0.89	0.02	97.19
41	10.31	0.02	4.29	0.47	0.97	0.49	0.66	0.85	0.01	102.14
48	10.17	0.02	4.29	0.46	0.96	0.51	0.69	0.93	0.01	101.94
50D	9.25	0.02	4.20	0.39	0.95	0.75	0.85	0.90	0.01	96.82
51	10.66	0.03	3.88	0.41	0.65	0.64	0.60	0.85	0.02	100.63
52	10.03	0.02	4.27	0.54	1.05	0.52	0.67	0.87	0.01	101.32
53	10.74	0.02	4.07	0.40	0.66	0.64	0.37	0.75	0.01	100.20
54	10.38	0.02	4.30	0.43	0.70	0.62	0.37	0.78	0.01	99.81
57	10.31	0.03	4.58	0.30	0.77	0.32	0.19	0.94	0.02	99.87
59	10.38	0.02	4.71	0.32	0.78	0.30	0.18	0.93	0.02	100.87
60	10.74	0.03	4.52	0.37	0.80	0.27	0.16	0.91	0.02	102.10
61	10.46	0.02	4.44	0.44	0.86	0.28	0.16	0.86	0.02	100.19
64	10.46	0.02	3.56	0.46	0.50	0.88	0.58	0.54	0.01	95.64
69	8.39	0.02	3.99	0.74	0.92	1.49	1.47	1.37	0.02	101.43

Table 14. Concentrations of major elements in Lake Winnipeg surface sediment samples (0-20 cm, homogenized).†

	mMoles/gram dry weight					
Station Number	Ca	Mg	Al	Fe	Mn	Ti
01	1.12	0.70	1.52	0.25	0.009	0.044
02	1.12	1.07	2.45	0.50	0.019	0.081
03	1.15	1.07	2.56	0.50	0.016	0.075
03C	1.02	1.03	2.22	0.43	0.014	0.069
03D	1.02	0.95	2.41	0.48	0.019	0.073
04	0.82	0.95	2.82	0.61	0.021	0.084
04B	0.62	0.99	2.71	0.57	0.019	0.084
05	0.42	0.78	2.93	0.65	0.020	0.088
06	0.55	0.86	2.82	0.57	0.016	0.088
07	1.45	1.48	1.96	0.22	0.007	0.050
08	1.00	1.15	2.33	0.32	0.012	0.067
10	0.27	0.62	3.11	0.54	0.027	0.088
12	0.27	0.25	1.52	0.16	0.011	0.027
14	0.50	0.49	2.63	0.36	0.016	0.071
15	0.45	0.49	2.74	0.38	0.015	0.067
17	0.57	0.49	3.74	0.39	0.014	0.067
18	0.37	0.70	3.00	0.52	0.013	0.088
21	0.67	0.66	2.78	0.39	0.012	0.069
23C	0.35	0.78	3.22	0.63	0.021	0.096
23E	0.37	0.82	3.22	0.59	0.017	0.098
23H	0.70	1.07	2.85	0.54	0.020	0.084
25	0.62	0.99	3.04	0.56	0.021	0.086
26	0.92	1.23	2.82	0.50	0.017	0.081
27	0.70	1.85	2.37	0.36	0.016	0.071
31	2.32	2.14	1.59	0.18	0.016	0.031
33	2.64	1.28	2.11	0.18	0.011	0.065
34	0.87	1.11	2.59	0.45	0.011	0.079
35	0.37	0.78	3.15	0.61	0.015	0.094
39	0.42	0.78	2.93	0.52	0.025	0.084
41	0.47	0.86	3.00	0.54	0.024	0.084
47	0.55	0.91	2.89	0.52	0.012	0.081
48	0.37	0.70	2.71	0.47	0.013	0.077
50	0.45	0.66	3.15	0.52	0.012	0.088
50D	0.50	0.86	3.37	0.57	0.015	0.090
51	0.40	0.49	2.67	0.45	0.021	0.069
52	0.50	0.45	2.82	0.32	0.010	0.063
53	0.40	0.54	2.74	0.41	0.012	0.079
54	0.40	0.58	2.89	0.41	0.014	0.084
55	0.40	0.58	2.74	0.45	0.020	0.079
57	0.30	0.66	3.22	0.57	0.024	0.094
59	0.27	0.58	2.89	0.50	0.018	0.081
59B	0.30	0.66	3.08	0.56	0.030	0.092
60	0.35	0.66	2.96	0.54	0.023	0.088
60B	1.12	1.40	2.56	0.41	0.019	0.073
60C	0.70	0.91	2.74	0.45	0.017	0.081
60D	0.42	0.74	2.89	0.52	0.022	0.090
61	0.42	0.74	2.96	0.52	0.021	0.088
64	0.72	0.91	2.93	0.52	0.011	0.084
68	0.37	0.41	2.08	0.30	0.011	0.048
69	0.32	0.62	2.82	0.45	0.011	0.084
Average	$\bar{x}$ = 0.67	0.86	2.73	0.46	0.016	0.077
Standard Deviation	± 0.48	± 0.35	± 0.45	± 0.12	± 0.005	± 0.015

† These data are from acid refluxing of the sediment, and analysis by radio frequency plasma emission spectroscopy. The data were provided to us by Dr. R. J. Allan.

Table 15. Concentrations of some trace elements in Lake Winnipeg surface sediment samples (0-20 cm, homogenized).†

Station					μMoles/gram dry weight of total sediment						
Number	Cd	Pb	Be	Co	Cu	Ni	Sr	Cr	Zn	V	As	P
01	0.009	0.08	0.12	0.34	0.25	0.49	2.10	1.44	1.88	1.73	0.027	14.2
02	0.018	0.15	0.22	0.51	0.60	0.80	1.72	2.31	3.20	3.83	0.067	20.7
03	0.018	0.11	0.21	0.49	0.65	0.80	1.76	2.56	3.15	3.98	0.040	19.4
03C	0.018	0.09	0.19	0.46	0.54	0.75	1.67	2.21	3.04	3.49	0.040	18.4
03D	0.018	0.12	0.21	0.49	0.54	0.80	1.56	2.60	3.12	3.91	0.040	19.0
04	0.018	0.10	0.26	0.56	0.58	0.92	1.57	3.06	3.46	4.55	0.040	21.0
04B	0.018	0.09	0.22	0.54	0.55	0.90	1.56	2.83	3.30	4.28	0.040	19.0
05	0.018	0.27	0.27	0.56	0.58	0.95	1.62	2.85	3.44	4.50	0.040	20.3
06	0.018	0.06	0.22	0.59	0.54	0.92	1.99	2.81	3.04	3.97	0.040	19.0
07	0.009	0.04	0.13	0.41	0.33	0.63	2.21	1.65	2.37	1.90	0.027	15.2
08	0.018	0.15	0.19	0.53	0.50	0.87	2.07	2.27	2.88	2.89	0.013	17.4
10	0.018	0.13	0.26	0.59	0.61	1.04	1.73	2.90	3.30	4.38	0.027	19.0
12	0.009	0.14	0.12	0.29	0.24	0.46	2.19	1.19	1.32	1.24	0.027	10.7
14	0.018	0.08	0.19	0.53	0.58	0.92	2.41	2.40	2.46	2.87	0.027	19.4
15	0.018	0.11	0.18	0.48	0.58	0.83	2.41	2.17	2.37	2.45	0.040	18.7
17	0.018	0.12	0.21	0.54	0.47	1.11	2.44	2.23	2.63	2.47	0.027	20.0
18	0.018	0.12	0.26	0.66	0.72	1.18	2.31	3.37	3.30	3.65	0.040	20.3
21	0.018	0.06	0.21	0.54	0.44	0.94	2.41	2.42	2.46	2.55	0.027	17.8
23C	0.027	0.09	0.29	0.71	0.81	1.34	2.20	3.79	3.64	4.18	0.040	22.6
23E	0.018	0.07	0.29	0.71	0.83	1.33	2.23	3.75	3.69	4.20	0.040	21.6
23H	0.018	0.06	0.27	0.68	0.76	1.23	2.18	3.42	3.63	3.61	0.027	21.6
25	0.018	1.34	0.26	0.66	0.71	1.19	2.18	3.35	3.43	3.47	0.053	21.0
26	0.018	0.14	0.23	0.61	0.66	1.16	2.13	3.17	3.32	3.18	0.040	21.6
27	0.018	0.26	0.18	0.53	0.54	0.89	2.16	2.37	2.69	2.20	0.040	16.8
31	0.009	0.35	0.11	0.39	0.17	0.58	2.21	1.58	2.07	1.04	0.027	12.3
33	0.018	0.01	0.19	0.63	0.50	0.92	2.28	2.58	2.72	2.24	0.027	15.8
34	0.018	0.13	0.23	0.63	0.66	1.12	2.23	3.06	3.18	3.08	0.027	19.7
35	0.027	0.24	0.28	0.73	0.82	1.36	2.26	3.62	3.70	3.98	0.027	23.2
39	0.018	0.13	0.21	0.56	0.74	1.00	2.15	2.92	2.81	3.22	0.040	18.1
41	0.018	0.17	0.21	0.56	0.77	1.04	2.13	3.00	3.04	3.26	0.040	19.4
47	0.018	0.13	0.21	0.61	0.79	1.02	2.13	2.98	3.04	3.22	0.040	18.4
48	0.018	0.11	0.22	0.63	0.74	1.07	2.18	3.15	3.12	3.55	0.027	19.0
50	0.018	0.57	0.21	0.54	0.66	0.94	2.32	2.81	2.72	3.18	0.040	18.7
50D	0.018	0.23	0.20	0.66	0.74	1.12	2.37	3.10	2.97	3.08	0.040	18.1
51	0.018	0.20	0.17	0.53	0.47	0.77	2.28	2.50	2.65	2.43	0.013	19.0
52	0.018	0.25	0.19	0.41	0.49	0.70	2.43	2.06	2.20	2.16	0.053	17.8
53	0.018	0.36	0.22	0.56	0.69	0.97	2.36	2.62	2.68	3.24	0.040	18.4
54	0.018	0.14	0.21	0.54	0.79	0.94	2.29	2.65	2.55	3.16	0.053	18.1
55	0.018	0.15	0.21	0.56	0.66	0.95	2.31	2.58	2.49	3.04	0.067	18.1
57	0.018	0.14	0.27	0.56	0.66	0.97	1.63	3.06	3.21	4.48	0.053	19.7
59	0.018	0.52	0.23	0.49	0.60	0.85	1.52	2.73	2.95	4.12	0.040	17.4
59B	0.018	0.13	0.28	0.56	0.65	0.94	1.56	2.98	3.12	4.53	0.067	20.7
60	0.018	0.15	0.26	0.53	0.61	0.90	1.51	3.02	3.14	4.50	0.067	19.7
60B	0.018	0.17	0.19	0.51	0.52	0.83	1.59	2.50	2.91	3.40	0.053	16.5
60C	0.018	0.14	0.22	0.53	0.60	0.82	1.64	2.81	3.23	4.20	0.067	19.0
60D	0.018	0.18	0.26	0.53	0.63	0.95	1.50	2.92	3.04	4.28	0.053	17.8
61	0.018	0.09	0.26	0.54	0.60	0.92	1.59	3.00	3.20	4.50	0.040	18.7
64	0.018	0.14	0.21	0.56	0.66	1.06	2.18	3.12	3.01	3.30	0.040	19.0
68	0.009	0.11	0.14	0.34	0.49	0.68	2.35	1.98	1.87	2.00	0.053	14.5
69	0.018	0.87	0.22	0.53	0.69	0.97	2.18	2.94	2.69	3.55	0.040	16.5
$\bar{X}$	0.018	0.19	0.22	0.54	0.59	0.94	2.04	2.65	2.90	3.32	0.040	18.6
Standard Deviation	±0.004	±0.22	±0.04	±0.12	±0.17	±0.20	±0.32	±0.64	±0.50	±0.90	±0.013	±2.4

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† These data are largely from determinations by radio frequency plasma emission spectroscopy and were provided to us by Dr. R. J. Allan.

Table 16. Relative atomic variation of trace elements in proportion to selected conservative elements (Fe, Ti, Al) in Lake Winnipeg sediments.*

	n	Ni	Cu	Co	Cr	V	P	Zn
		Trace Element/Fe x 10^{-4}						
South Basin	21	10	8	5	38	73	167	35
North Basin	21	12	12	4	38	55	168	28

	n	Ni	Cu	Co	Cr	V	P	Zn
		Trace Element/Ti x 10^{-4}						
South Basin	21	82	66	42	305	559	1270	276
North Basin	21	111	107	45	343	484	1390	249

	n	Ni	Cu	Co	Cr	V	P	Zn
		Trace Element/Al x 10^{-4}						
South Basin	21	3	2	1	11	20	41	9
North Basin	21	3	2	1	7	11	39	5

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* n = number of sediment stations sampled and analyzed. The numbers given are the slopes ($\times 10^{-4}$) of linear regressions of each trace element against the indicated conservative element, and can be thought of as the average ratio of trace: conservative element. All regressions are significant at the 95% level.

Table 17. Element concentration in suspended sediments from Red River drainage into the South Basin of Lake Winnipeg, May 2-9, 1975.†

	Location		
µmoles/g dry weight	Station 00B, Assiniboine River upstream from City of Winnipeg	Station 00A, Red River upstream from City of Winnipeg	Station 00C, Red River downstream from City of Winnipeg
Ca	975	850	975
Mg	1 864	823	905
Na	174	130	130
Fe	430	448	412
Mn	18.5	18.7	18.4
Al	2444	2667	2519
Ti	73	77	73
P	18.3	19.1	18.7
As	0.080	0.067	0.093
Be	0.222	0.211	0.200
Cd	0.017	0.018	0.016
Co	0.492	0.509	0.441
Cu	0.709	0.535	0.504
Cr	2.50	2.75	2.50
Pb	0.189	0.189	0.094
Ni	0.767	0.818	0.733
Sr	1.72	1.55	1.69
V	3.97	4.40	3.91
Zn	2.95	3.03	2.81

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† These data were supplied by Dr. R. J. Allan, and the elements were determined by radio frequency plasma emission spectroscopy.

Table 19. Annual rates of supply of major and trace elements to the south basin of Lake Winnipeg and sedimentation rates, derived from Red River suspended sediment chemistry and discharge data over 1969-1973.

Elements	Range of Annual Supply, Tonnes yr^{-1}	Average sedimentation rate μMoles m^{-2} yr^{-1}	Sedimentation rate range (1969-1973)
Ni	11-147	0.8	0.1-1.4
Cu	8.2-109	8.2-109	0.07-1.0
Co	6.7-89	0.5	0.07-0.9
Cr	33-446	2.9	0.4-4.9
As	1.8-24	0.1	0.01-0.2
V	51-682	4.6	0.6-7.7
Be	0.46-6.2	0.2	0.03-0.4
Zn	47-631	3.3	0.4-5.6
Cd	0.46-6.2	0.02	0.002-0.03
Pb	2.6-34	0.06	0.007-0.1
Sr	38-507	2	0.3-3.3
Mn	260-3460	21	2.7-36
P	148-1980	22	3-37
Ti	900-1200	86	11-144
Fe	5900-79,000	480	61-810
Al	19,400-258,900	3280	413-5,526
Si	64,700-866,260	10,530	1,326-17,760
Ca	8,210-108,900	940	118-1,580
Mg	6,850-91,640	1,290	162-2,170
Na	2,350-31,520	470	60-790
K	4,910-65,660	570	72-970
Total Dry (110°C) Sediment		1170 g m^{-2} yr^{-1}	150-1970 g m^{-2} yr^{-1}

Table 18. Suspended sediment chemistry for Lake Winnipeg and Red River, by sodium metaborate fusion and atomic absorption spectrophotometric determination. Si and P were determined by coloremetric methods of Stainton et al. 1974.

Location Description	Date (1969)	mMoles/g dry weight								
		Si	Al	Ca	Mg	Na	K	Fe	Mn	P
Composite of all Lake Winnipeg stations sampled	Sept. 2-10	10.18	1.31	0.459	0.156	2.55	0.563	0.090	0.005	-
	Oct. 3-13	10.47	1.37	0.459	0.156	2.64	0.573	0.010	0.004	0.034
	Oct. 27-31	10.15	1.37	0.459	0.156	2.55	0.567	0.090	0.005	-
Lake Winnipeg Station 701 Mouth of Red River	Oct. 3	2.57	0.437	4.84	0.424	0.339	0.123	0.095	0.009	0.032
Lake Winnipeg Station 735 Center of North Basin	Oct. 8	4.64	1.23	0.961	0.395	0.631	0.315	0.251	0.010	0.068
Red River south of Winnipeg (Station 00A)	Apr. 13	6.50	1.99	1.44	1.73	1.05	0.425	0.440	0.033	-
	Apr. 27	9.31	3.22	0.614	0.913	0.244	0.517	0.688	0.010	0.023
Red River north of Winnipeg (Station 00C)	Apr. 21	9.04	3.00	0.671	0.995	0.365	0.509	0.609	0.015	0.026
	June 8	8.94	2.59	0.921	1.25	0.439	0.473	0.591	0.022	-

Table 20. Description of Lake Winnipeg sediment cores taken with a weighted Benthos corer on 3-12 October 1969.

Core No.	Location Long./Lat.	Date Taken	Date Extruded	Depth in Sediment	Munsell Color	Texture	% H_2O of Dry Wt.	Remarks
04	South Basin 98°48'00" W 50°28'30" N	3 Oct 1969	11 Jan 1971	0-5 cm			75.4	Water above core. A few cm of flocculent orange sediment at surface. Sewage and hydrocarbon smell.
				10-15			70.0	
				20-25			64.8	
				30-35			58.8	
				40-45	5Y3/1	Fine plastic	57.5	
				50-55	Bluish-	clay	57.0	
				60-65	black		59.8	
				70-75			57.0	
				80-85			55.9	
				90-95		Conchoidally	51.6	
				100-105		fractured	45.9	
				110-115		clay	45.0	
				120-125	5Y2/2	Granular	42.7	
				130-135		clay	42.9	
08	Traverse Bay 96°28'30" 50°44'45"	4 Oct 1969	22 Jan 1971	0-5 cm			60.9	Water above core.
				10-15	5Y3/1	Fine	57.8	
				20-25	Bluish	plastic	50.5	
				30-35	black	clay	48.3	
				40-45			48.0	
				50-55	5Y3/1	Conchoidally	43.1	
				60-65		fractured	40.6	
				70-75		clay	35.5	
				80-85	5Y3/1	Sandy	32.9	
				90-95		silt	30.6	
10	South Basin 96°33'30" 50°55'30"	4 Oct 1969	8 June 1971	0-5 cm			70.7	No water above core but surface sediment was wet.
				10-15		Fine	65.9	
				20-25	5Y2/1	plastic	65.3	
				30-35		clay	66.2	
				40-45			68.3	
				50-55			63.7	
				60-65	5Y2/2	Conchoidally	49.4	
				70-75		fractured	49.0	
						clay		
				80-85	5Y2/2	Granular	48.2	
						clay		
14	Narrows 96°38'30" 51°26'30"	5 Oct 1969	13 May 1971	0-5 cm			64.0	Water above core.
				10-15			65.2	
				20-25			64.2	
				30-35		Fine	65.7	
				40-45	5Y2/2	plastic	63.7	
				50-55		clay	61.8	
				60-65			46.1	
				70-75			58.1	
				80-85			58.4	
				90-95			55.4	
				100-105	5Y2/1	Conchoidally	45.4	
				110-115		fractured		
					Black	clay	48.7	
				120-125		Granular	42.9	
						clay		
25	North Basin 98°53'30" 53°12'45"	6 Oct 1969	1 Feb 1971	0-5 cm			69.3	No water above core. Dry surface Bluish blebs in surface sediment.
				10-15		Fine	55.4	
				20-25	2.5Y3/1	plastic	70.4	
				30-35	Bluish	clay	70.0	
				40-45	grey		69.4	
				50-55		Slightly	68.7	
				60-65		conchoidally	69.7	
				70-75		fractured		
						clay	67.2	
				80-85		Conchoidally	57.3	
						fractured		
				90-95	5Y3/1	clay	48.3	
				100-105	Very dark	Granular	48.4	
				110-115	grey	clay	45.9	

Table 20. Cont'd.

Core No.	Location Long./Lat.	Date Taken	Date Extruded	Depth in Sediment	Munsell Color	Texture	% H_2O of Dry Wt.	Remarks
35-1	North Basin 98°34'45" 53°39'15"	8 Oct 1969	20 May 1971	0-5 cm			72.2	No water above sediment, oxidation to 22 cm depth.
				10-15			72.3	
				20-25			74.3	
				30-35	5Y4/1	Fine	73.8	
				40-45	Bluish	plastic	73.1	
				50-55	black	clay	72.4	
				60-65			71.1	
				70-75		Conchoidally	-	
				80-85		fractured		
					5Y2/1	clay	50.2	
				90-95		Granular	51.0	
						clay		
35-2	North Basin 98°34'45" 53°30'15"	8 Oct 1969	7 Jan 1971	0-5 cm	Brown		70.2	No water over core. Some oxidation to 30 cm.
				10-15	(oxidized)		69.4	
				20-25		Fine	72.2	
				30-35	5Y4/1	plastic	72.4	
				40-45		clay		
					Bluish		73.1	
				50-55	black			
							70.0	
				60-65		Conchoidally	68.9	Gas trapped in sediment, H_2S smell.
				70-75		fractured	56.4	
				80-85		clay		
							48.0	
				90-95	5Y2/1	Granular	48.5	
				100-105		clay	46.7	
39	North Basin 98°11'30" 53°02'30"	6 Oct 1969	4 June 1971	0-5 cm			70.1	
				10-15			71.4	
				20-25			73.4	
				30-35			72.5	
				40-45	5Y2/2	Fine	72.0	
				50-55	Black	plastic	71.7	
						clay		
				60-65			71.0	
				70-75			68.7	
				80-85			70.1	
				90-95			72.5	
				100-105			70.8	
				110-115	5Y2/1	Conchoidally	52.5	
						fractured		
						clay		
				120-125	(Black)	Granular	52.1	
						clay		
52	Narrows (Pigeon Bay) 97°08'00" 52°17'30"	5 Oct 1969	31 May 1971	0-5 cm	5Y3/1		54.1	Water above core.
				10-15	Very dark	Silty	49.1	
				20-25	grey	sand	26.3	
				30-35			26.4	
				40-45	5Y2/2	Granular	37.3	
						clay		
54	Narrows 97°03'00" 52°00'00"	5 Oct 1969	27 May 1971	0-5 cm			72.1	Water above core.
				10-15			70.9	
				20-25			69.1	
				30-35	5Y4/1	Fine	66.7	
				40-45	Dark	plastic	65.2	
				50-55	grey	clay	63.8	
				60-65			63.2	
				70-75			59.9	
				80-85	5Y2/1	Conchoidally	57.7	
				90-95	Black	fractured	40.8	
				100-105		clay	43.7	
				110-115	5Y2/2	Granular	52.5	
						clay		

Table 20. Cont'd.

Core No.	Location Long./Lat.	Date Taken	Date Extruded	Depth in Sediment	Munsell Color	Texture	% H_2O of Dry Wt.	Remarks
57	South Basin 96°47'00" 50°51'30"	4 Oct 1969	3 June 1971	0-5 cm			75.6	Water above core.
				10-15			75.3	
				20-25	Marbled 5Y3/1 and 5Y2/1 Very dark grey and black	Fine plastic clay	73.0	
				30-35			71.7	
				40-45			71.3	
				50-55			70.2	
				60-65			69.4	
				70-75			69.4	
				80-85			62.1	Noticeable oxidation.
				90-95	5Y2/1	Conchoidally fractured clay	50.7	
				100-105	Black	Granular clay	46.8	
59	South Basin 96°44'45" 50°42'00"	4 Oct 1969	2 May 1971	0-5 cm			-	No water above core, Oxidized to 60 cm.
				10-15	5Y3/2	Fine plastic clay	-	
				20-25			-	
				30-35			-	
				40-45			-	
				50-55			-	
				60-65	5Y2/2	Conchoidally fractured clay	-	
				70-75			-	
				80-85		Granular clay	-	
				90-95			-	
60	South Basin 96°47'15" 50°34'30"	3 Oct 1969	20 May 1971	0-5 cm			67.1	Very hard to extrude. Compressed during extrusion.
				10-15			-	
				20-25			-	
				30-35	5Y3/2	Fine plastic clay	54.2	
				40-45			-	
				50-55			-	
				60-65			50.7	
				70-75			-	
				80-85			44.1	
61	South Basin 96°48'15" 50°31'00"	3 Oct 1969	13 May 1971	0-5 cm			75.3	Water above core.
				10-15			70.9	
				20-25	5Y3/2 Dark olive grey	Fine plastic clay	68.1	
				30-35			67.8	
				40-45			67.2	
				50-55			67.1	
				60-65			69.0	
				70-75	5Y2/2 Black	Conchoidally fractured clay	60.9	
				80-85			49.7	
				90-95		Granular clay	46.5	
				100-105			37.0	

Table 21. Percent loss on ignition at 900°C (L.O.I.), μmoles/gm dry weight (110°C) of total carbon (ΣC), carbonate carbon (C_i), organic carbon (C_o), total nitrogen (ΣN), total phosphorus (ΣP), and molal ratios of selected Lake Winnipeg sediment cores taken October 3-12, 1969.

Core	Depth	L.O.I.	ΣC	C_i	C_o	ΣN	ΣP	$C_o:\Sigma N$	$C_o:\Sigma P$	$\Sigma N:\Sigma P$
04	0-5	10.09	2083	475	1608	136	22	11.8	73.1	6.2
	10-15	9.82	1583	491	1092	93	20	11.7	54.6	4.7
	20-25	9.70	1500	525	975	78	20	12.5	48.8	3.9
	30-35	10.00	1667	809	858	93	18	9.2	47.7	5.2
	40-45	9.33	1667	700	967	71	20	13.6	48.4	3.6
	50-55	9.09	1833	750	1083	78	19	13.9	57.0	4.1
	60-65	8.94	1417	650	767	64	22	12.0	34.9	2.9
	70-75	9.18	2000	683	1317	64	22	20.6	59.9	2.9
	80-85	9.80	1750	733	1017	29	20	35.1	50.9	1.5
	90-95	8.88	2000	592	1408	100	18	14.1	78.2	5.6
	100-105	9.33	1583	641	942	64	23	14.7	41.0	2.8
	110-115	9.74	1500	600	900	86	19	10.5	47.4	4.5
	120-125	10.70	1917	592	1325	86	21	15.4	63.1	4.1
	130-135	10.43	1667	767	900	71	20	12.7	45.0	3.6
08	0-5	12.70	2792	1542	1250	86	13	14.5	96.2	6.6
	10-15	11.88	2775	1517	1258	64	14	19.7	89.9	4.6
	20-25	12.69	2783	1283	1500	57	14	26.3	107.1	4.1
	30-35	11.87	2800	1717	1083	57	13	19.0	83.3	4.4
	40-45	12.54	2525	1767	758	57	13	13.3	58.3	4.4
	50-55	13.99	3150	1900	1250	71	12	17.6	104.2	5.9
	60-65	12.97	2850	2092	758	57	12	13.3	63.2	4.8
	70-75	13.23	2967	2209	758	64	13	11.8	58.3	4.9
	80-85	13.04	2725	1967	758	57	13	13.3	58.3	4.4
	90-95	12.80	2800	-	-	36	14	-	-	2.6
10	0-5	20.17								
	10-15	19.71								
	20-25	10.26								
	30-35	12.48								
	40-45	10.03								
	50-55	10.34								
	60-65	9.96								
	70-75	11.97								
	80-85	12.03								
14	0-5	7.41	1833	41	1792	100	20	17.9	89.6	5.0
	10-15	8.81	2083	83	2000	129	22	15.5	90.9	5.9
	20-25	10.18	2167	109	2058	121	22	17.0	93.5	5.5
	30-35	8.69	1583	100	1483	100	19	14.8	78.1	5.3
	40-45	8.59	1583	100	1483	93	22	15.9	67.4	4.2
	50-55	8.49	1500	100	1400	86	22	20.6	63.6	3.9
	60-65	8.99	1333	83	1250	86	21	14.5	59.5	4.1
	70-75	8.06	1333	83	1250	86	24	14.5	52.1	3.6
	80-85	9.52	1667	109	1558	107	23	14.6	67.7	4.7
	90-95	8.62	1333	116	1217	100	22	12.2	55.3	4.5
	100-105	6.21	1333	33	1300	100	22	13.0	59.1	4.5
	110-115	8.39	1417	92	1325	100	23	13.3	57.6	4.3
	120-125	8.30	1333	91	1242	100	22	12.4	56.5	4.5
25	0-5	11.22	1583	450	1133	100	25	11.3	45.3	4.0
	10-15	10.02	1500	450	1050	93	25	11.3	42.0	3.7
	20-25	10.71	1667	642	1025	79	25	13.0	41.0	3.2
	30-35	10.78	1833	675	1158	93	29	12.5	39.9	3.2
	40-45	9.94	1500	983	517	79	32	6.5	16.2	2.5
	50-55	10.46	1833	533	1300	100	27	13.0	48.1	3.7
	60-65	9.13	1417	392	1025	121	32	8.5	32.0	3.8
	70-75	9.97	1750	542	1208	100	24	12.1	50.3	4.2
	80-85	9.67	1500	450	1050	129	25	8.1	42.0	5.2
	90-95	10.28	1583	591	992	79	25	12.6	39.7	3.2
	100-105	9.23	1667	592	1075	71	25	15.1	43.0	2.8
	110-115	10.23	1750	617	1133	79	25	14.3	45.3	3.2

Table 21. Cont'd.

Core	Depth	L.O.I.	ΣC	C_i	C_o	ΣN	ΣP	$C_o:\Sigma N$	$C_o:\Sigma P$	$\Sigma N:\Sigma P$
35-1	0-5	8.27								
	10-15	8.08								
	20-25	7.49								
	30-35	7.79								
	40-45	7.70								
	50-55	6.25								
	60-65	7.64								
	70-75	-								
	80-85	7.73								
	90-95	-								
35-2	0-5	12.36	1833	41	1792	164	22	10.9	81.5	7.5
	10-15	9.95	1333	66	1267	121	19	10.5	66.7	6.4
	20-25	8.13	1417	59	1358	136	17	10.0	79.9	8.0
	30-35	7.75	1250	50	1200	114	17	10.5	70.6	6.7
	40-45	7.31	1000	42	958	114	21	8.4	45.6	5.4
	50-55	7.62	1167	84	1083	114	14	9.5	77.4	8.1
	60-65	7.50	1167	25	1042	100	16	10.8	65.1	6.3
	70-75	7.34	6000	42	958	107	19	9.0	50.4	5.6
	80-85	7.44	1083	100	983	121	17	8.1	57.8	7.1
	90-95	7.83	1167	117	1050	121	20	8.7	52.5	6.1
	100-105	7.77	1000	75	925	114	23	8.1	40.2	5.0
39	0-5	12.39								
	10-15	11.27								
	20-25	9.58								
	30-35	10.28								
	40-45	10.32								
	50-55	10.64								
	60-65	9.21								
	70-75	10.28								
	80-85	9.58								
	90-95	9.97								
	100-105	9.91								
	110-115	8.60								
	120-125	8.83								
52	0-5	48.00								
	10-15	10.82								
	20-25	5.22								
	30-35	5.39								
	40-45	9.87								
54	0-5	11.52	2758	75	2683	164	22	16.4	122.0	7.5
	10-15	10.24	2067	50	2017	136	22	14.8	91.7	6.2
	20-25	20.19	1900	58	1842	114	22	16.2	83.7	5.2
	30-35	10.40	2433	33	2400	129	26	18.6	92.3	5.0
	40-45	8.97	2008	41	1967	129	20	15.2	98.4	6.5
	50-55	8.00	1508	25	1483	79	28	18.8	53.0	2.8
	60-65	17.31	1342	25	1317	121	24	10.9	54.9	5.0
	70-75	6.93	942	25	917	129	25	7.1	36.7	5.2
	80-85	8.34	1600	25	1575	114	24	13.8	65.6	4.8
	90-95	6.45	1158	25	1133	79	22	14.3	51.5	3.6
	100-105	6.51	950	42	908	93	29	9.8	31.3	3.2
	110-115	6.50	1067	34	1033	71	26	14.5	39.7	2.7
57	0-5	11.77								
	10-15	12.17								
	20-25	11.09								
	30-35	10.25								
	40-45	10.85								
	50-55	13.13								
	60-65	8.71								
	70-75	9.74								
	80-85	9.38								
	90-95	9.72								
	100-105	10.61								

Table 21. Cont'd.

Core	Depth	L.O.I.	ΣC	C_i	C_o	ΣN	ΣP	$C_o:\Sigma N$	$C_o:\Sigma P$	$\Sigma N:\Sigma P$
59	0-5	9.57	917	100	817	79	23	10.3	35.5	3.4
	10-15	8.52	750	83	667	71	23	9.4	29.0	3.1
	20-25	9.83	750	83	667	71	22	9.4	30.3	3.2
	30-35	8.20	708	116	592	64	21	9.3	28.2	3.1
	40-45	7.95	667	92	575	64	22	9.0	26.1	2.9
	50-55	7.79	708	109	617	71	21	8.7	29.4	3.4
	60-65	7.74	667	67	600	64	22	9.4	27.3	2.9
	70-75	7.70	667	100	567	71	20	8.0	28.4	3.6
	80-85	7.65	750	75	675	57	22	11.8	30.7	2.6
	90-95	7.68	917	75	842	57	23	14.8	36.6	2.5
60	0-5	8.99	1000			100				
	10-15	-	-			-				
	20-25	-	-			-				
	30-35	8.63	1083			79				
	40-45	-	-			-				
	50-55	-	-			-				
	60-65	8.96	1083			71				
	70-75	-	-			-				
	80-85	8.71	1000			71				
61	0-5	11.26	1667			100				
	10-15	9.38	1250			79				
	20-25	9.66	1250			71				
	30-35	10.61	1166			71				
	40-45	9.70	1166			71				
	50-55	10.29	1083			64				
	60-65	9.37	1083			64				
	70-75	9.58	833			57				
	80-85	9.52	1000			64				
	90-95	9.49	1083			71				
	100-105	9.26	1083			71				

Table 22. Major element chemistry of Lake Winnipeg sediment cores, taken 3-12 October 1969. These data were provided to us by Dr. R. J. Allan. Total element concentrations were determined by radio frequency plasma emission spectroscopy.

Station and Location	Depth in Core (cm)	Ca	Mg	Na	Al	Fe	Ti	Mn	P
					mMoles/gram				
04 South Basin, Near Red River	0-5	0.55	0.78	0.087	2.71	0.45	0.079	0.015	0.019
	10-15	0.57	0.82	0.130	2.78	0.47	0.081	0.016	0.022
	20-25	0.57	0.82	0.130	2.63	0.45	0.081	0.018	0.017
	30-35	0.75	0.86	0.130	2.52	0.41	0.084	0.019	0.017
	50-55	0.70	0.90	0.174	2.52	0.39	0.084	0.022	0.018
	70-75	0.70	0.82	0.130	2.56	0.41	0.084	0.026	0.017
08 Traverse Bay, Near Winnipeg River	0-5	1.07	1.19	0.304	2.22	0.32	0.071	0.011	0.016
	10-15	1.00	1.11	0.304	2.19	0.30	0.067	0.011	0.016
	20-25	1.27	1.32	0.348	2.03	0.27	0.059	0.010	0.015
	30-35	1.20	1.23	0.348	2.08	0.27	0.059	0.009	0.015
	50-55	1.37	1.40	0.304	1.89	0.25	0.056	0.009	0.014
	70-75	1.50	1.52	0.348	1.96	0.25	0.059	0.007	0.015
10 South Basin, North End	0-5	0.32	0.66	0.174	3.19	0.57	0.094	0.023	0.020
	10-15	0.32	0.70	0.217	3.30	0.61	0.102	0.029	0.021
	20-25	0.32	0.66	0.217	3.15	0.57	0.100	0.026	0.019
	30-35	0.32	0.66	0.217	3.19	0.56	0.100	0.025	0.019
	50-55	0.32	0.70	0.217	3.30	0.59	0.107	0.025	0.019
	70-75	0.35	0.66	0.217	3.11	0.54	0.098	0.021	0.019
14 Narrows South End	0-5	0.45	0.45	0.565	2.67	0.38	0.075	0.014	0.019
	10-15	0.45	0.45	0.565	2.67	0.38	0.077	0.016	0.019
	20-25	0.42	0.49	0.478	2.74	0.41	0.084	0.018	0.019
	30-35	0.45	0.53	0.565	2.93	0.41	0.086	0.016	0.019
	50-55	0.42	0.53	0.522	2.85	0.43	0.088	0.016	0.018
	70-75	0.42	0.49	0.565	2.93	0.39	0.083	0.015	0.019
25 North Basin Near Saskatchewan River mouth	0-5	0.62	0.99	0.261	2.93	0.56	0.086	0.013	0.019
	10-15	0.62	1.03	0.304	2.97	0.56	0.088	0.018	0.020
	20-25	0.78	1.07	0.261	2.82	0.56	0.086	0.023	0.020
	30-35	0.80	1.11	0.304	3.00	0.57	0.094	0.027	0.023
	50-55	0.72	1.07	0.304	3.04	0.59	0.096	0.027	0.022
	70-75	0.75	1.11	0.304	3.19	0.61	0.102	0.022	0.021
35 North Basin	0-5	0.37	0.70	0.348	2.93	0.57	0.090	0.025	0.024
	10-15	0.37	0.78	0.348	3.15	0.63	0.098	0.020	0.023
	20-25	0.27	0.58	0.217	2.26	0.59	0.073	0.012	0.017
	30-35	0.40	0.86	0.348	3.34	0.63	0.107	0.016	0.022
	50-55	0.37	0.86	0.391	3.37	0.63	0.104	0.017	0.022
	70-75	0.42	0.80	0.348	3.34	0.64	0.111	0.018	0.021
39 North Basin	0-5	0.47	0.82	0.348	3.19	0.56	0.093	0.011	0.020
	10-15	0.42	0.82	0.348	3.22	0.57	0.098	0.014	0.021
	20-25	0.37	0.82	0.304	3.15	0.57	0.093	0.015	0.020
	30-35	0.42	0.86	0.304	3.22	0.61	0.098	0.015	0.020
	50-55	0.42	0.86	0.348	3.34	0.59	0.102	0.015	0.020
	70-75	0.40	0.82	0.304	3.04	1.54	0.090	0.014	0.019
54 Narrows North End	0-5	0.40	0.58	0.435	2.74	0.43	0.086	0.012	0.018
	10-15	0.40	0.66	0.391	2.78	0.50	0.094	0.013	0.019
	20-25	0.37	0.66	0.391	2.89	0.52	0.102	0.012	0.019
	30-35	0.42	0.62	0.391	3.19	0.50	0.100	0.012	0.019
	50-55	0.42	0.62	0.435	3.19	0.50	0.096	0.011	0.019
	70-75	0.40	0.58	0.565	3.08	0.45	0.093	0.011	0.020
57 South Basin	0-5	0.30	0.66	0.217	3.26	0.41	0.098	0.025	0.019
	10-15	0.30	0.66	0.174	3.26	0.36	0.094	0.023	0.020
	20-25	0.30	0.70	0.174	3.30	0.57	0.098	0.025	0.020
	30-35	0.30	0.66	0.174	3.30	0.57	0.098	0.026	0.019
	50-55	0.30	0.66	0.174	3.30	0.56	0.102	0.025	0.019
	70-75	0.30	0.70	0.174	3.41	0.59	0.100	0.025	0.020

Table 22. Cont'd.

Station and Location	Depth in Core (cm)	Ca	Mg	Na	Al	Fe	Ti	Mn	P
					mMoles/gram				
59	0-5	0.32	0.78	0.174	3.30	0.63	0.100	0.014	0.024
South Basin	10-15	0.30	0.74	0.217	3.11	0.61	0.094	0.021	0.024
	20-25	0.32	0.78	0.217	3.19	0.63	0.100	0.018	0.023
	30-35	0.35	0.74	0.217	3.00	0.57	0.096	0.012	0.022
	50-55	0.35	0.82	0.217	3.41	0.66	0.106	0.019	0.024
	70-75	0.30	0.74	0.174	3.11	0.61	0.096	0.020	0.022
61	0-5	0.45	0.82	0.130	2.93	0.56	0.090	0.018	0.022
South Basin	10-15	0.40	0.82	0.174	2.89	0.52	0.088	0.021	0.022
	20-25	0.47	0.86	0.130	2.85	0.54	0.094	0.022	0.021
	30-35	0.40	0.82	0.174	2.74	0.50	0.084	0.023	0.021
	50-55	0.37	0.82	0.174	2.71	0.50	0.084	0.022	0.020
	70-75	0.37	0.82	0.174	2.67	0.47	0.077	0.022	0.021

Table 23. Trace element chemistry of Lake Winnipeg sediment cores, taken 3-12 October 1969. These data were provided to us by Dr. R. J. Allan, and the total element concentrations were measured by radio frequency plasma emission spectroscopy.

Station and Location	Depth in Core (cm)	Cd	Pb	Be	Co	Cu	Ni	Sr	Cr	Zn	V	As	Mo
							μMoles/gram						
04 South Basin Near Red River	0-5	0.018	0.17	0.27	0.49	0.55	1.06	1.50	3.29	3.66	4.69	-	0.052
	10-15	0.018	0.12	0.26	0.49	-	0.83	1.52	2.85	3.30	4.44	-	-
	20-25	0.018	0.05	0.23	0.49	0.50	0.85	1.55	2.87	3.11	4.34	-	-
	30-35	0.018	0.08	0.27	0.49	0.46	0.78	1.62	2.48	3.27	3.97	-	-
	50-55	0.018	0.12	0.26	0.49	0.46	0.82	1.70	2.67	3.01	4.12	-	-
	70-75	0.018	0.08	0.24	0.49	0.46	0.83	1.60	2.73	2.89	4.38	-	-
08 Traverse Bay Near Winnipeg River	0-5	0.018	0.13	0.21	0.46	0.46	0.73	2.04	2.27	2.59	2.77	0.013	<0.021
	10-15	0.018	0.07	0.18	0.46	0.44	0.73	2.10	2.42	2.40	2.81	0.013	0.042
	20-25	0.018	0.06	0.15	0.42	0.36	0.68	2.18	2.23	2.19	2.26	0.013	0.021
	30-35	0.009	0.04	0.15	0.42	0.39	0.65	2.21	2.10	2.11	2.20	0.013	0.021
	50-55	0.009	0.13	0.14	0.42	0.35	0.66	2.13	2.15	2.08	2.14	0.027	0.042
	70-75	0.009	0.09	0.12	0.37	0.27	0.61	2.25	1.87	2.05	1.90	0.013	0.021
10 South Basin North End	0-5	0.018	0.13	0.30	0.61	0.66	1.04	1.81	3.40	3.30	4.79	0.080	0.084
	10-15	0.018	0.16	0.32	0.64	0.69	1.12	1.95	3.63	3.50	5.08	0.053	0.042
	20-25	0.018	0.14	0.30	0.61	0.63	1.07	1.93	3.56	3.18	4.73	0.053	<0.021
	30-35	0.018	0.11	0.30	0.61	0.58	1.06	1.99	3.42	3.14	4.87	0.080	0.063
	50-55	0.018	0.09	0.30	0.66	0.61	1.12	2.03	3.58	3.30	4.93	0.067	0.021
	70-75	0.018	0.14	0.29	0.59	0.60	1.04	2.02	3.27	3.18	4.63	0.053	0.021
14 Narrows South End	0-5	0.018	0.08	0.23	0.51	0.58	0.99	2.40	2.71	2.36	2.96	0.040	0.021
	10-15	0.018	0.07	0.22	0.49	0.69	0.89	2.40	2.58	2.33	3.02	0.040	0.021
	20-25	0.018	0.06	0.23	0.51	0.65	1.00	2.39	2.77	2.46	3.36	0.040	<0.021
	30-35	0.018	0.11	0.23	0.53	0.69	0.97	2.40	2.75	2.52	3.36	0.040	0.021
	50-55	0.018	0.10	0.26	0.51	0.63	1.00	2.40	2.85	2.54	3.38	0.053	0.042
	70-75	0.018	0.10	0.26	0.49	0.63	0.89	2.40	2.65	2.45	3.28	0.040	0.021
25 North Basin Near Saskatchewan River	0-5	0.018	0.10	0.23	0.54	0.66	1.09	2.09	3.13	3.12	3.38	0.053	0.042
	10-15	0.018	0.05	0.27	0.59	0.65	1.14	2.17	3.38	3.27	3.55	0.053	0.042
	20-25	0.018	0.04	0.23	0.59	0.66	1.12	2.07	3.27	3.09	3.47	0.053	0.042
	30-35	0.018	0.08	0.28	0.63	0.68	1.19	2.19	3.48	3.23	3.67	0.040	0.042
	50-55	0.018	0.03	0.27	0.61	0.69	1.16	2.17	3.35	3.14	3.67	0.040	0.042
	70-75	0.018	0.09	0.29	0.64	0.71	1.23	2.20	3.44	3.29	3.75	0.067	0.042
35 North Basin	0-5	0.018	0.11	0.30	0.66	0.79	1.23	2.26	3.56	3.43	3.91	0.067	0.052
	10-15	0.018	0.09	0.32	0.66	0.76	1.29	2.26	3.75	3.53	4.12	0.040	0.052
	20-25	0.018	0.10	0.22	0.46	0.56	0.99	1.84	2.79	2.51	3.00	-	-
	30-35	0.018	0.14	0.30	0.68	0.79	1.33	2.27	3.58	3.33	4.14	-	-
	50-55	0.018	0.13	0.30	0.73	0.79	1.38	2.27	3.65	3.41	4.38	0.027	-
	70-75	0.018	0.08	0.32	0.68	0.77	1.28	2.26	3.67	3.41	4.24	-	-
39 North Basin	0-5	0.027	0.10	0.28	0.59	0.72	1.12	2.23	3.38	3.18	3.67	0.040	<0.021
	10-15	0.018	0.12	0.29	0.70	0.83	1.29	2.26	3.63	3.30	4.06	0.053	0.042
	20-25	0.027	0.08	0.28	0.66	0.83	1.24	2.26	3.58	3.37	3.99	0.080	0.063
	30-35	0.018	0.08	0.28	0.63	0.76	1.26	2.23	3.79	3.40	4.06	0.027	-
	50-55	0.018	0.08	0.30	0.66	0.83	1.24	2.29	3.77	3.43	4.14	0.027	-
	70-75	0.018	0.13	0.27	0.59	0.79	1.14	2.27	3.73	3.23	3.91	0.013	-
54 Narrows North End	0-5	0.018	0.08	0.27	0.54	0.79	1.04	2.36	3.06	2.80	3.51	0.107	0.042
	10-15	0.018	0.07	0.28	0.54	0.72	1.04	2.31	3.29	2.95	3.93	0.080	0.084
	20-25	0.018	0.10	0.29	0.61	0.74	1.09	2.32	3.31	3.04	4.20	0.067	0.063
	30-35	0.018	0.06	0.30	0.61	0.74	1.12	2.34	3.33	3.03	4.18	0.080	0.042
	50-55	0.018	0.10	0.27	0.63	0.63	1.04	2.36	3.21	2.88	3.95	0.080	0.042
	70-75	0.018	0.14	0.29	0.53	0.66	0.97	2.41	3.00	2.91	3.73	0.053	0.021
57 South Basin	0-5	0.018	0.10	0.32	0.63	0.72	1.03	1.77	3.54	3.43	5.10	0.067	0.042
	10-15	0.018	0.15	0.33	0.59	0.66	1.02	1.77	3.19	3.35	4.81	0.067	0.063
	20-25	0.018	0.12	0.34	0.63	0.71	1.09	1.83	3.60	3.52	5.42	0.053	0.042
	30-35	0.018	0.10	0.31	0.63	0.61	1.11	1.81	3.31	3.44	5.24	0.080	0.042
	50-55	0.018	0.04	0.32	0.61	0.61	1.09	1.80	3.15	3.35	5.08	0.067	0.084
	70-75	0.018	0.06	0.34	0.63	0.65	1.09	1.81	3.42	3.40	5.30	0.067	0.042

Table 23. Cont'd.

Station and Location	Depth in Core (cm)	Cd	Pb	Be	Co	Cu	Ni	Sr	Cr	Zn	V	As	Mo
							µMoles/gram						
59 South Basin	0-5	0.018	0.13	0.30	0.59	0.72	1.12	1.68	3.48	3.30	4.97	0.053	0.063
	10-15	0.026	0.10	0.26	0.63	0.66	1.14	1.77	3.37	3.15	4.99	0.053	0.021
	20-25	0.018	0.07	0.26	0.59	0.61	1.12	1.68	3.48	3.12	4.93	0.080	<0.021
	30-35	0.018	0.08	0.24	0.56	0.60	1.09	1.78	3.04	2.97	4.61	0.067	<0.021
	50-55	0.018	0.09	0.26	0.64	0.61	1.16	1.83	3.50	3.15	5.08	0.040	0.084
	70-75	0.018	0.09	0.26	0.59	0.60	1.11	1.69	3.17	3.11	4.99	0.080	0.021
61 South Basin	0-5	0.027	0.12	0.22	0.49	0.77	1.02	1.50	3.19	3.21	4.69	0.093	<0.021
	10-15	0.018	0.12	0.24	0.53	0.58	1.04	1.60	2.79	3.17	4.67	0.053	0.021
	20-25	0.018	0.10	0.22	0.51	0.55	0.99	1.53	3.00	2.95	4.57	0.053	0.021
	30-35	0.018	0.08	0.26	0.54	0.58	1.02	1.54	2.65	3.00	4.73	0.053	<0.021
	50-55	0.018	0.08	0.26	0.54	0.83	1.04	1.54	2.88	2.97	4.73	0.053	0.042
	70-75	0.018	0.10	0.26	0.54	0.58	1.06	1.50	2.79	3.01	4.71	0.053	0.021

Table 24. Concentrations of mercury, arsenic, and molybdenum in south basin Lake Winnipeg sediment cores taken in July 1975.†

Station and Location	Depth in Core (cm)	Hg nMoles/gram	As µMoles/gram	Mo µMoles/gram
1	0-2	0.47	0.027	0.042
	2-4	1.12	<0.013	0.021
South Basin	4-6	0.75	0.040	0.021
	6-8	0.97	0.093	0.042
	8-10	0.82	0.093	0.042
	10-14	0.90	0.093	0.031
	14-18	0.75	0.107	0.031
	18-22	0.30	0.093	0.021
	22-30	0.30	0.080	0.021
	30-40	0.34	0.067	0.021
	40-50	0.36	0.027	0.021
	50-60	0.27	0.053	0.021
	60-70	0.34	0.067	0.021
2	0-2	0.48	0.013	0.021
	2-4	0.60	0.093	0.021
South Basin	4-6	0.75	0.080	<0.021
	6-8	0.75	0.040	<0.021
	8-10	0.75	0.067	<0.021
	10-14	0.67	<0.013	<0.021
	14-18	0.67	<0.013	<0.021
	18-22	0.67	0.053	<0.021
	22-30	0.55	0.040	0.021
	30-40	0.30	0.027	<0.021
	40-50	0.34	0.040	<0.021
	50-60	0.30	0.053	<0.021
	60-70	0.40	0.067	<0.021
3	0-2	0.52	0.067	<0.021
	2-4	0.52	0.040	<0.021
South Basin	4-6	0.52	0.040	<0.021
	6-8	0.60	0.067	<0.021
	8-10	0.52	0.093	<0.021
	10-14	0.60	0.107	<0.021
	14-18	0.50	0.067	0.031
	18-22	0.37	0.027	<0.021
	22-30	0.38	0.027	0.031
	30-40	0.31	0.027	0.021
	40-50	0.41	0.027	<0.021
	50-60	0.37	0.027	<0.021
	60-70	0.36	0.040	0.021
4	0-2	0.75	0.067	0.021
	2-4	0.47	0.040	0.021
South Basin	4-6	0.47	0.040	0.042
	6-8	0.50	0.040	<0.021
	8-10	0.47	0.040	0.021
4	10-14	0.30	<0.013	<0.021
	14-18	0.35	<0.013	<0.021
South Basin	18-22	0.43	0.013	<0.021
	22-30	0.47	0.053	<0.021
	30-40	0.40	0.040	<0.021
	40-50	0.30	0.027	<0.021
	50-60	0.27	0.053	0.021
	60-70	0.34	0.053	<0.021
5	0-2	0.60	0.080	<0.021
	2-4	1.42	0.080	0.042
South Basin	4-6	0.75	0.013	0.021
	6-8	0.82	0.013	0.042
	8-10	0.60	0.013	0.021
	10-14	0.56	0.013	0.021
	14-18	0.78	0.027	<0.021
	18-22	0.47	0.027	0.031
	22-30	0.55	0.027	0.031
	30-40	0.43	0.040	0.031
	40-50	0.35	0.040	<0.021
	50-60	0.54	0.040	0.021
	60-70	0.37	0.040	0.021
6	0-2	0.47	0.120	0.021
	2-4	0.47	0.093	<0.021
South Basin	4-6	0.53	0.067	0.021
	6-8	0.47	0.053	0.042
	8-10	0.47	0.067	0.042
	10-14	0.38	0.080	0.042
	14-18	0.30	0.080	0.042
	18-22	0.27	0.080	0.031
	22-30	0.28	0.080	0.021
	30-40	0.34	0.053	0.021
	40-50	0.34	0.026	<0.021
	50-60	0.28	0.026	0.021
	60-70	0.28	0.013	0.021
7	0-2	0.27	0.053	0.021
	2-4	0.40	0.067	0.021
South Basin	4-6	0.47	0.027	<0.021
Traverse Bay	6-8	0.34	0.093	<0.021
	8-10	0.53	0.107	0.021
	10-14	0.43	0.053	0.031
	14-18	0.30	0.067	0.021
	18-22	0.33	0.067	<0.021

Table 24. Cont'd.

Table 24. Cont'd.

Station and Location	Depth in Core (cm)	Hg nMoles/gram	As µMoles/gram	Mo µMoles/gram
8	0-2	0.40	.027	0.021
	2-4	0.40	.053	0.021
Traverse Bay	4-6	0.27	.053	0.021
	6-8	0.27	.053	<0.021
	8-10	0.21	.027	0.042
	10-14	0.17	.027	<0.021
	14-18	0.14	.013	0.031
	18-22	0.14	<.013	0.042
	22-30	0.16	.013	0.042
	30-40	0.14	.013	0.031
	40-50	0.14	.027	0.031
	50-60	0.14	.013	<0.021
9	0-2	0.60	.067	<0.021
	2-4	0.53	.040	<0.021
Traverse Bay	4-6	0.34	.053	0.021
	6-8	0.27	.093	<0.021
	8-10	0.27	.067	<0.021
	10-14	0.27	.027	0.021
	14-18	0.24	.040	0.021
	18-22	0.24	.027	0.031
	22-30	0.22	.013	0.021
	30-40	0.21	.013	0.021
	40-50	0.22	.013	<0.021
	50-60	0.21	.013	<0.021
	60-70	0.14	<.013	<0.021

† These data were provided to us by Dr. R. J. Allan, and the total element concentrations were measured by radio frequency plasma emission spectroscopy. Station locations are given in Fig. 24.

Table 25. Overlying lake water and interstitial water chemistry (in µmoles/L) of sediment samples (0-20 cm homogenized) from Lake Winnipeg, collected October 3-12, 1969, squeezed February 1970. Interstitial water samples were immediately filtered through a Whatman GF/C filter. LW = Lake water, IW = Interstitial water, (-) = Not measured.

Station	Ca		Mg		Na		K		Cl		SO_4		HCO_3	Si		Fe	Mn
	LW	IW	LW	IW	LW	IW	LW	IW	LW	IW	LW	IW	LW	LW	IW	IW	IW
01	-	1525	-	1872	-	2109	-	34	-	1211	-	-	2740	186	-	3	35
02	1015	2475	790	2243	900	1630	118	46	379	789	583	-	-	123	-	23	152
03	-	3025	-	3004	-	1243	-	269	412	546	593	13	2860	123	694	1	64
03C	-	1988	-	1564	-	965	-	157	158	721	250	13	1420	68	925	1	77
04	716	1150	502	1111	883	1109	76	174	237	507	364	-	1880	86	-	<0.4	77
04B	-	1288	-	945	-	648	-	120	-	310	-	26	-	-	758	1	66
05	-	1301	-	1029	-	765	-	113	-	372	-	13	-	134	865	1	64
06	-	1163	-	872	-	591	-	552	-	676	-	13	-	103	769	1	54
07	324	1668	173	741	78	461	18	58	39	828	62	-	-	66	-	36	46
08	334	800	202	691	87	365	21	59	39	197	62	-	800	70	-	20	44
10	-	810	-	593	-	478	-	90	175	197	323	<13	1720	133	936	2	69
12	-	770	-	761	-	578	-	101	-	254	-	-	-	129	-	<0.4	58
14	599	740	395	774	287	565	58	113	152	225	239	-	1520	109	-	-	59
15	-	1988	-	1325	-	357	-	59	-	-	-	13	-	43	-	2	78
17	-	605	-	461	-	626	-	818	327	451	167	350	1350	38	665	2	17
18	422	1075	284	765	296	796	38	190	203	535	146	26	1160	40	-	49	31
21	691	715	494	700	565	1000	58	123	429	676	239	-	1940	33	-	<0.4	12
23C	723	1475	551	576	639	687	61	104	305	535	281	-	2220	23	-	<0.4	36
23E	736	1350	518	638	639	804	61	86	496	479	271	-	1980	26	-	<0.4	38
23H	-	1063	-	716	-	696	-	59	-	394	-	38	-	-	-	<0.4	57
25	721	1050	502	720	648	687	61	57	513	451	250	13	2020	29	-	<0.4	63
26	-	660	-	802	-	817	-	147	-	451	-	-	-	36	-	<0.4	54
27	-	2575	-	1626	-	848	-	86	-	423	-	625	-	36	-	<0.4	96
31	-	1850	-	1169	-	8696	-	143	-	569	-	50	-	27	-	22	82
34	-	1175	-	757	-	678	-	59	-	366	-	26	-	27	-	2	40
35	793	2190	539	630	626	774	60	94	429	535	177	-	8240	19	-	<0.4	54
39	753	830	526	588	648	648	53	57	468	423	250	50	2120	18	-	<0.4	30
41	851	3543	588	630	617	904	60	91	389	451	208	-	2300	26	-	<0.4	29
47	-	1200	-	872	-	1009	-	109	-	845	-	100	-	23	-	<0.4	32
48	589	590	428	576	548	870	52	86	440	563	239	-	1640	36	-	57	36
50	-	685	-	473	-	328	-	32	-	225	-	363	-	40	-	<0.4	26
51	-	1600	103	845	78	491	13	76	34	197	42	-	310	73	-	3	161
52	-	745	-	658	-	600	-	78	107	197	125	-	1020	48	-	98	26
53	-	670	-	617	-	543	-	83	-	254	-	-	-	-	-	8	31
54	536	760	358	597	252	587	47	87	147	225	156	-	1340	40	-	26	39
55	-	1088	-	823	-	385	-	101	-	197	-	375	-	-	587	1	44
57	654	2819	457	733	413	665	74	107	181	338	323	-	1820	140	-	<0.4	80
59	619	3019	440	774	378	709	63	244	158	366	250	-	-	130	-	<0.4	62
59B	-	1250	-	938	-	991	-	81	-	197	-	63	-	-	-	1	131
60	1000	2343	769	774	870	652	116	134	372	366	604	-	2640	118	-	<0.4	73
60B	996	1838	790	1374	861	743	119	141	367	197	65	-	-	194	779	1	101
60C	-	1500	-	1095	-	826	-	137	-	394	-	688	-	70	762	1	49
60D	-	1150	-	897	-	539	-	102	-	225	-	13	-	-	826	2	73
61	868	1791	650	794	709	761	101	157	310	422	489	-	2340	100	-	<0.4	76
64	549	1804	403	617	557	1122	52	107	491	845	219	-	1420	42	-	<0.4	16
68	-	2725	-	1975	-	922	-	141	-	507	-	-	-	37	-	<0.4	126
69	-	770	-	584	-	426	-	95	-	225	-	963	-	38	402	2	11

Table 26. General definition of graphic moment measures applied to sediment particle size distributions (modified after Thomas et al., 1976).

Parameter	Moment	Value for normal distribution	Comments
Mean particle size	First moment about zero	any	Large positive values = fine sediments.
Standard Deviation	Second moment about the mean	>0	Large values = poor sorting of sediment particle sizes.
Skewness	Standardized third moment about the mean	0.0	Relative to a normal distribution: positive values = extension of the tail of the distribution towards fine sediment particle sizes. Negative values = extension of the tail of the distribution towards coarse particle sizes.
Kurtosis	Standardized fourth moment about the mean	0.0	Relative to a normal distribution: large positive values = distribution of sediment sizes narrowly peaked at the mean. Large negative values = distribution of sediment sizes flat or bimodal.

Table 27. Moment parameters (mean particle size, standard deviation, skewness, and kurtosis) of the distribution of particle sizes of Lake Winnipeg sediment samples given in Table 2. Our calculations follow Folk and Ward (1957).

Station	Mean ϕ	Standard Deviation	Skewness	Kurtosis
		South Basin		
01	4.20	1.91	0.479	1.64
02	8.43	1.74	-0.150	1.02
03	8.23	2.14	-0.271	0.989
03C	8.00	1.71	-0.009	0.973
03D	8.20	1.83	-0.107	0.984
04	7.43	2.76	-0.286	0.713
04B	8.70	1.74	-0.148	1.10
05	9.03	1.55	-0.169	1.05
06	8.00	2.02	-0.172	0.981
07	6.40	2.20	0.022	0.912
08	8.73	1.66	-0.158	1.02
10	9.40	1.58	-0.236	1.25
12	4.13	2.04	0.509	2.36
57	8.97	1.54	-0.144	1.07
59	9.20	1.72	-0.297	1.21
59B	9.83	1.34	-0.174	1.34
60	9.30	1.55	-0.223	1.21
60B	9.07	1.76	-0.314	1.17
60C	8.83	1.64	-0.168	1.01
60D	8.93	1.73	-0.238	1.03
61	8.90	1.63	-0.194	1.02
Composite of all stations	8.13	2.40	-0.384	0.916
		Narrows		
14	6.93	2.45	-0.074	0.798
15	6.13	2.47	0.187	0.778
51	7.03	2.59	-0.076	0.751
52	8.77	2.33	-0.483	1.28
53	7.47	2.68	-0.324	0.710
54	8.50	1.96	-0.246	0.987
55	7.40	2.56	-0.232	0.788
56	8.43	1.74	-0.150	0.973
69	7.33	2.78	-0.291	0.615
Composite of all stations	7.53	2.59	-0.272	0.79
		North Basin		
17	5.63	2.87	0.611	0.611
18	7.70	1.90	-0.040	0.993
21	6.37	2.88	0.163	0.597
23C	8.97	1.58	-0.217	1.03
23H	7.10	1.71	0.026	1.02
26	7.87	1.77	-0.040	0.967
27	7.47	1.83	-0.030	0.984
28	8.87	2.09	-0.422	1.23
31	3.70	1.62	0.365	2.02
33	7.83	1.82	-0.069	1.04
34	7.97	1.85	-0.054	0.926
35	8.20	1.51	0.000	1.02
39	6.17	2.74	0.264	0.643
41	8.40	1.67	-0.099	0.998
47	8.60	1.28	0.118	1.04
48	9.37	1.65	-0.285	1.40
50	8.03	2.39	-0.380	0.878
50D	10.77	0.864	-0.047	0.990
64	9.10	1.84	-0.300	1.25
68	5.70	2.74	0.495	0.643
Composite of all stations	7.43	2.55	-0.230	0.78

Table 28. Clay mineralogy of the total clay fraction (<4 μm) of selected south basin Lake Winnipeg sediment samples. This data is from Kushnir (1971).

Station No.	% of Clay Fraction		
	Montmorillonite	Illite	Kaolinite and Chlorite†
00	53	34	13
01	53	33	14
02	48	39	13
03	60	28	12
03C	49	36	15
03D	48	34	18
04	60	27	13
04B	54	32	14
05	52	34	14
06	60	27	13
07	62	27	11
08	56	30	14
10	36	49	15
12	60	27	13
57	61	28	11
59	47	40	13
59B	29	45	26
60	43	40	17
60B	61	28	11
60C	61	29	10
60D	50	35	15
61	58	29	13

† Kaolinite was found to be more abundant than chlorite in most samples subjected to heat treatment.

Table 29. Comparison of present-day sedimentation rate data for Lake Winnipeg and the St. Lawrence Great Lakes.

Lake	Deep basin average rate of sedimentation (g dry weight m^{-2} yr^{-1})	Range	Deep basin average thickness of sediment per year (mm)	Range
Winnipeg (Red River Basin)*	1170	0-1970	1.1	0-2
Erie[1]	2880	0-5050	6.1	0-24
Ontario[2]	563	0-1156	2.5	0-9.6
Huron[3]	266	65-495	1.2	0.3-8
Superior[4]	380	25-780	1.2	0.1-2.3
Michigan[5]	147	0-165	0.8	0-3.2

* Minimal sedimentation rate estimate, based on annual Red River suspended sediment supply only, see Table 19.

[1] Data from Kemp et al. 1976; Sly & Thomas 1974; Kemp et al. 1974.

[2] Data from Thomas et al. 1972; Sly & Thomas 1974.

[3] Data from Kemp et al. 1974; Kemp et al. 1978.

[4] Data from Bruland et al. 1975; Kemp et al. 1978.

[5] Data from Edgington & Robbins 1976.

Table 30. Comparison of average, deep basin, elemental sediment supply rates.

Element (mMoles m⁻² yr⁻¹)	Lake Winnipeg[1] (Red River Basin only)	Lake Superior[2]	Lake Huron[2]	Lake Erie[2] (Range)	Lake Ontario[2] (Range)	California Coastal Basins[3]
C	(4,000)	1060	935	(770-8710)	(491-842)	-
N	(420)	102	94	(300-1630)	(171-630)	-
P	22(34)	19	8.4	(32-213)	(23-52)	-
Fe	480	-	-	-	-	322
Mn	21	-	-	-	-	2.7
Al	2950	-	-	-	-	1000
Ni	0.06	0.34	0.38	2.4	1.0	0.08
Cu	0.6	0.93	0.27	1.3	0.66	0.2
Co	0.5	0.14	0.12	0.70	0.22	0.09
Cr	2.9	0.33	0.19	3.7	1.5	0.06
V	4.6	0.70	0.37	1.6	0.57	0.8
Zn	3.3	0.98	0.84	6.1	3.2	0.3
Cd	0.02	0.009	0.005	0.044	0.020	0.009
Pb	0.06	0.20	0.18	0.72	0.48	0.08
Hg	0.01[4]	0.0004	0.0005	0.006	0.0047	-

[1] Probably a minimal estimate, based on Red River sediment supply only. See Table 19. Data in parentheses are from twice monthly sampling of the Red River at Lockport, Manitoba. In this column, C is total carbon = organic plus inorganic C.

[2] Data from Kemp et al. (1974, 1976, 1978). C = organic carbon.

[3] Data averaged form Bruland et al. (1974).

[4] Estimated from Derksen (1973) and Armstrong and Hamilton (1973), assuming no release from sediment particles.

Table 31. Comparison of 1926 and 1969 sediment particle size data for Red River and Lake Winnipeg bottom sediments.†

	% Sand	% Silt	% Clay
Ward's Lake Winnipeg station, 4 miles north of the mouth of the Red River (1926)	6.82	36	57.13
Our Station 4, 4½ miles off mouth of Red River (1969)	19	36	44
Ward's St. Vital Bridge sample of Red River sediments (1926)	6.8	57.8	35.1
Our Red River sediment sample at the St. Vital Bridge (1969)	3.6	44.9	51.5

† The 1926 data are from Ward (1926), and the 1969 data are from Table 2. Ward's size limits were probably as follows: Clay = <4 μm, silt = 4-62.5 μm, and sand = >62.5 μm. These limits are slightly different than ours (see Table 2). The St. Vital Bridge is in the City of Winnipeg.

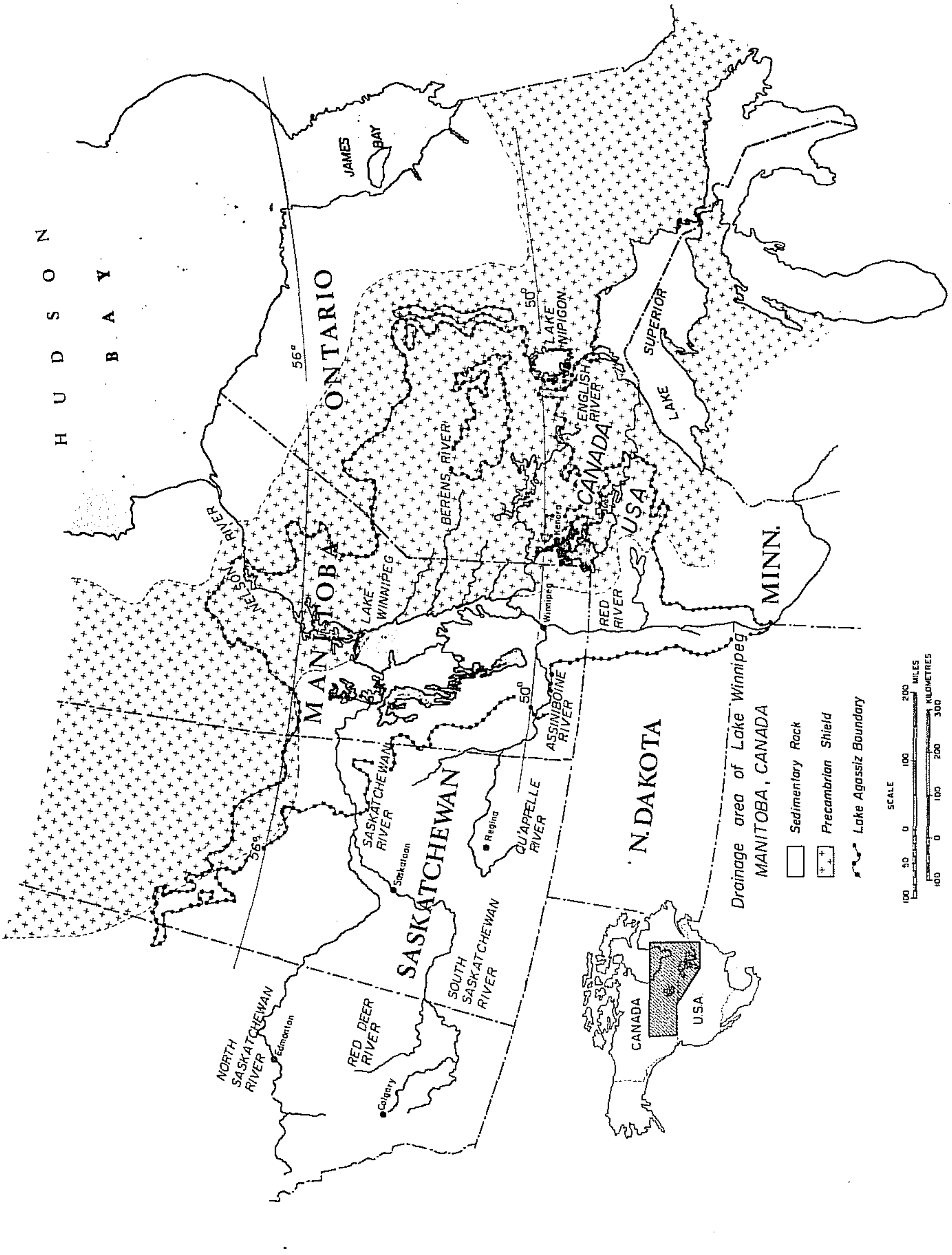

Fig. 1. Map of the watershed of Lake Winnipeg, its major tributaries, and the maximum extent of glacial Lake Agassiz sediments (dashed line, from Elson 1967).

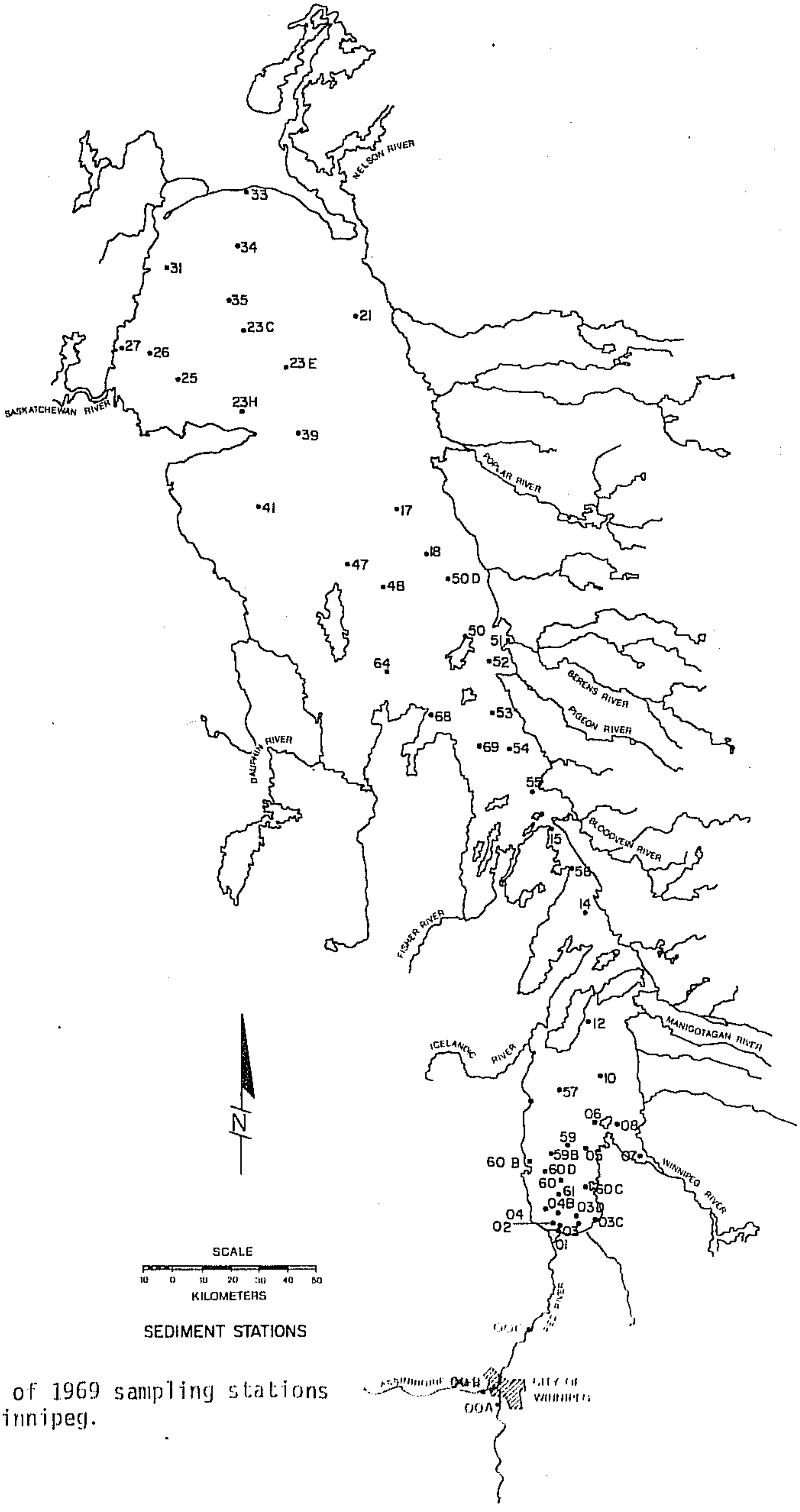

Fig. 2. Locations of 1969 sampling stations in Lake Winnipeg.

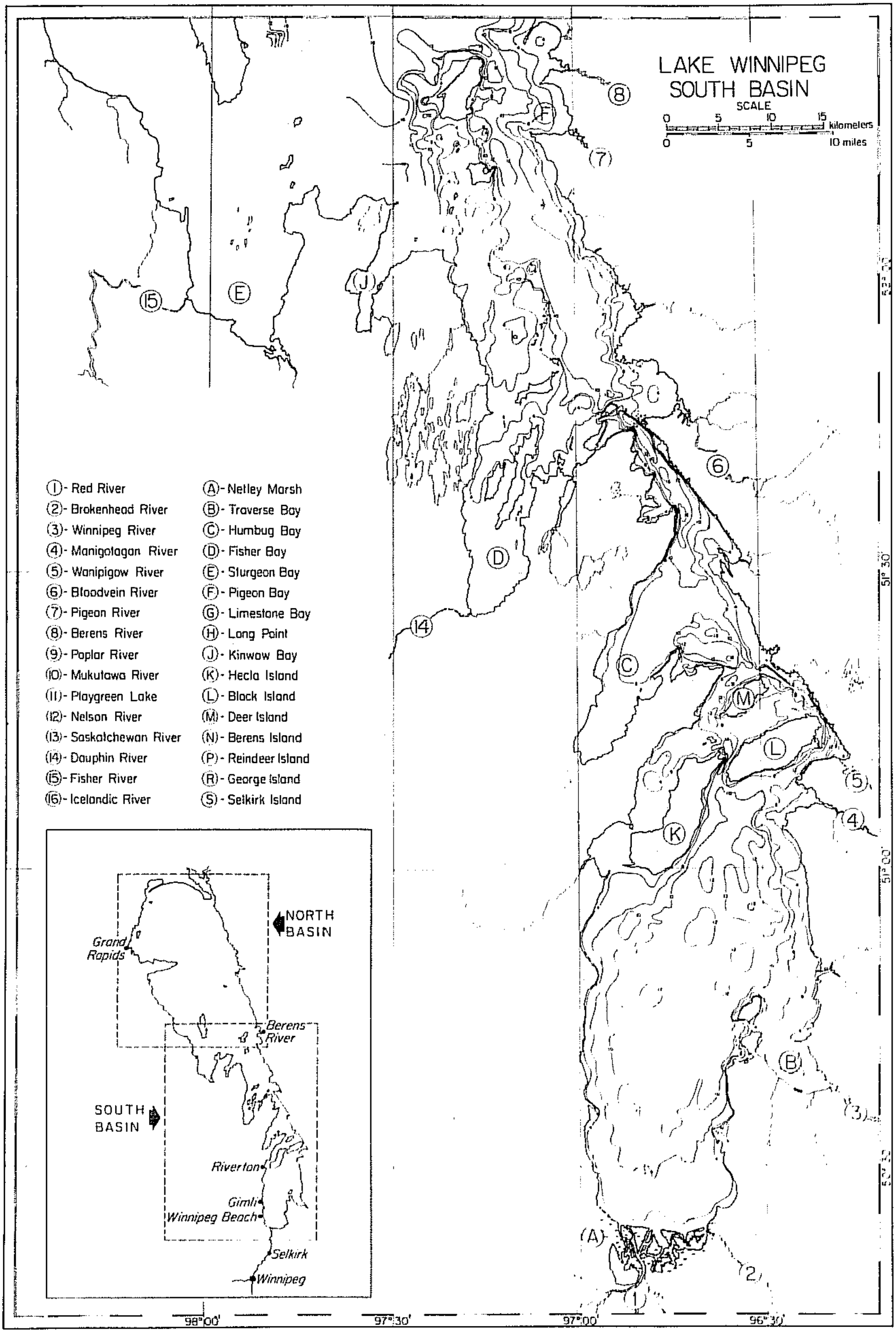

Fig. 3. Bathymetry of the south basin and narrows of Lake Winnipeg, from Brunskill, Elliott, and Campbell (1979). Depth contours are in meters.

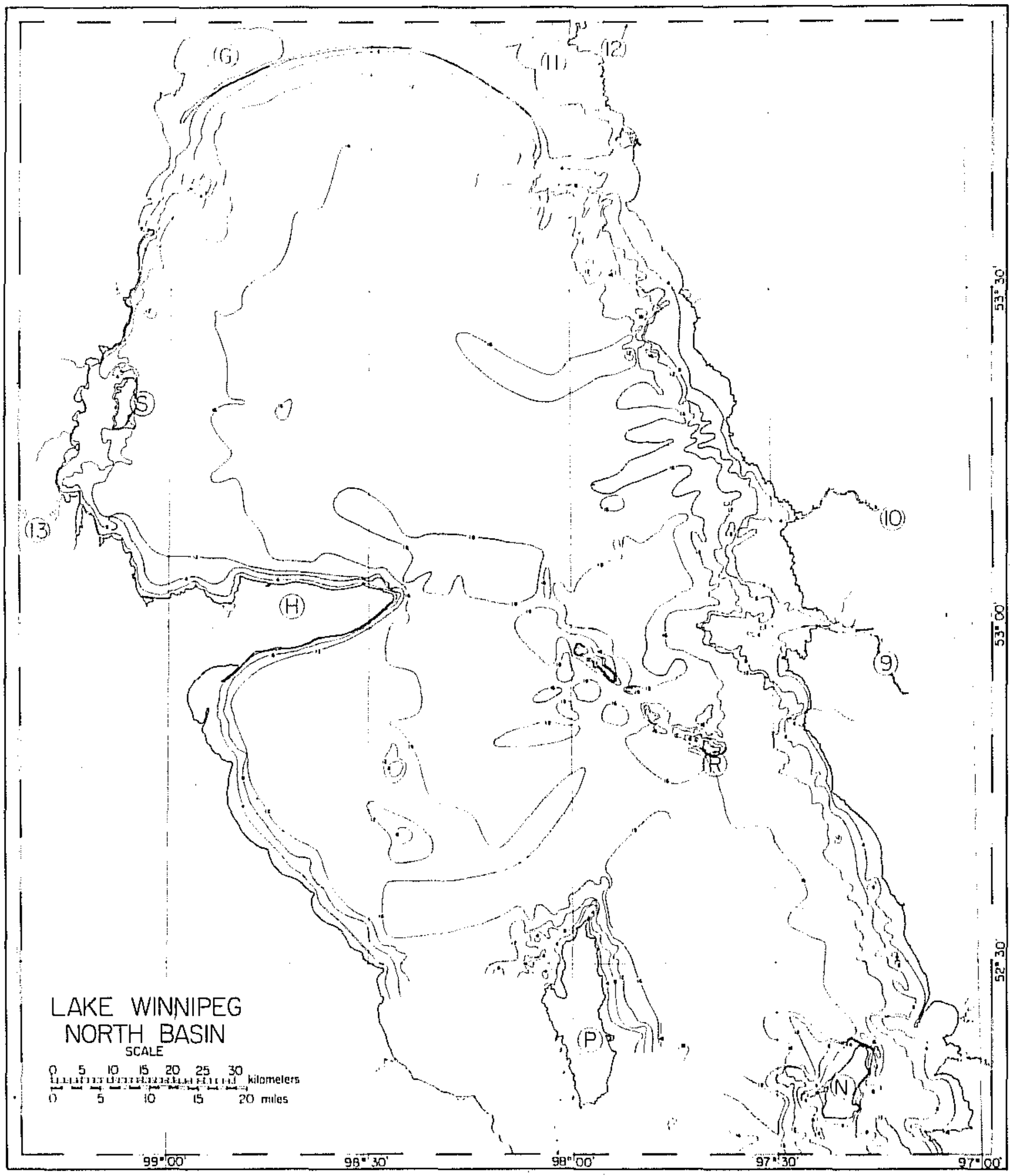

Fig. 4. Bathymetry of the north basin of Lake Winnipeg, from Brunskill, Elliott, and Campbell (1979). Depth contours are in meters.

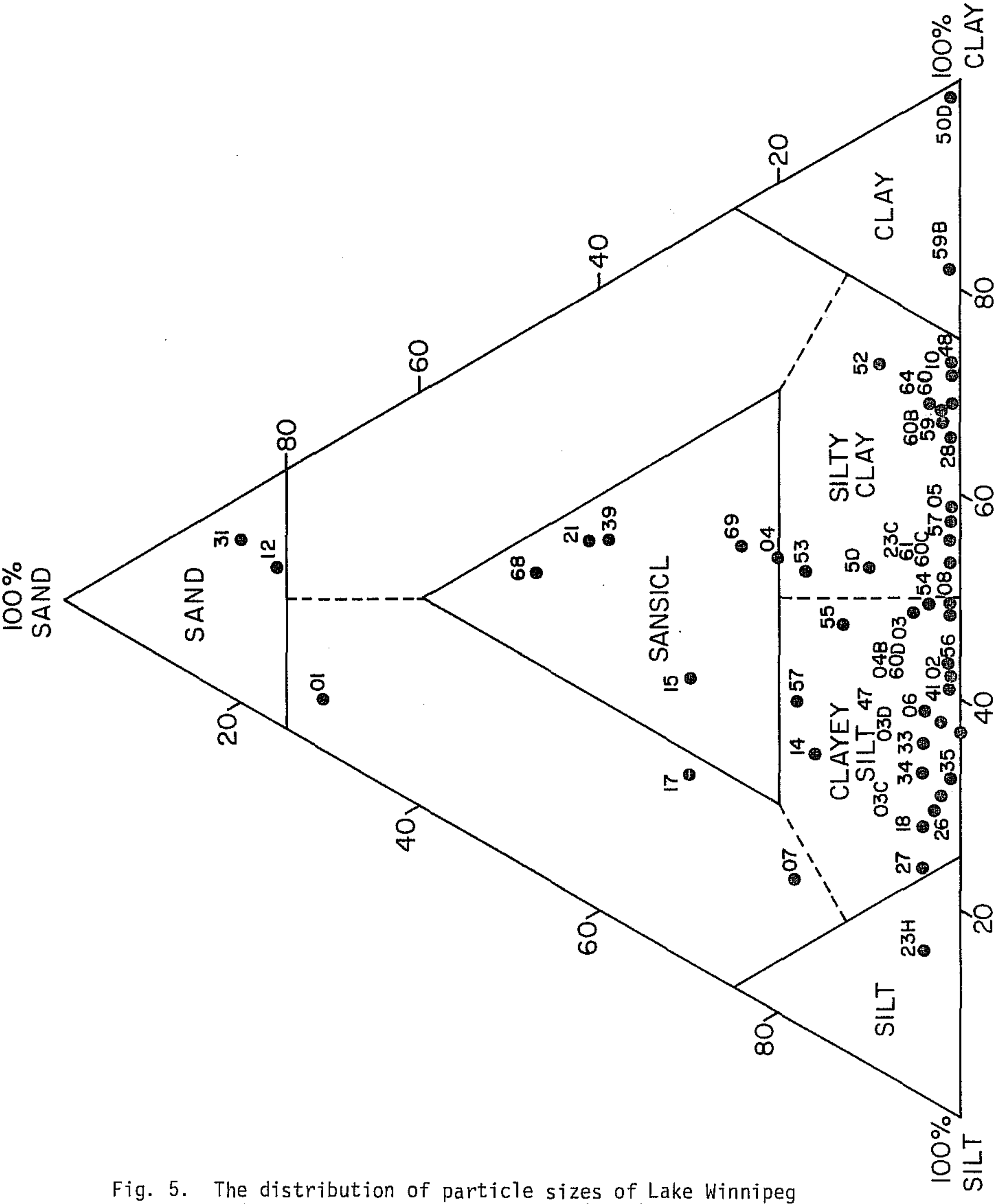

Fig. 5. The distribution of particle sizes of Lake Winnipeg sediments, according to Shepard (1954). Station numbers are from Fig. 2, and Tables 1 and 2 give data for this diagram.

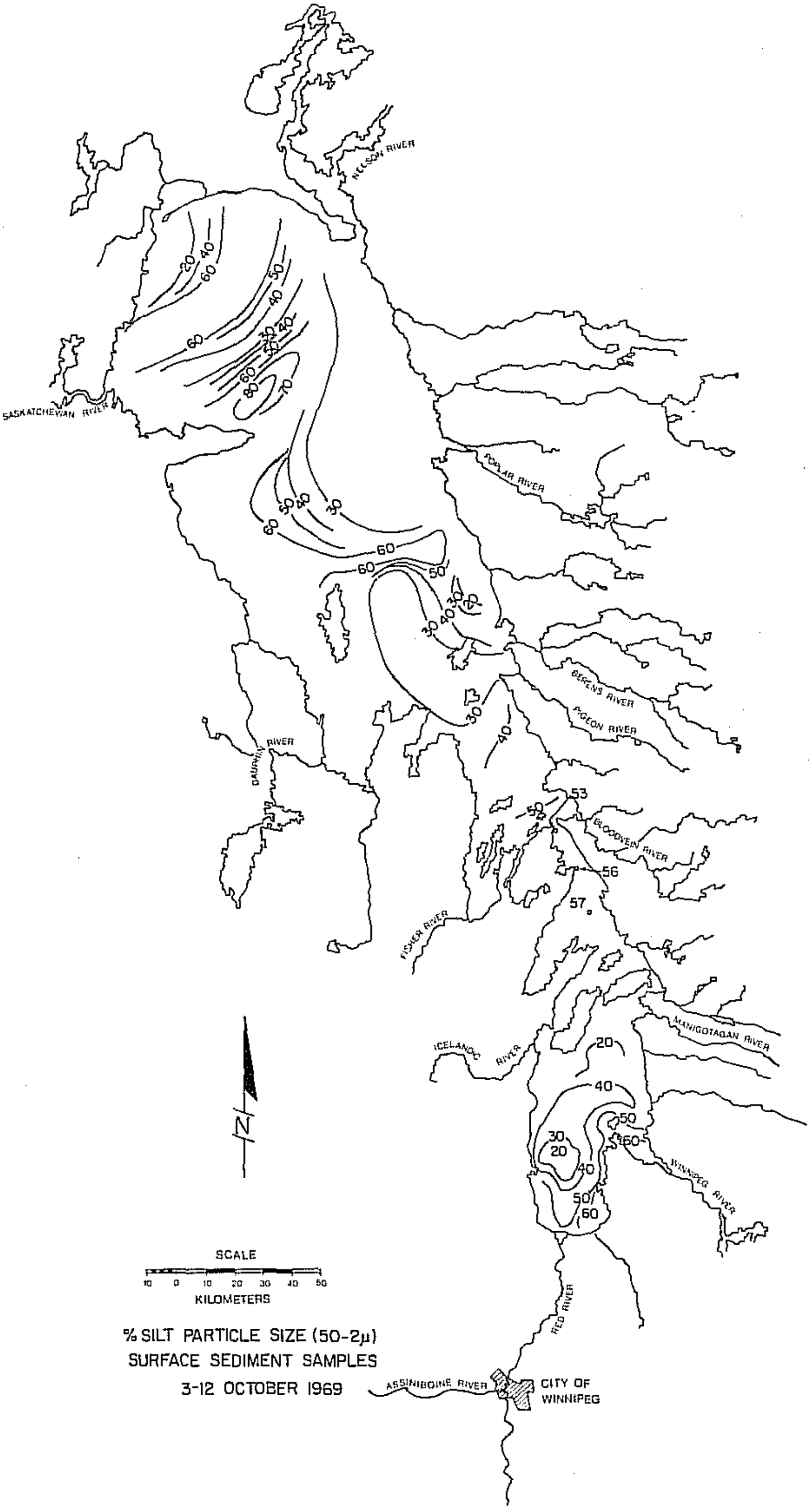

Fig. 6. Isopleths of % silt (50-2 μm) in Lake Winnipeg sediments, based on Table 2 data.

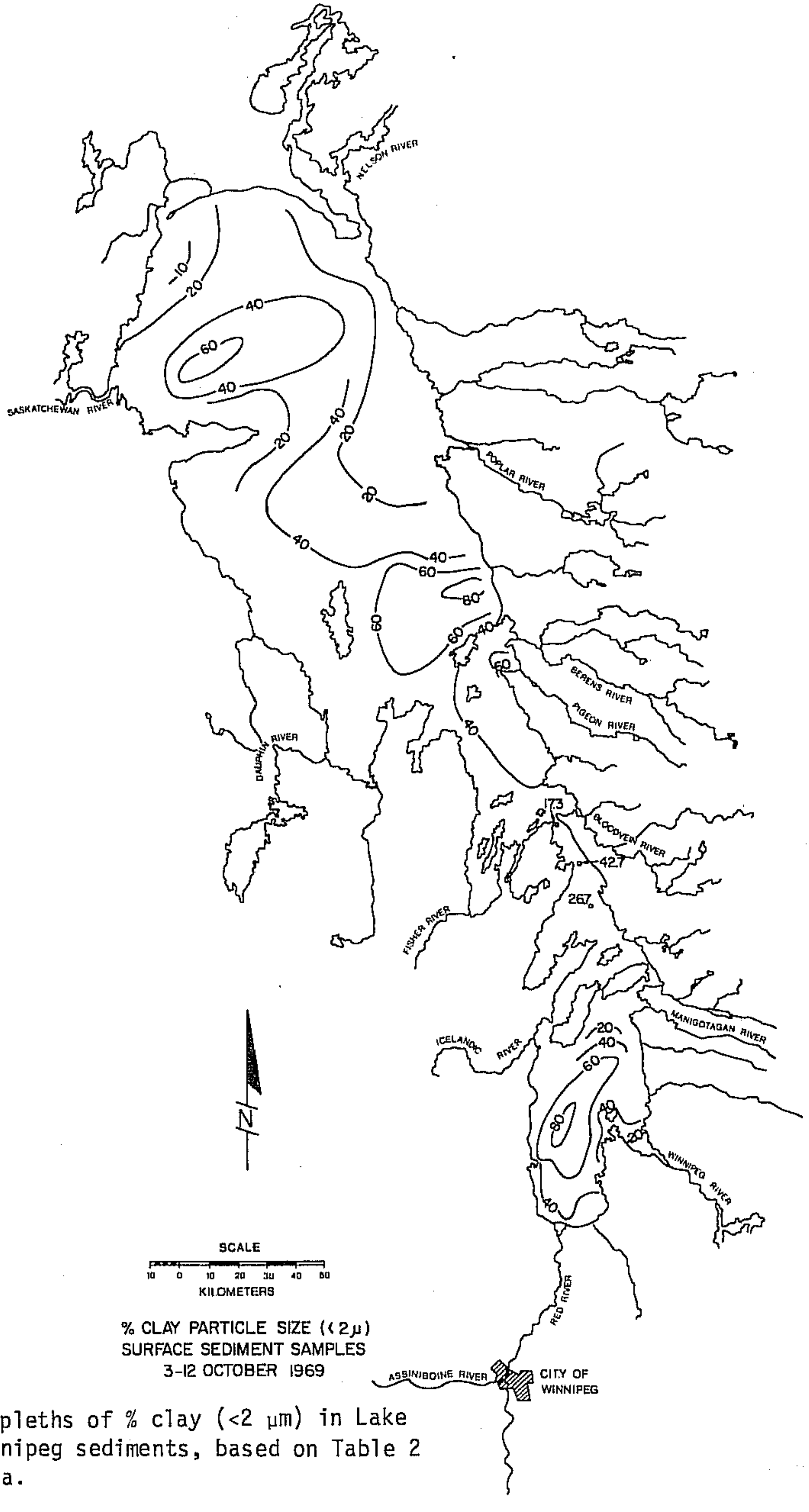

Fig. 7. Isopleths of % clay (<2 µm) in Lake Winnipeg sediments, based on Table 2 data.

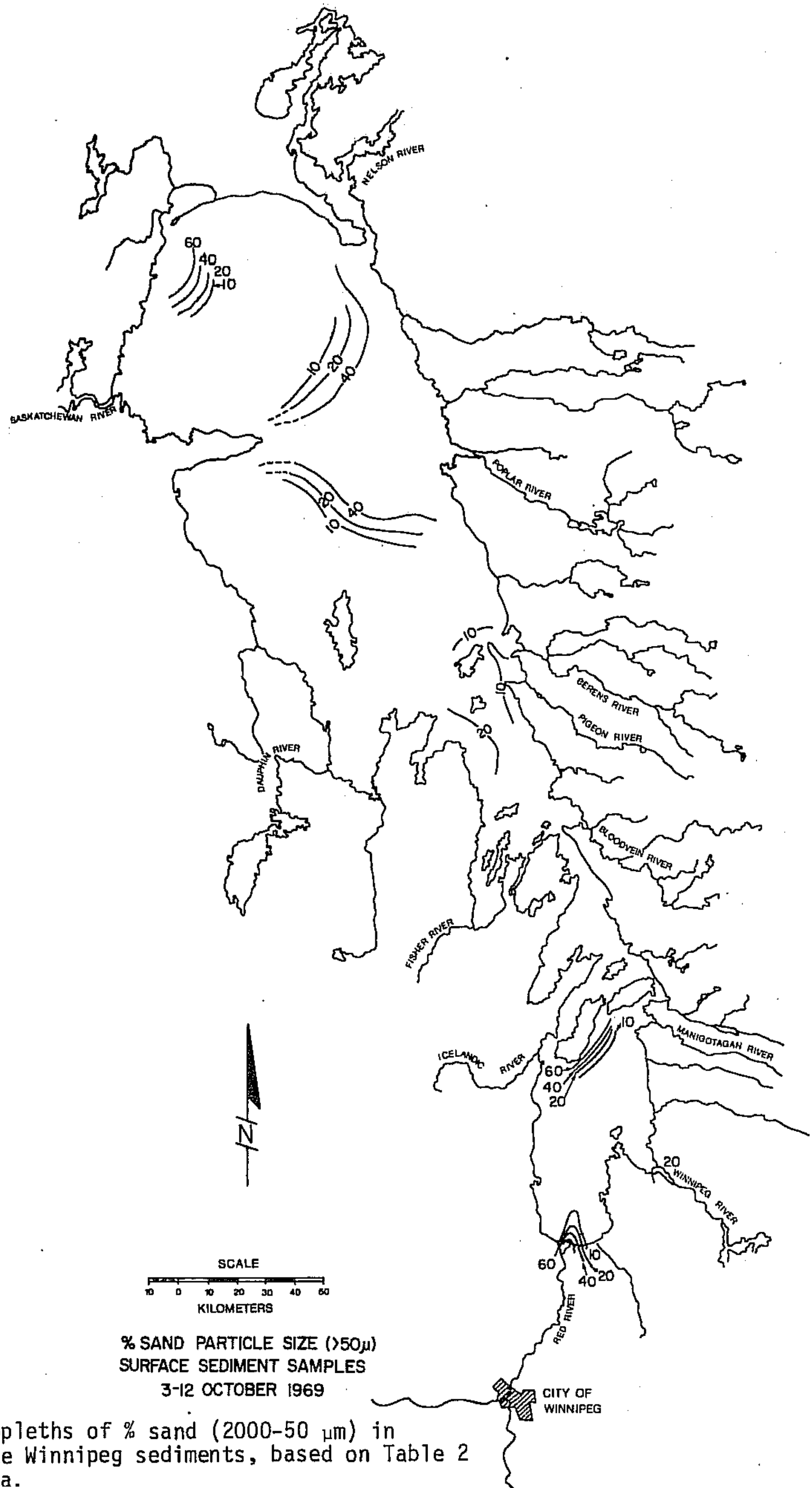

Fig. 8. Isopleths of % sand (2000-50 µm) in Lake Winnipeg sediments, based on Table 2 data.

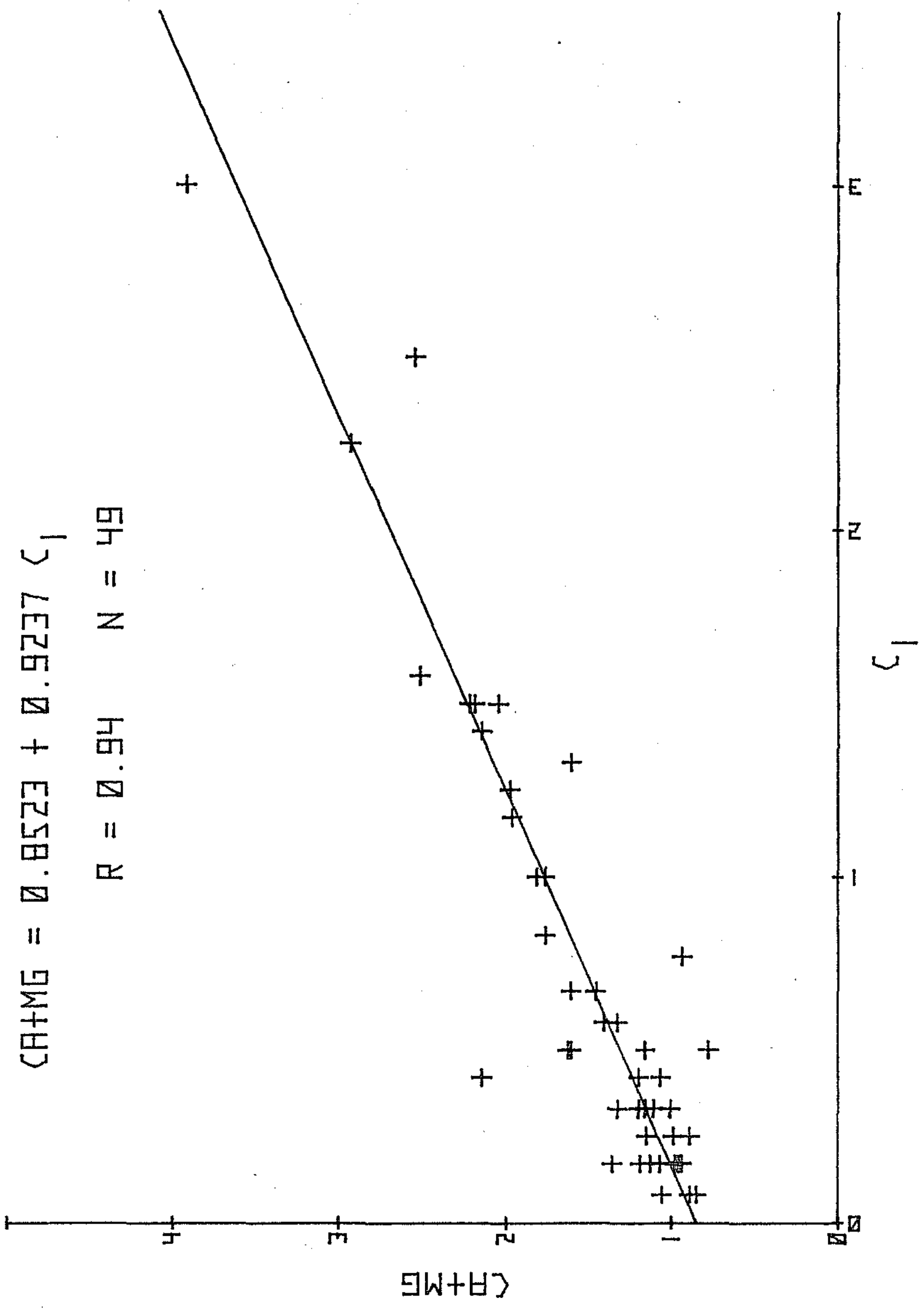

Fig. 9. The relationship between the sum of Ca and Mg (in mMoles/g) dry weight), and inorganic carbon (C_i) for sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

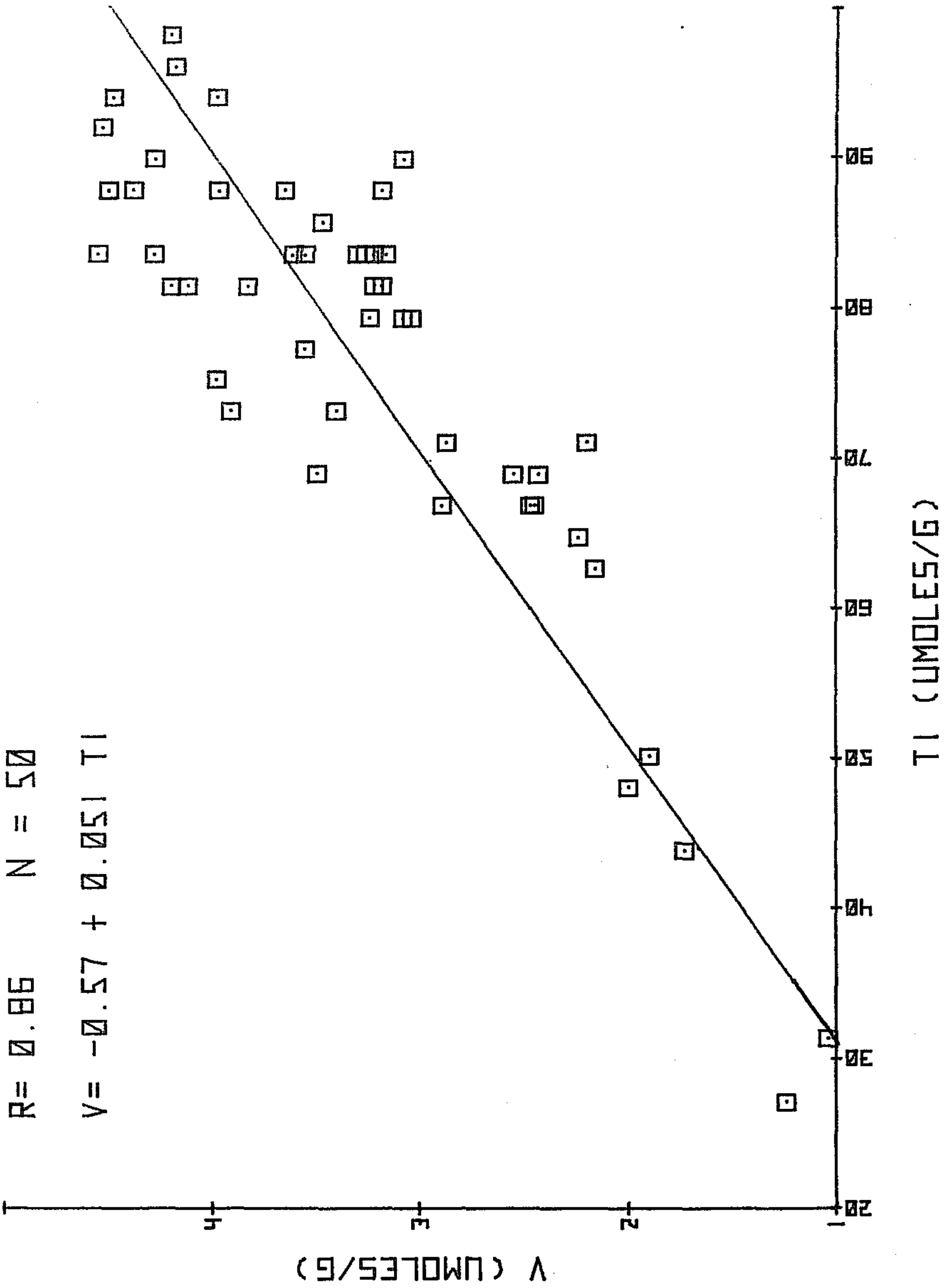

Fig. 10. The relationship between vanadium (V) and titanium (Ti), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

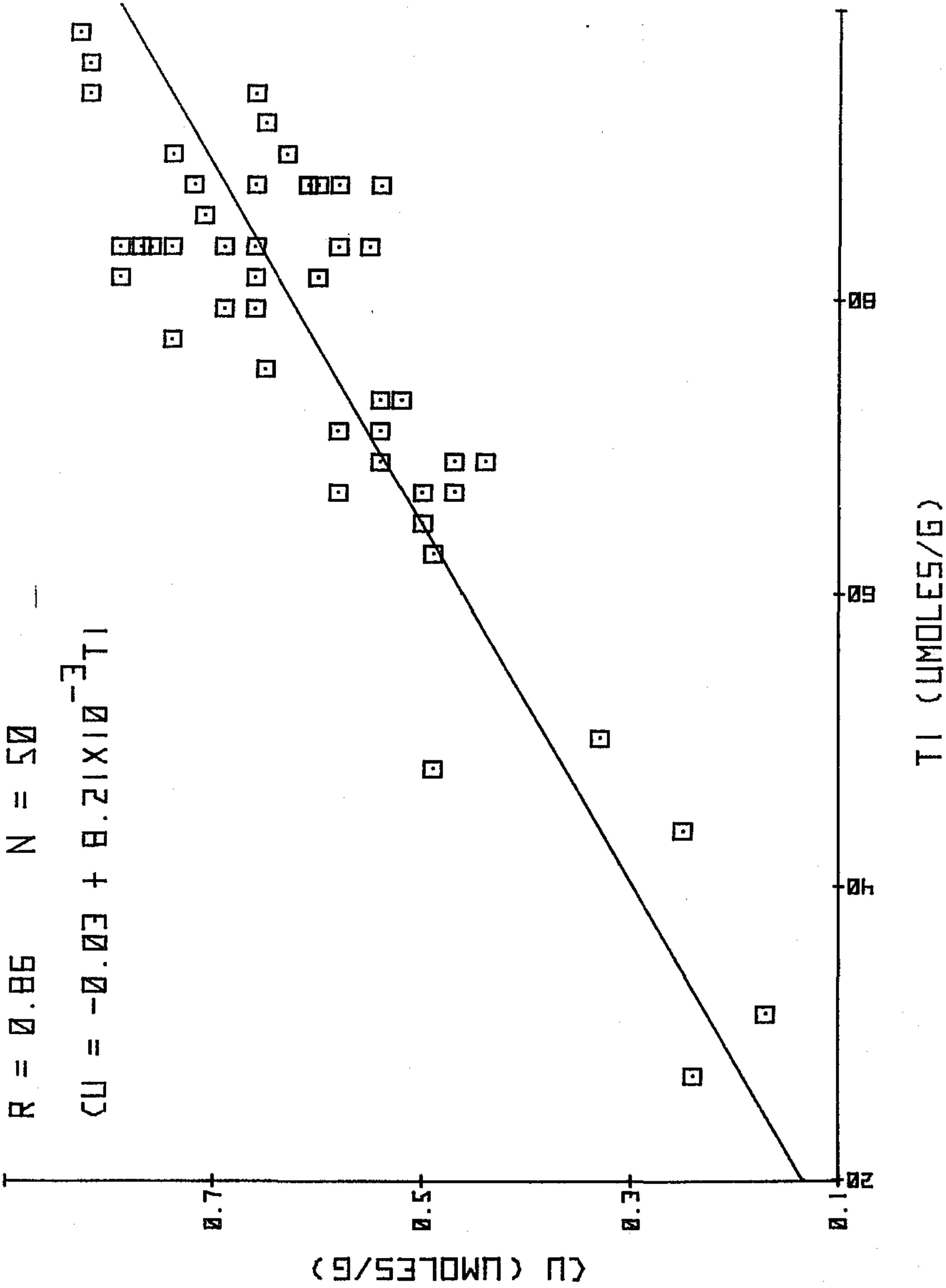

Fig. 11. The relationship between copper (Cu) and titanium (Ti), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

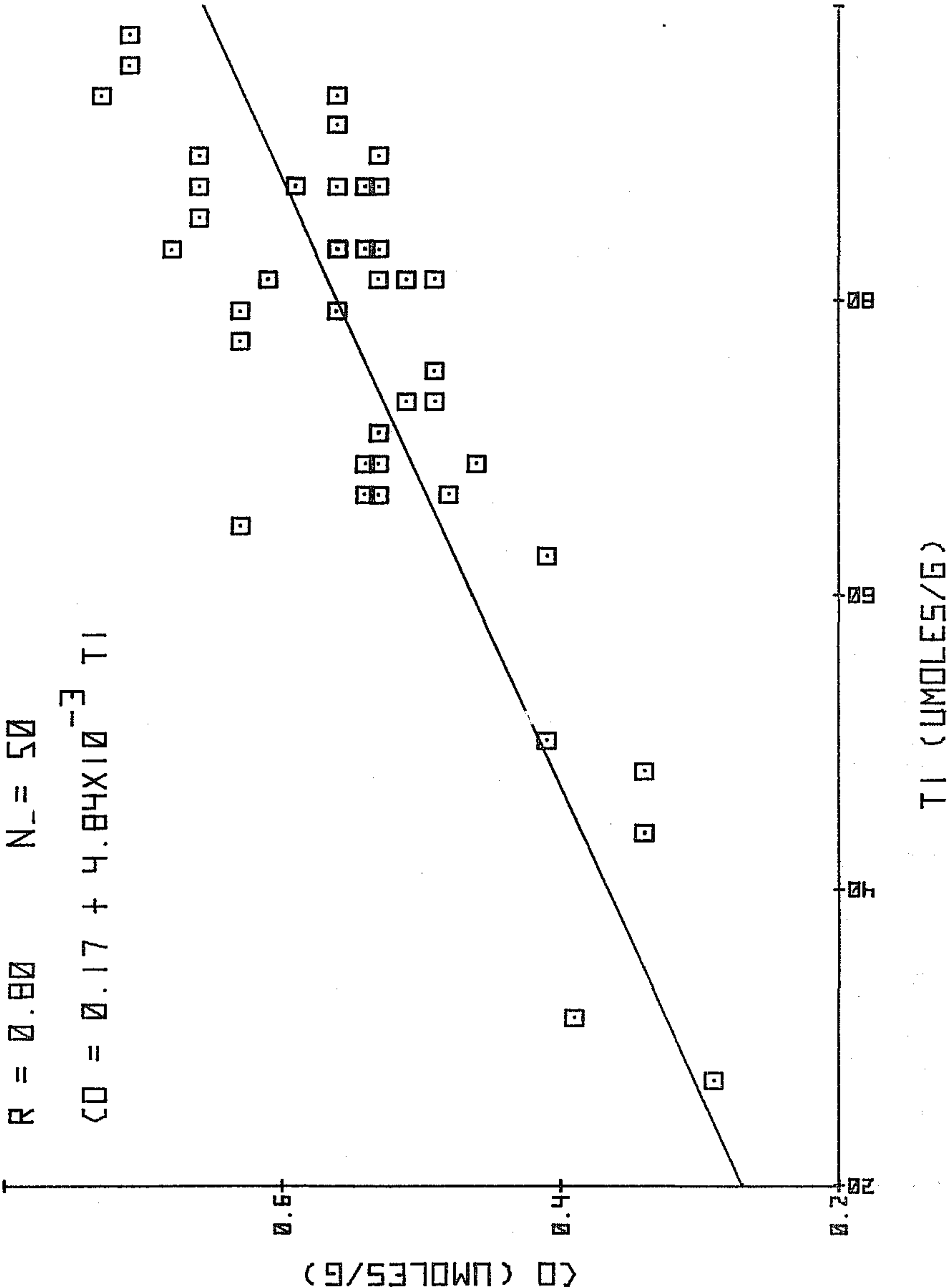

Fig. 12. The relationship between cobalt (Co) and titanium (Ti), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

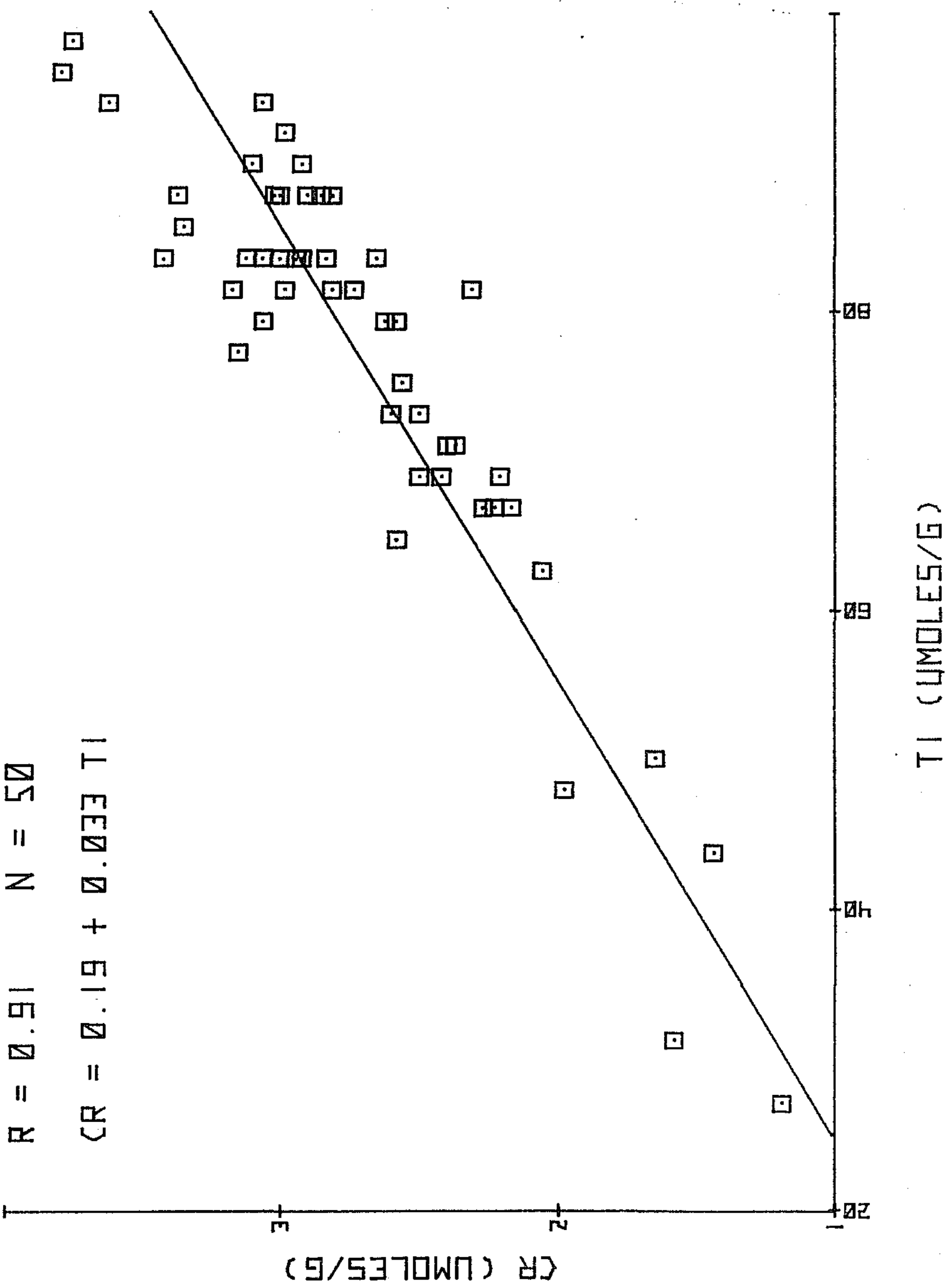

Fig. 13. The relationship between chromium (Cr) and titanium (Ti), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

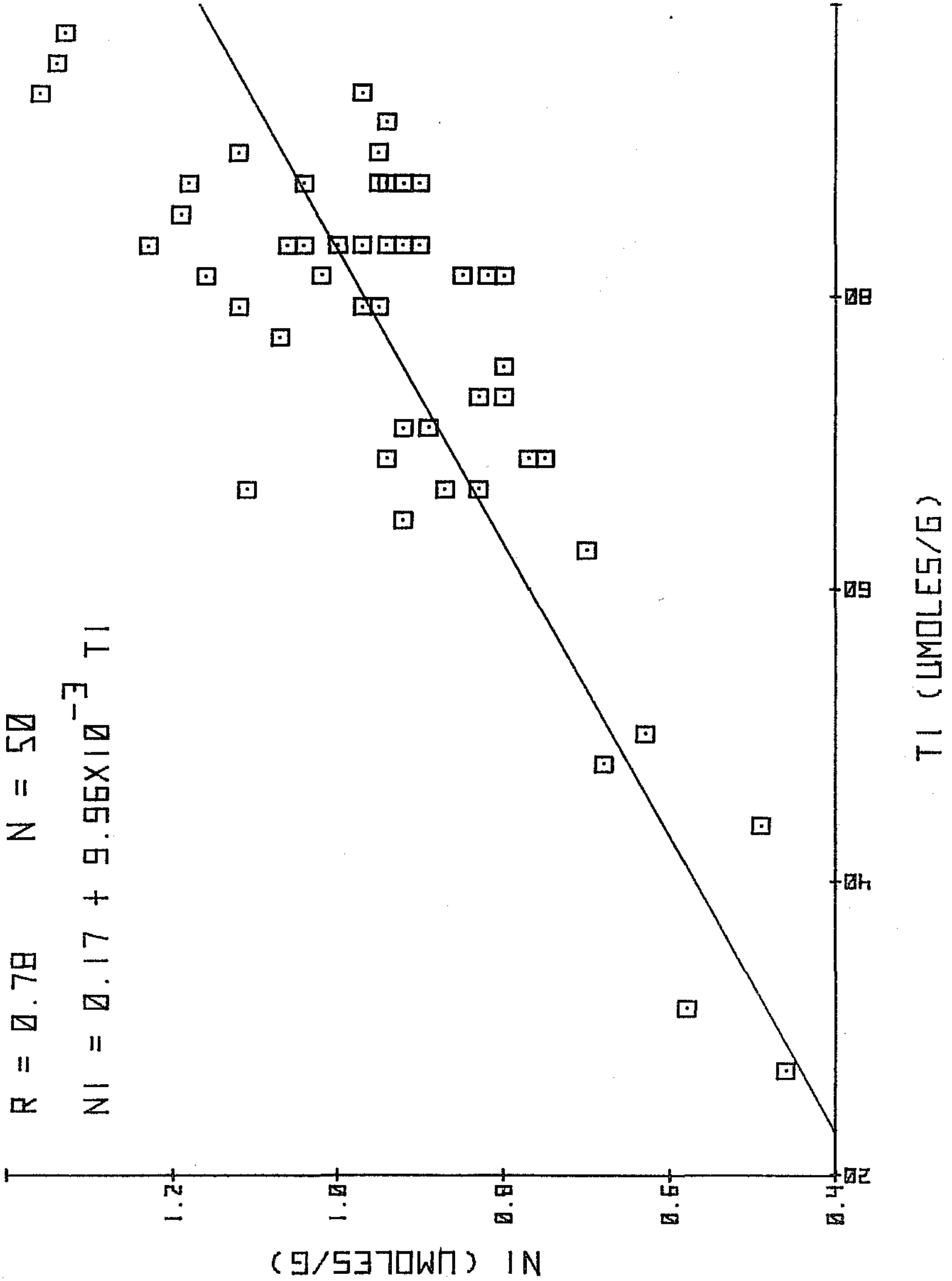

Fig. 14. The relationship between nickel (Ni) and titanium (Ti), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

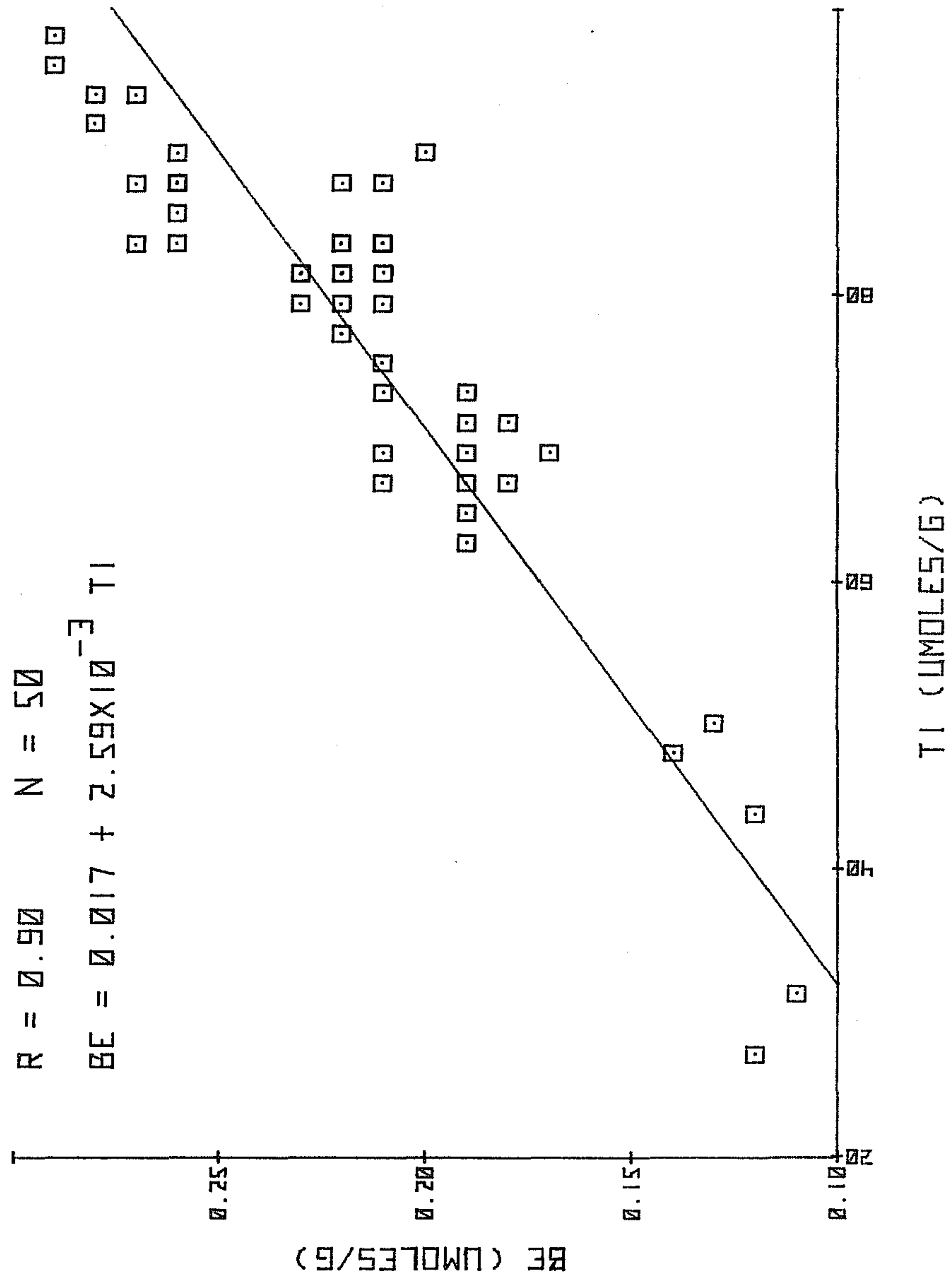

Fig. 15. The relationship between beryllium (Be) and titanium (Ti), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

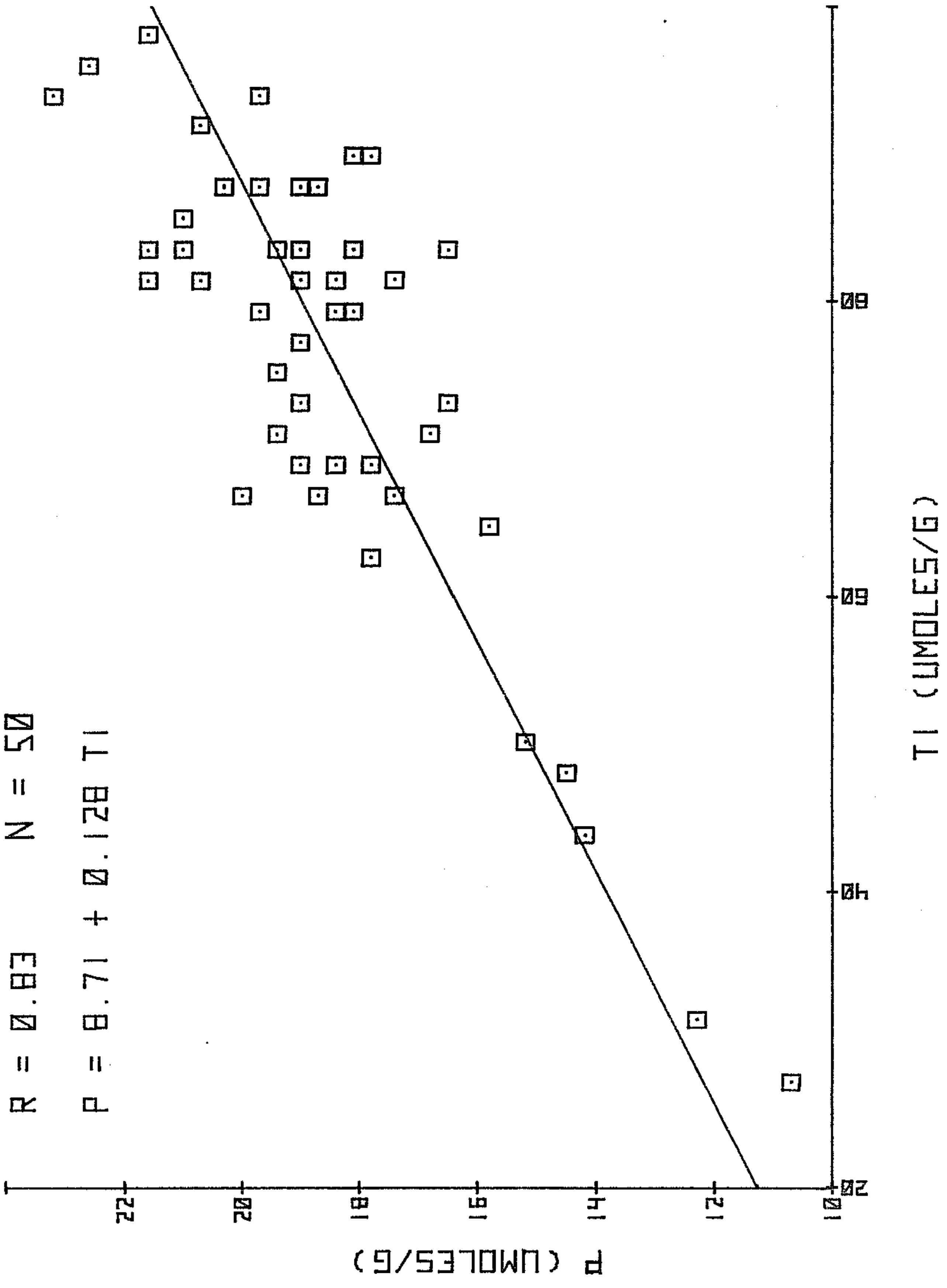

Fig. 16. The relationship between phosphorus (P) and titanium (Ti), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

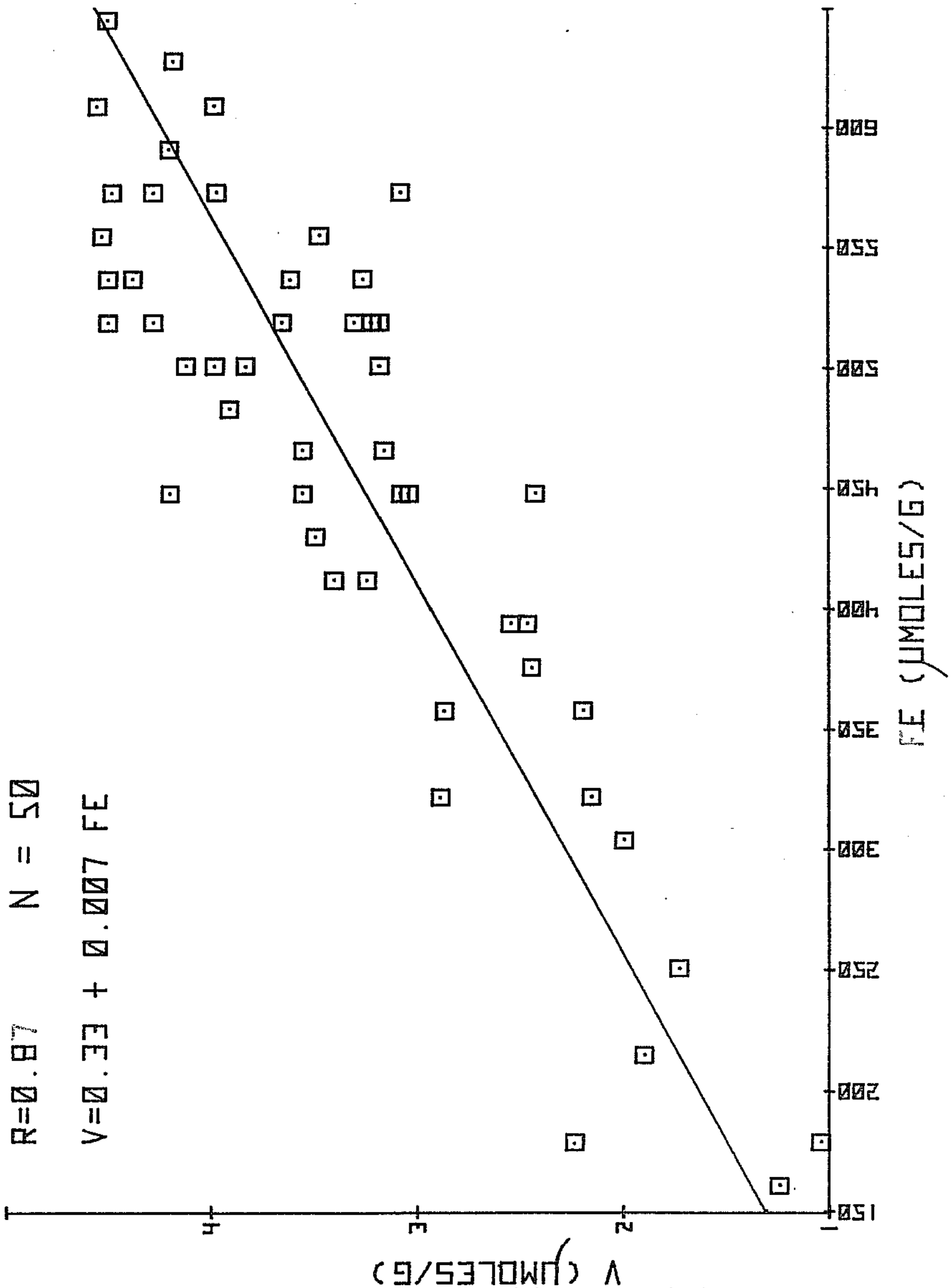

Fig. 17. The relationship between vanadium (V) and iron (Fe), in μmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

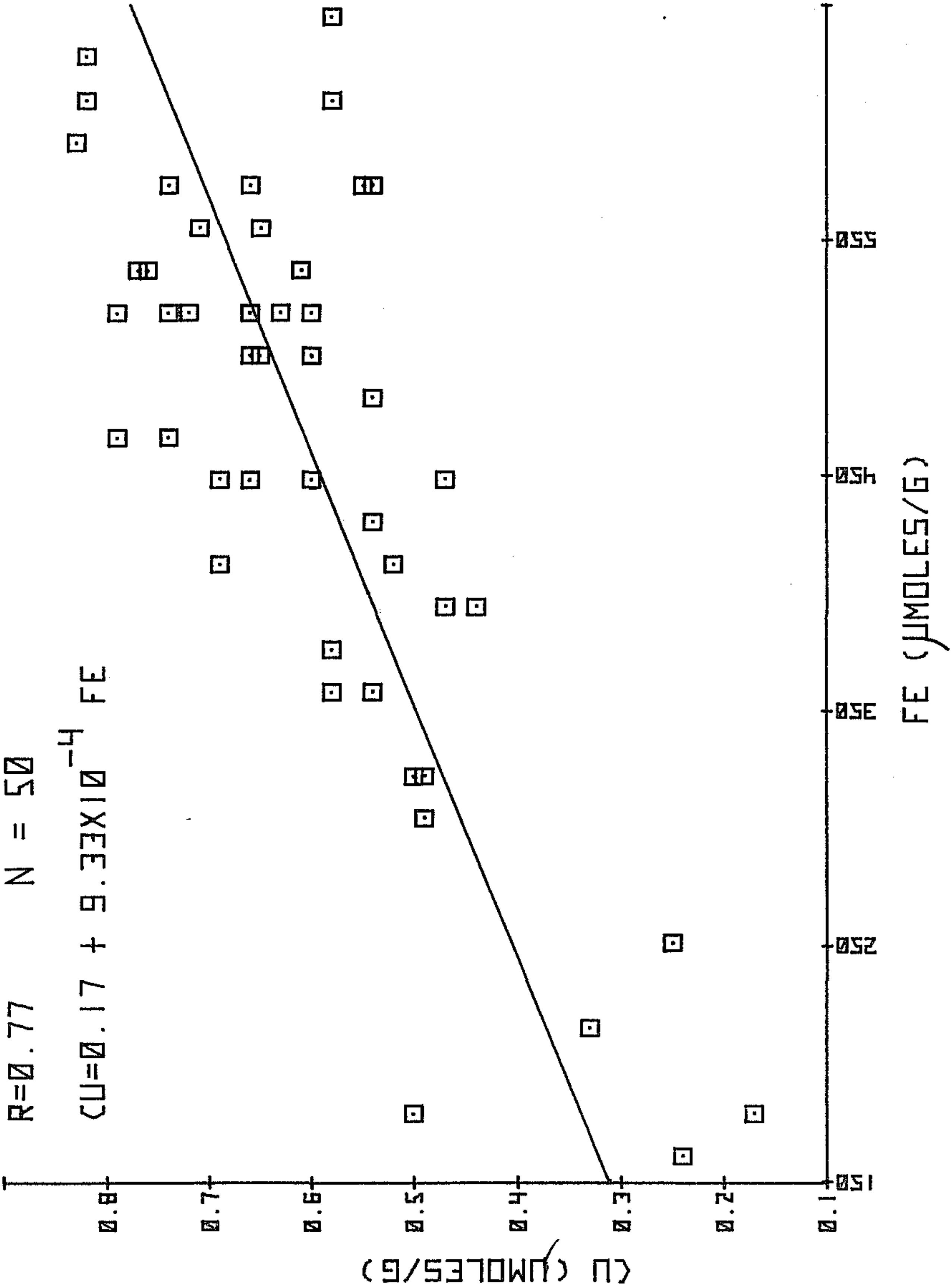

Fig. 18. The relationship between copper (Cu) and iron (Fe), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

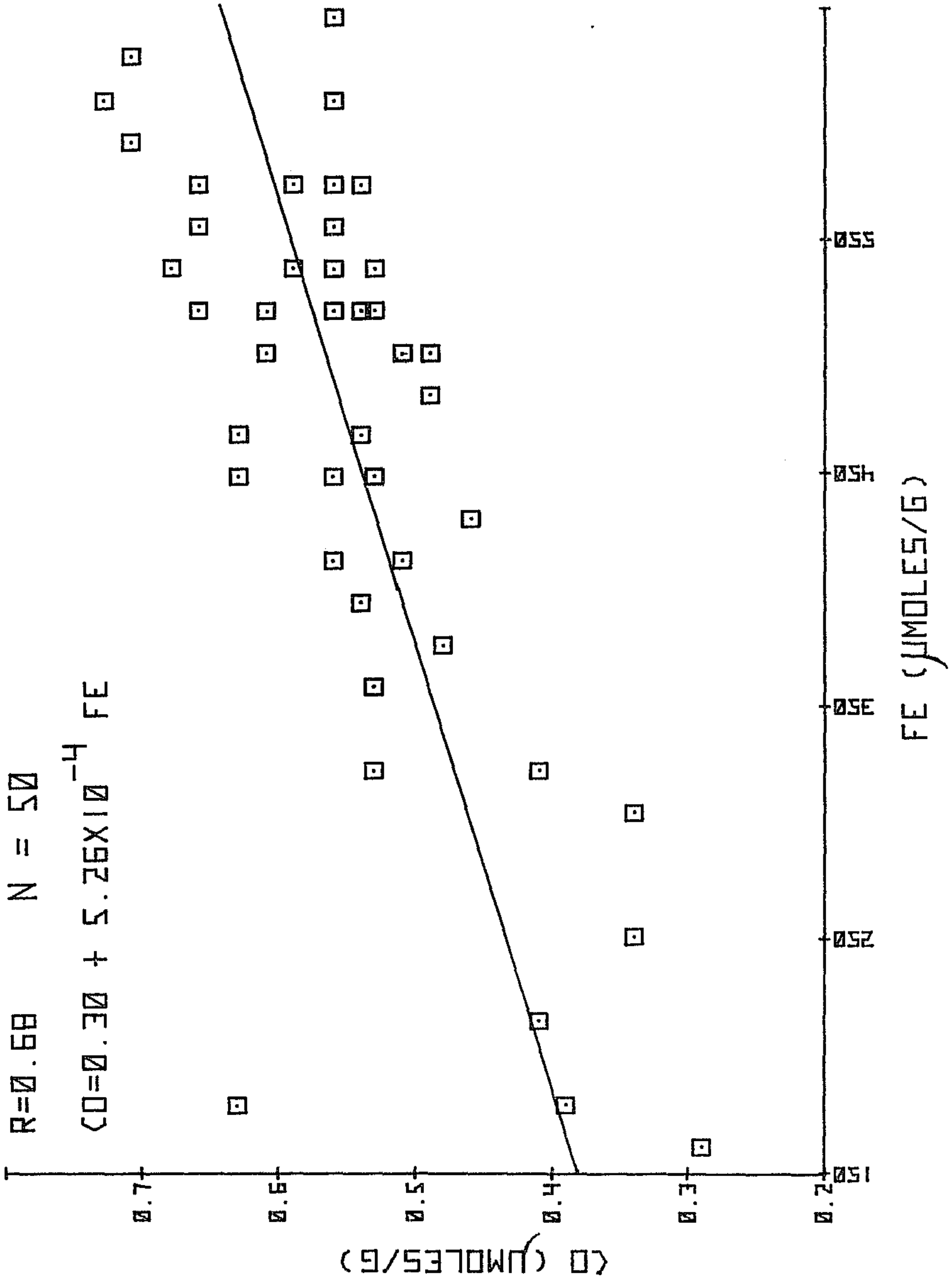

Fig. 19. The relationship between cobalt (Co) and iron (Fe), in μmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

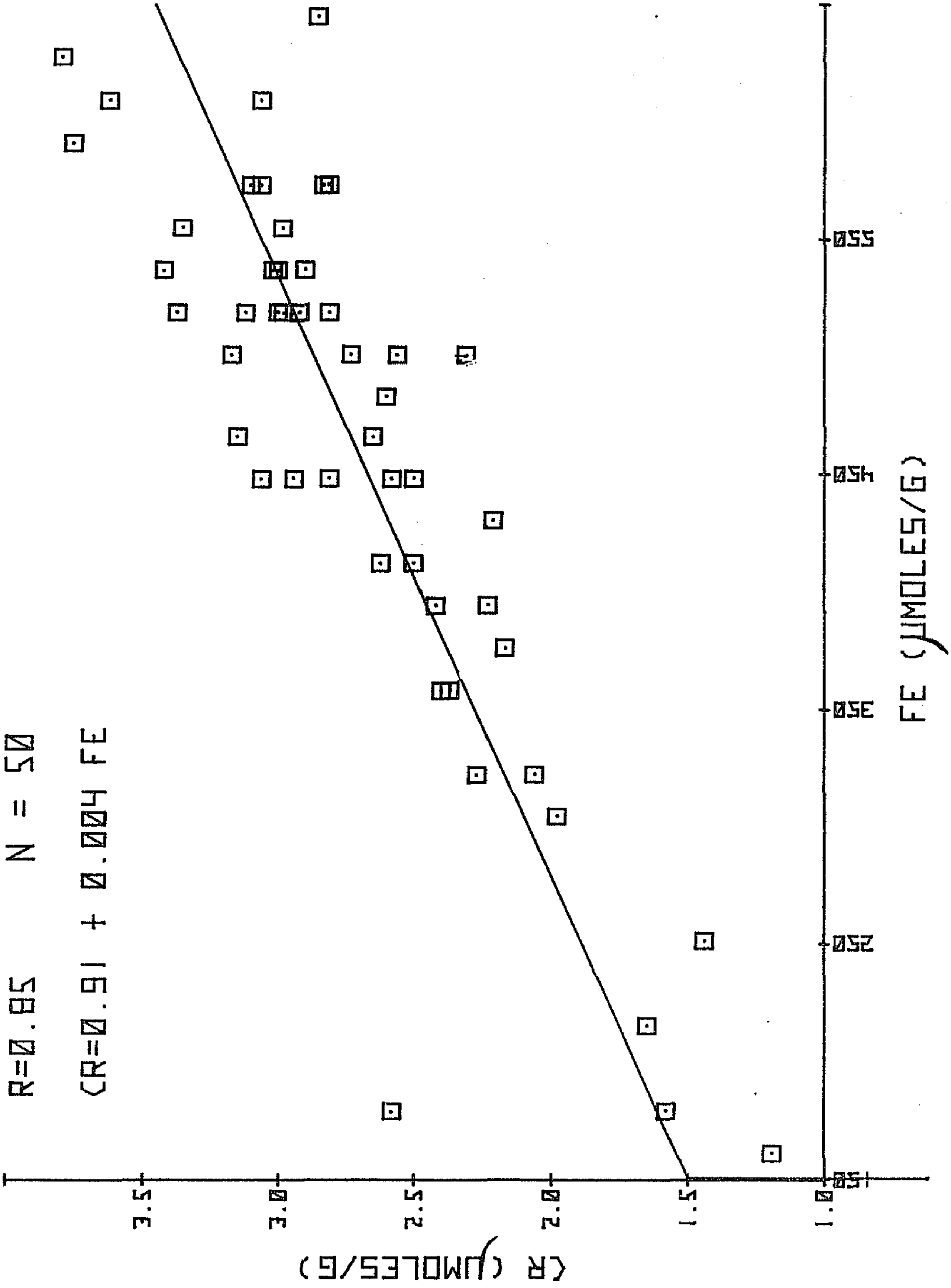

Fig. 20. The relationship between chromium (Cr) and iron (Fe), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

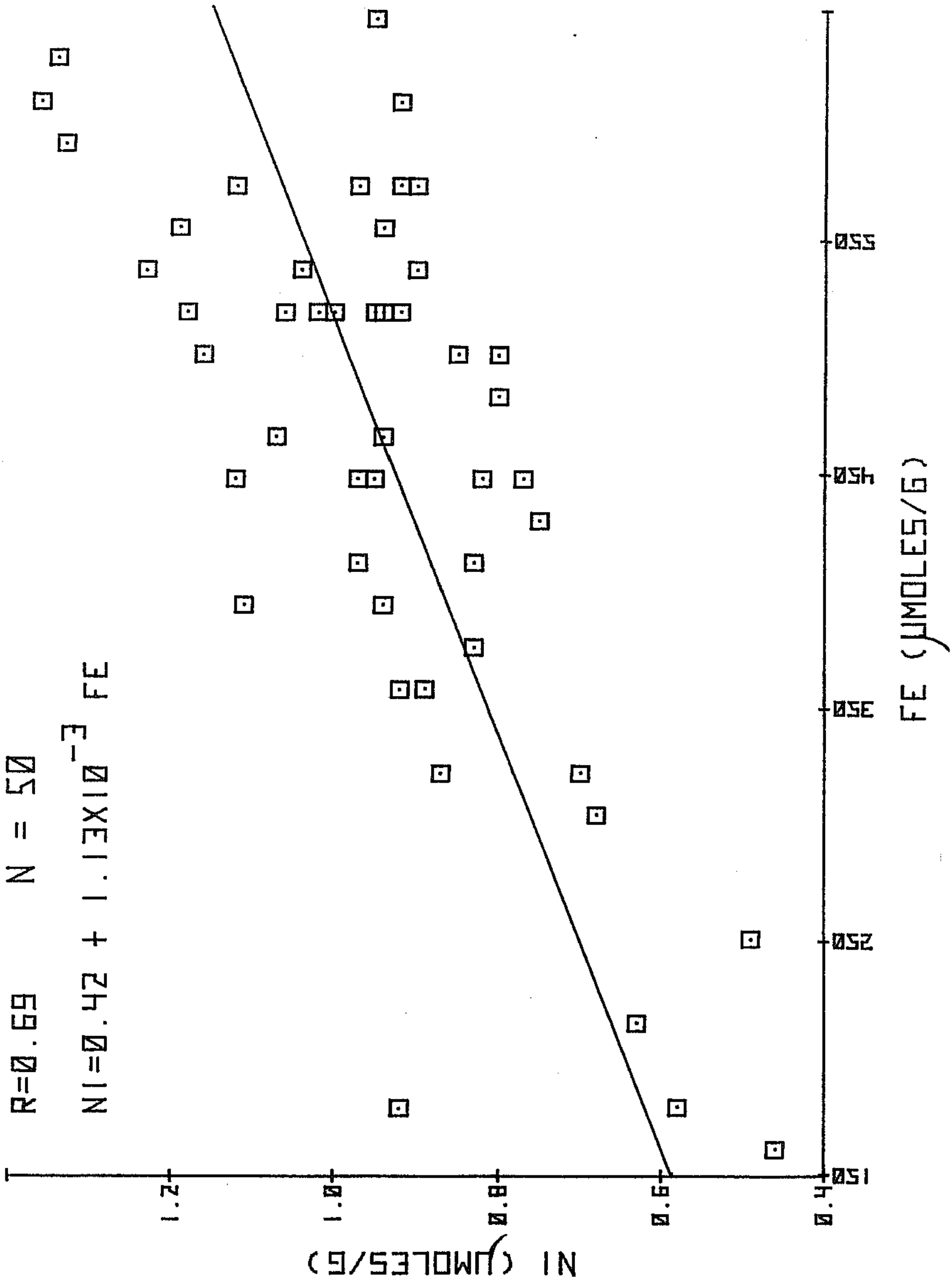

Fig. 21. The relationship between nickel (Ni) and iron (Fe), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

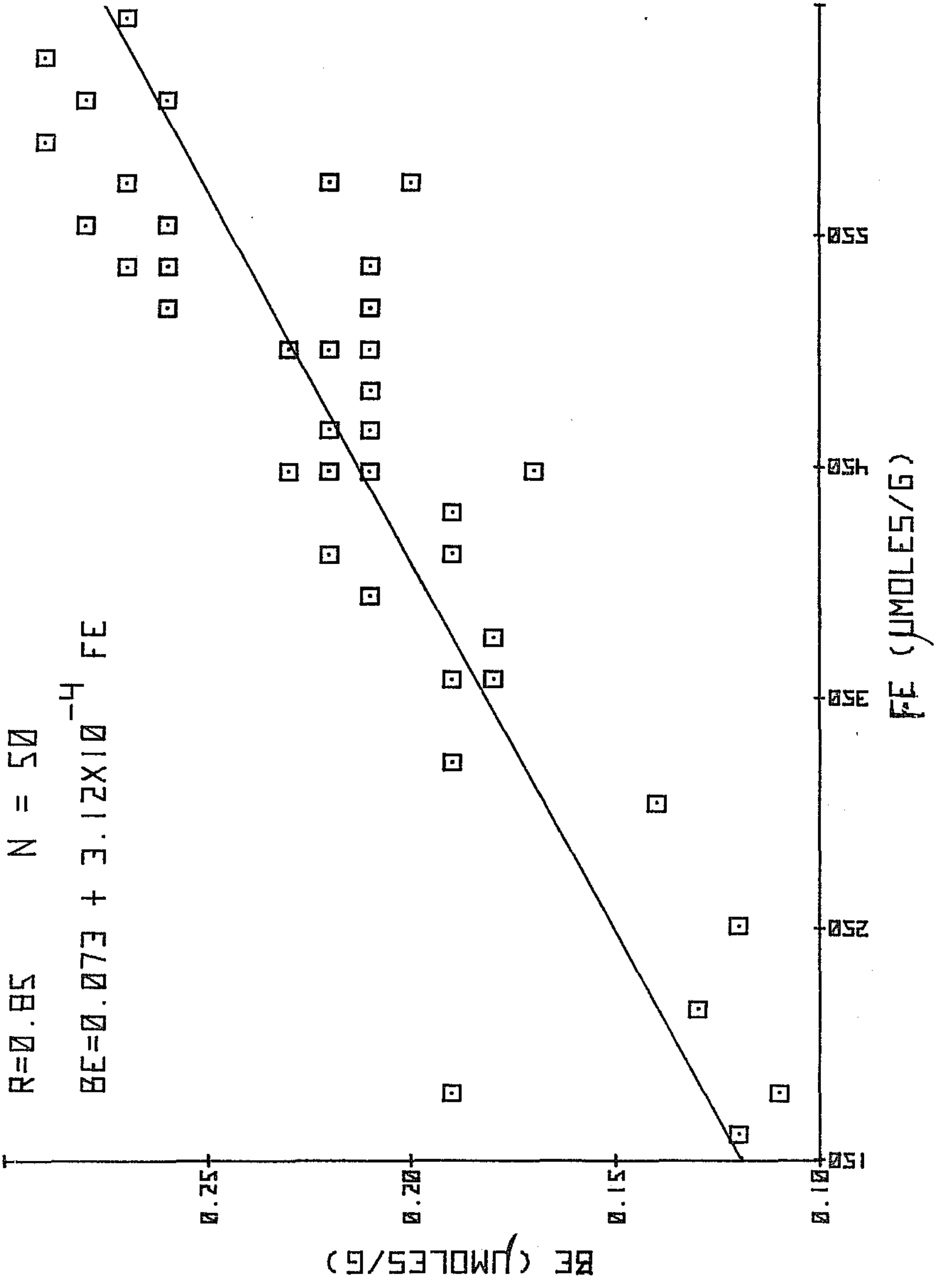

Fig. 22. The relationship between beryllium (Be) and iron (Fe), in µmoles/g dry weight, for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

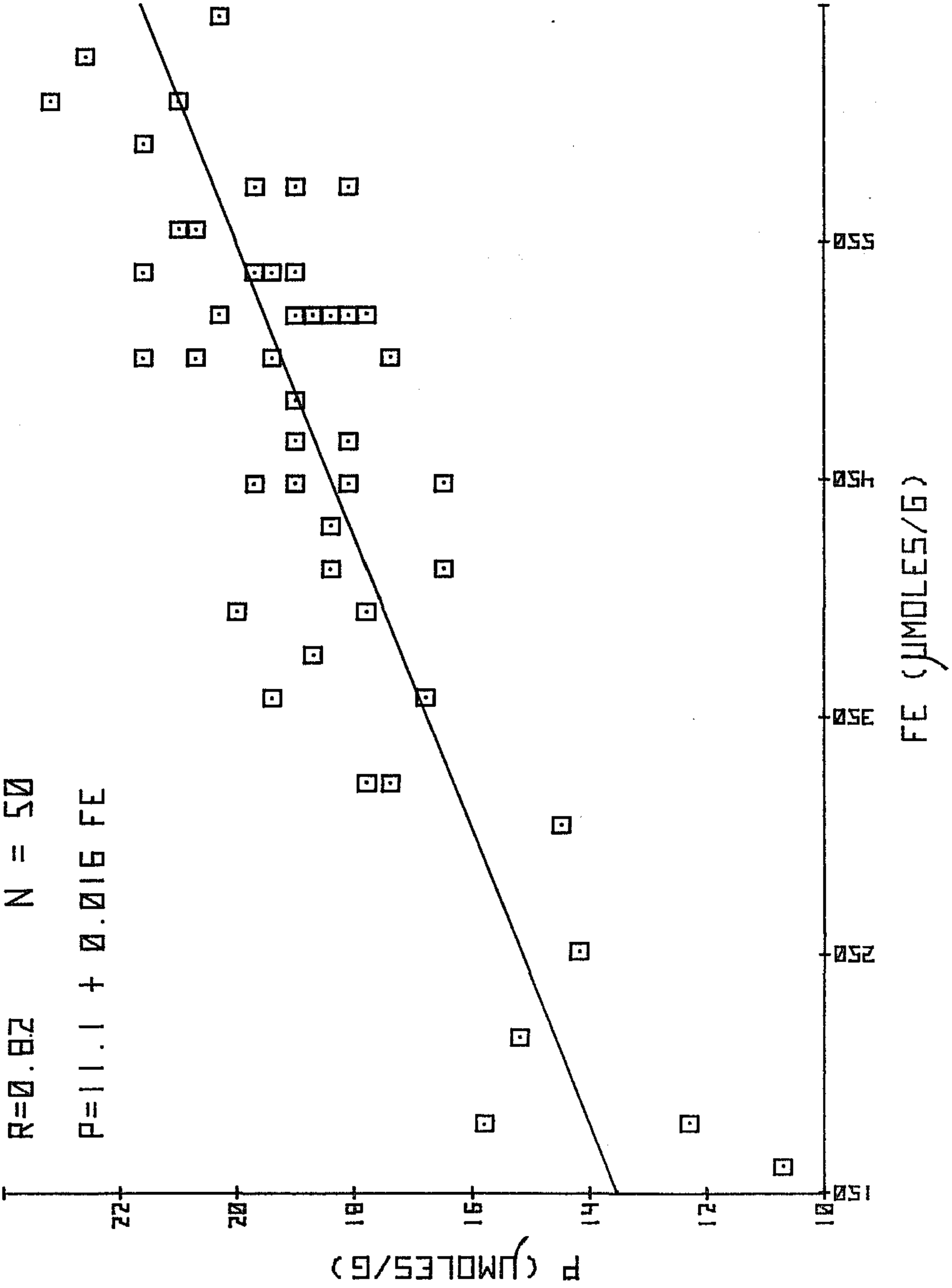

Fig. 23. The relationship between phosphorus (P) and iron (Fe), in μmoles/g dry weight; for surface sediment samples from Lake Winnipeg. r = correlation coefficient, n = number of samples.

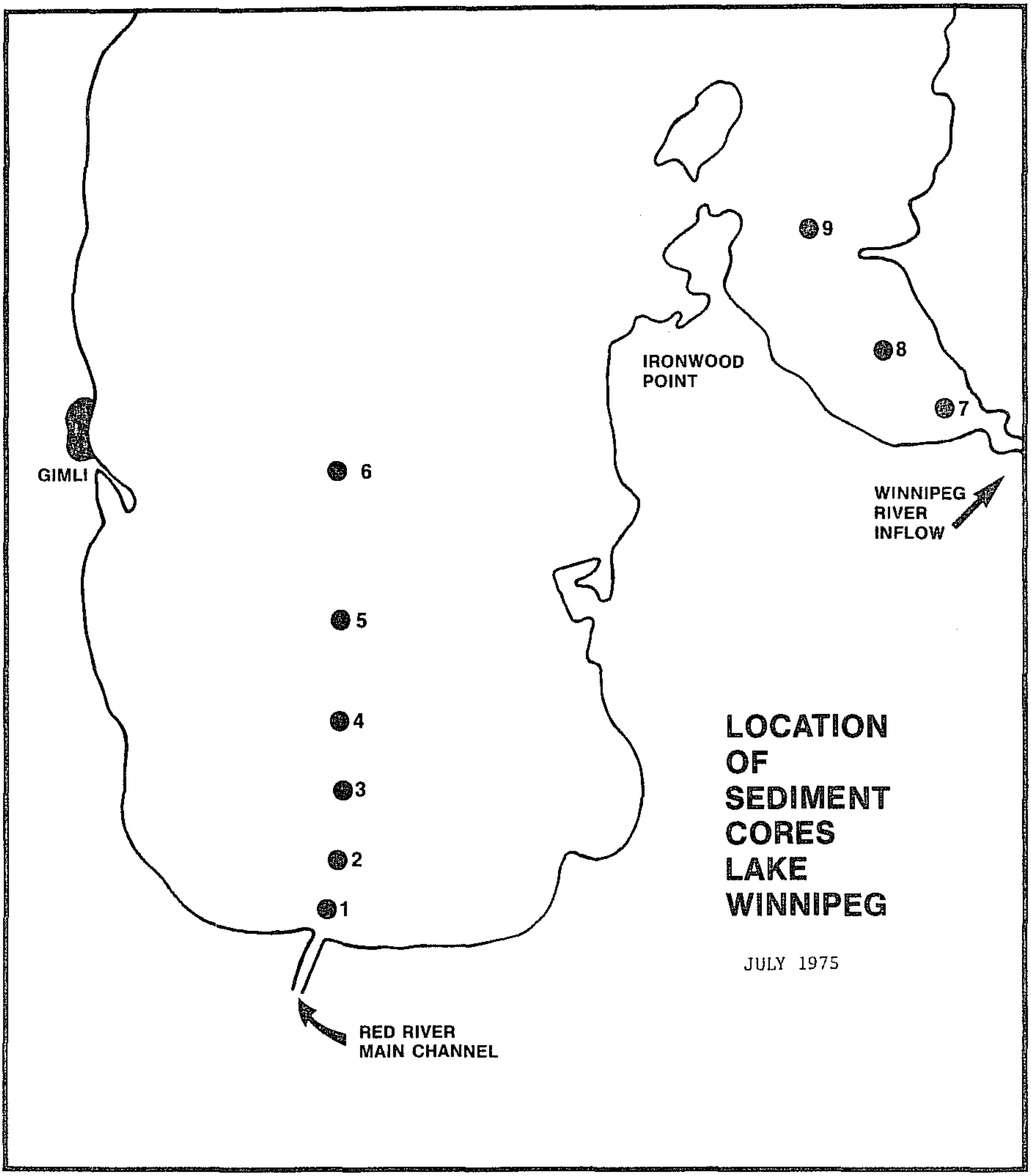

Fig. 24. Location of Lake Winnipeg sediment cores taken by Dr. R. J. Allan in 1975. These cores were analyzed for Hg, As, and Mo, and are reported in Table 24.

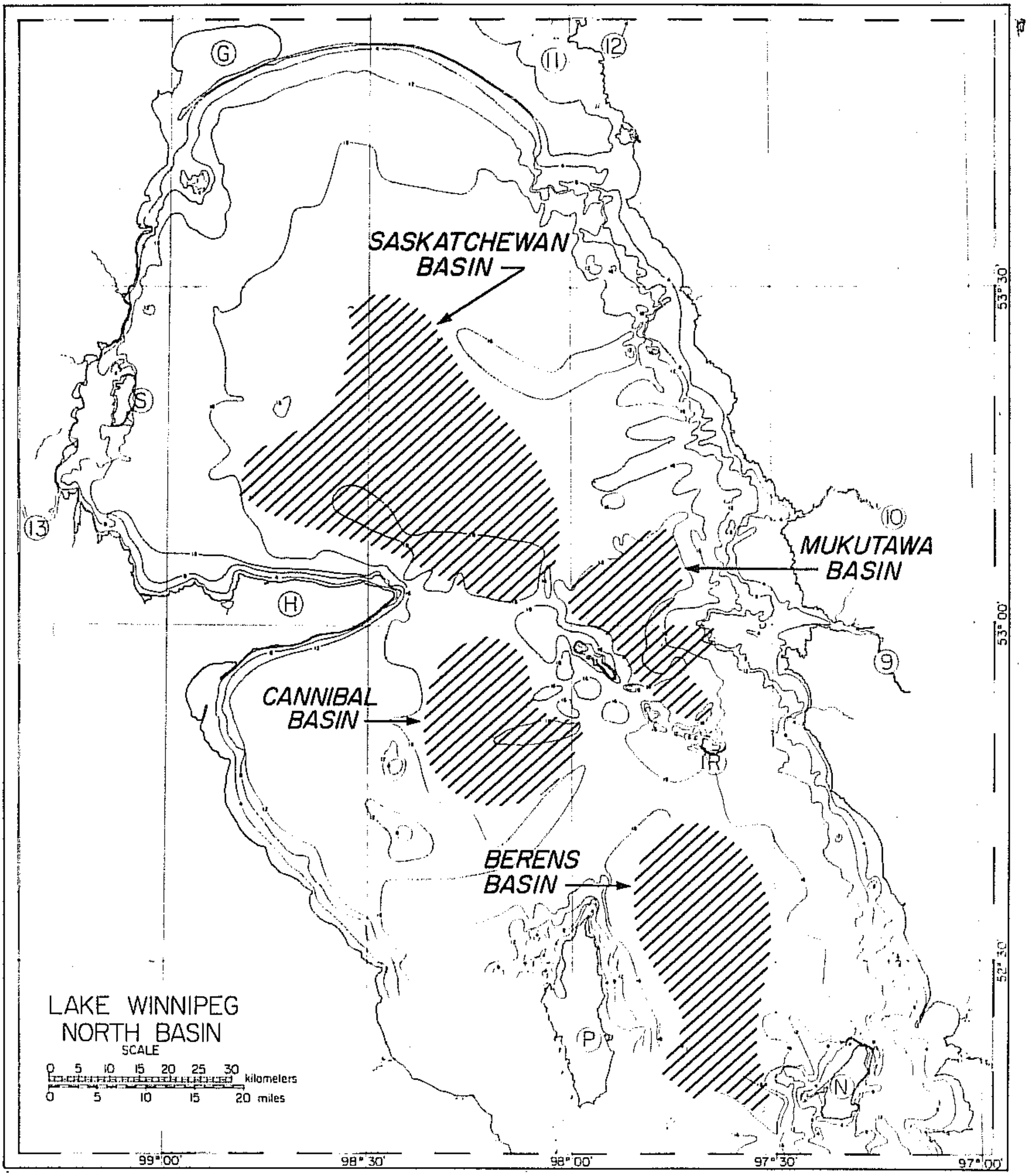

Fig. 25. Major regions of sediment accumulation in the north basin of Lake Winnipeg. The stippled areas are the depositional basins. See Fig. 26 for key to geographic features. Depth contour intervals are 4 m.

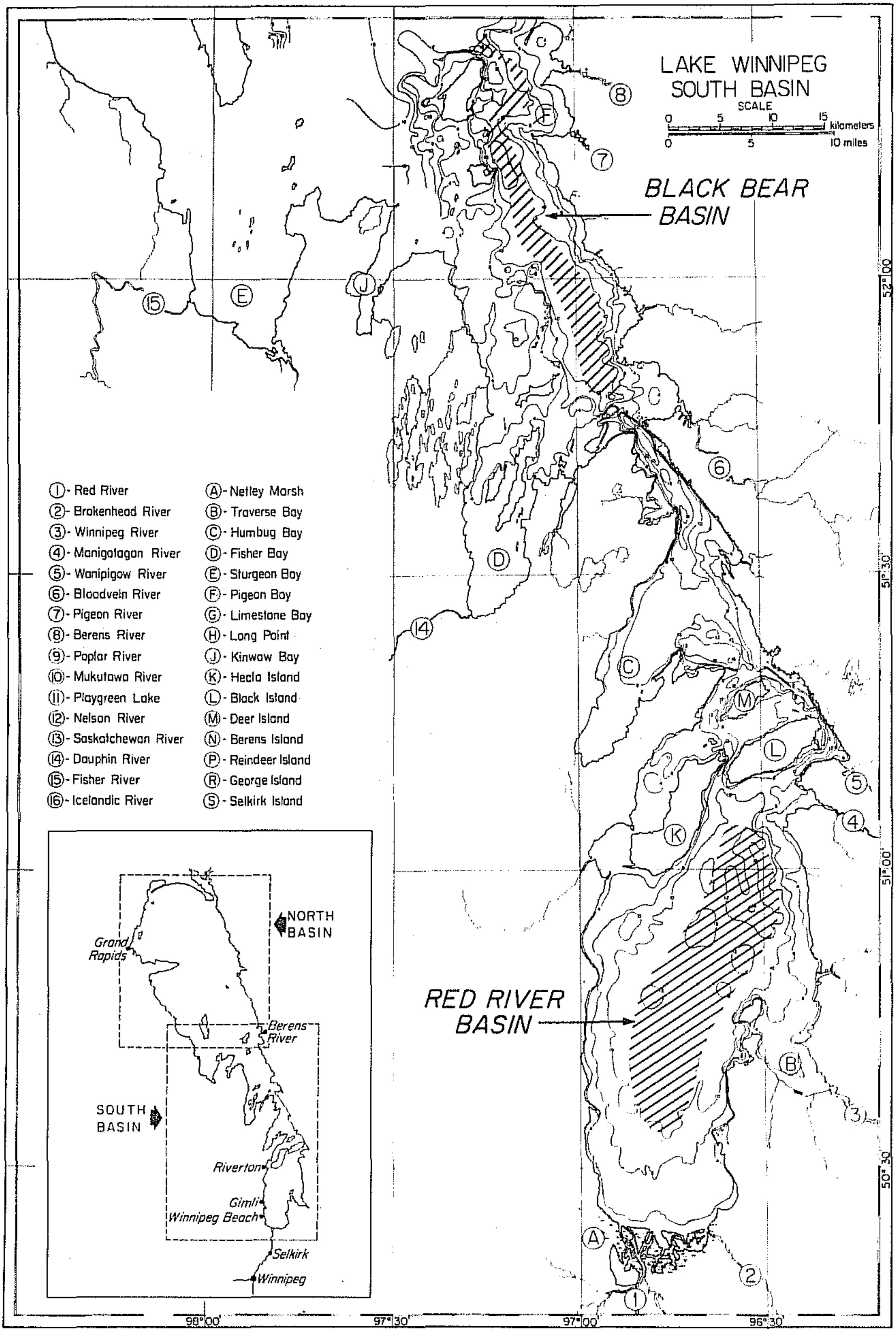

Fig. 26. Major regions of sediment accumulation in the narrows and south basin of Lake Winnipeg. The stippled areas are the depositional basins.

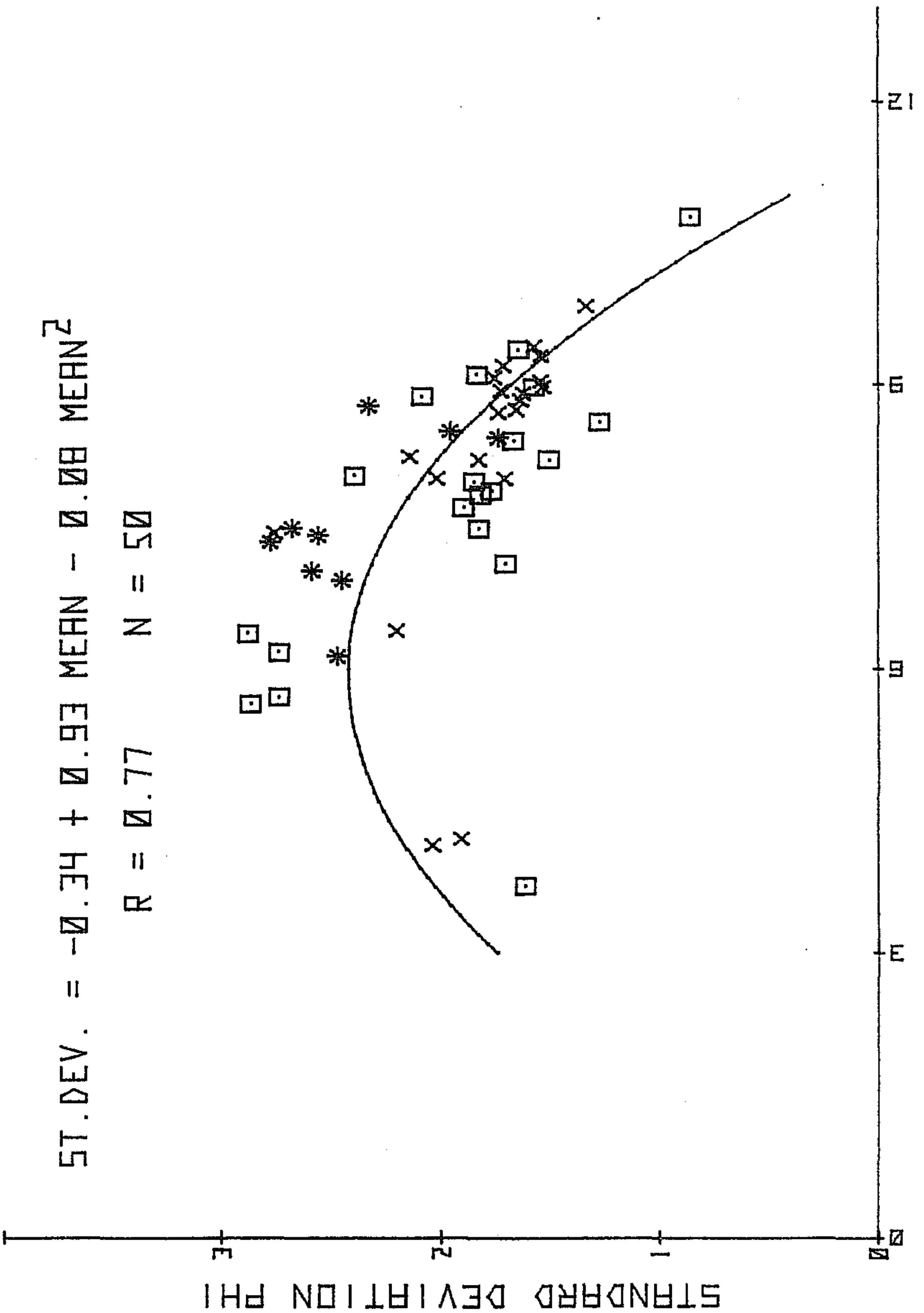

Fig. 27. The relationship between mean particle size ($\bar{X}_\phi$) and graphic standard deviation of X_ϕ for Lake Winnipeg off-shore sediment samples. X = south basin; * = narrows; ☐ = north basin.

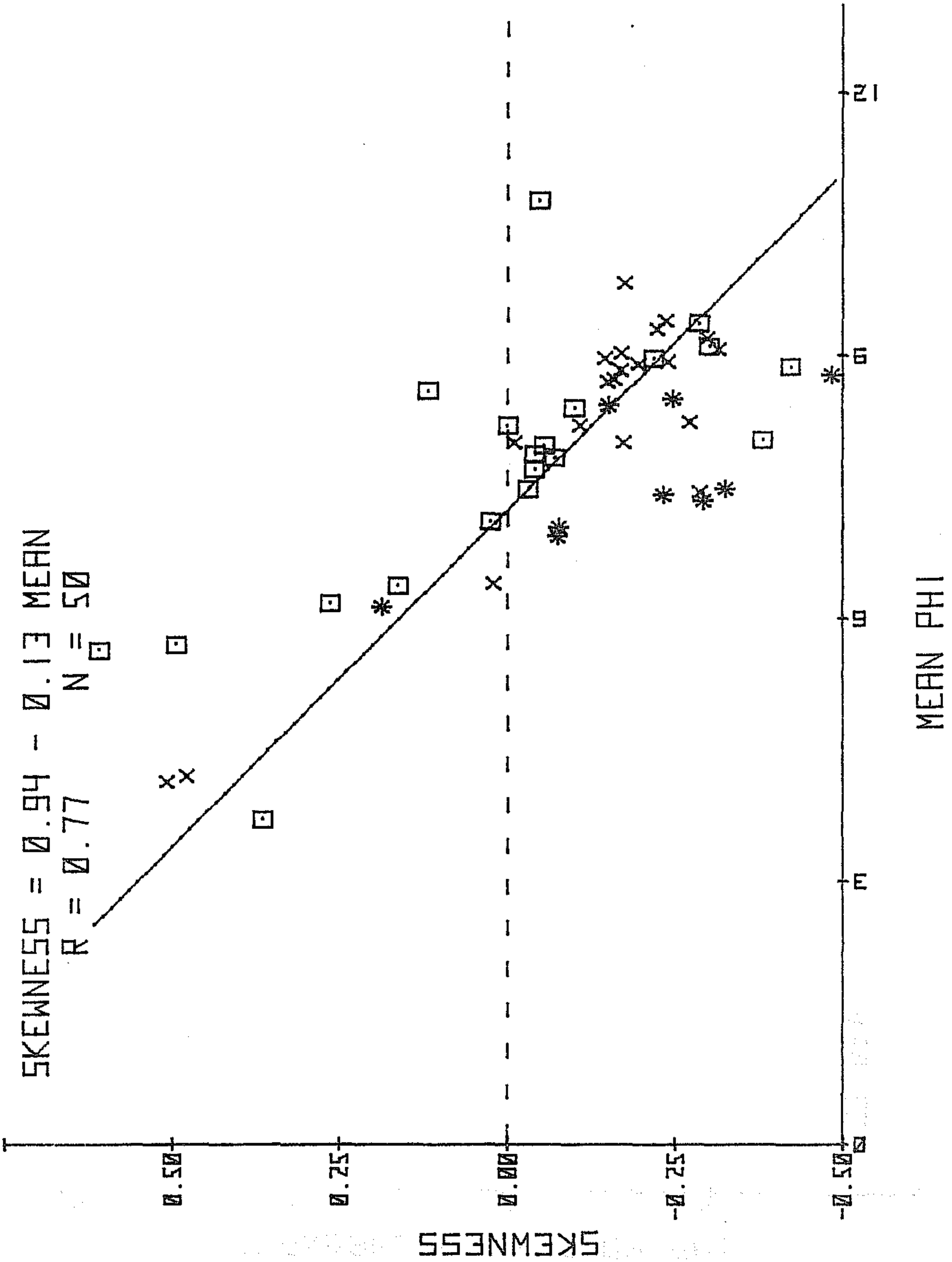

Fig. 28. The relationship between $\bar{X}_\phi$ and graphic skewness of the particle size distributions of Lake Winnipeg off-shore sediments. X = south basin; * = narrows; ◘ = north basin sediments.

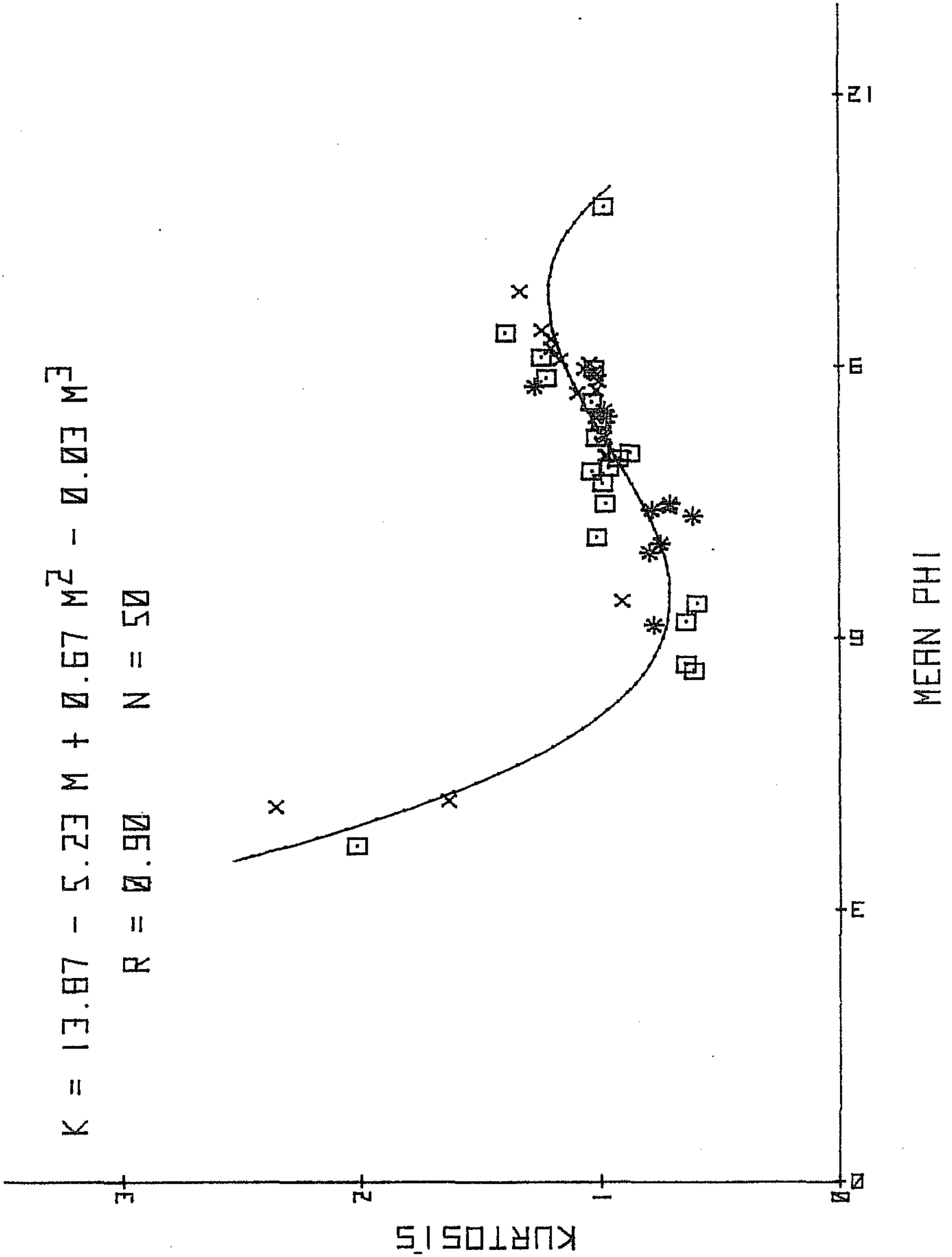

Fig. 29. The relationship between X_ϕ and graphic kurtosis of the particle size distributions of Lake Winnipeg off-shore sediments. X = south basin; * = narrows; ▭ = north basin.

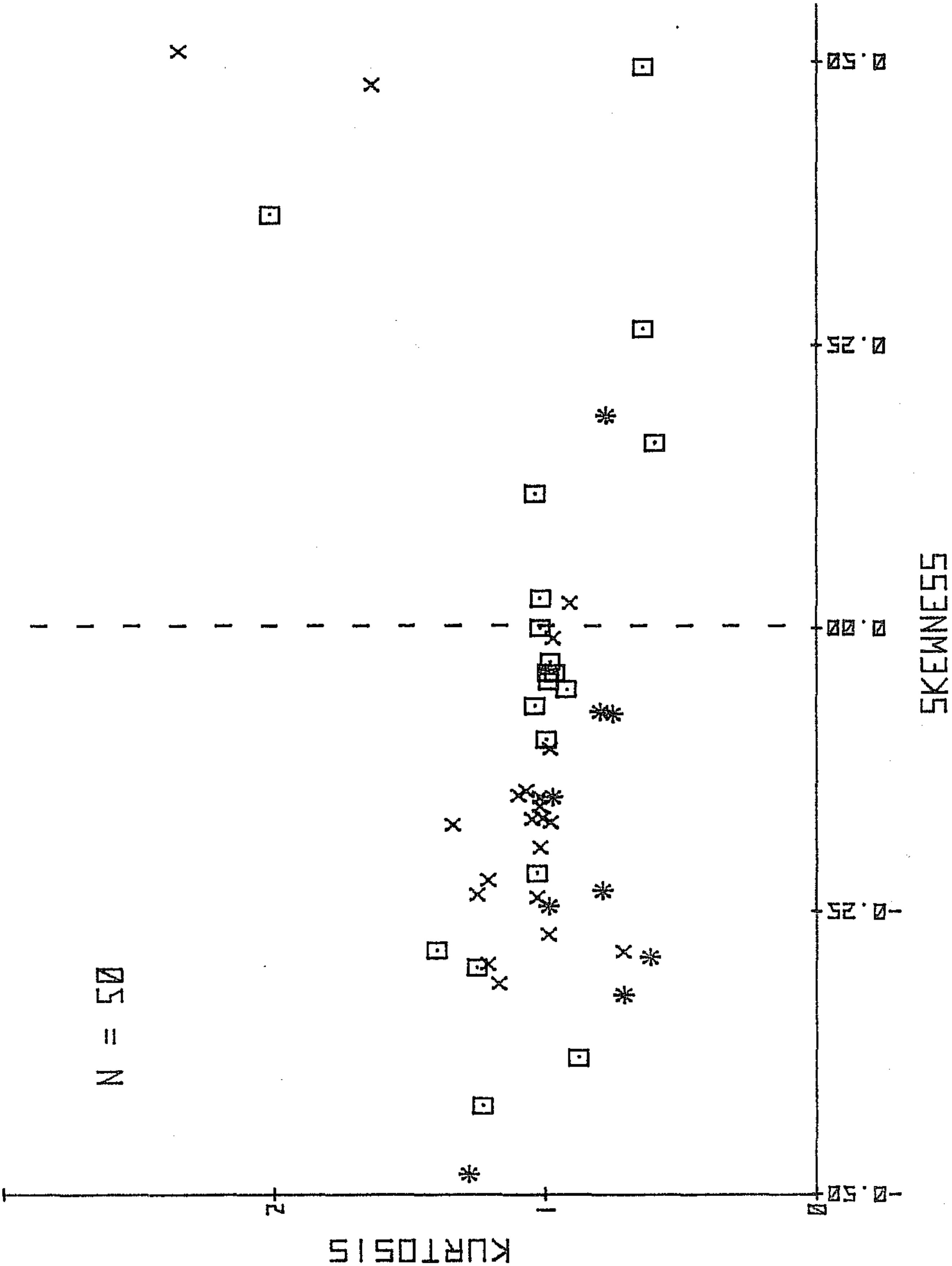

Fig. 30. The relationship of graphic skewness to kurtosis for the particle size distributions of Lake Winnipeg off-shore sediments. X = south basin; * = narrows; ◻ = north basin.

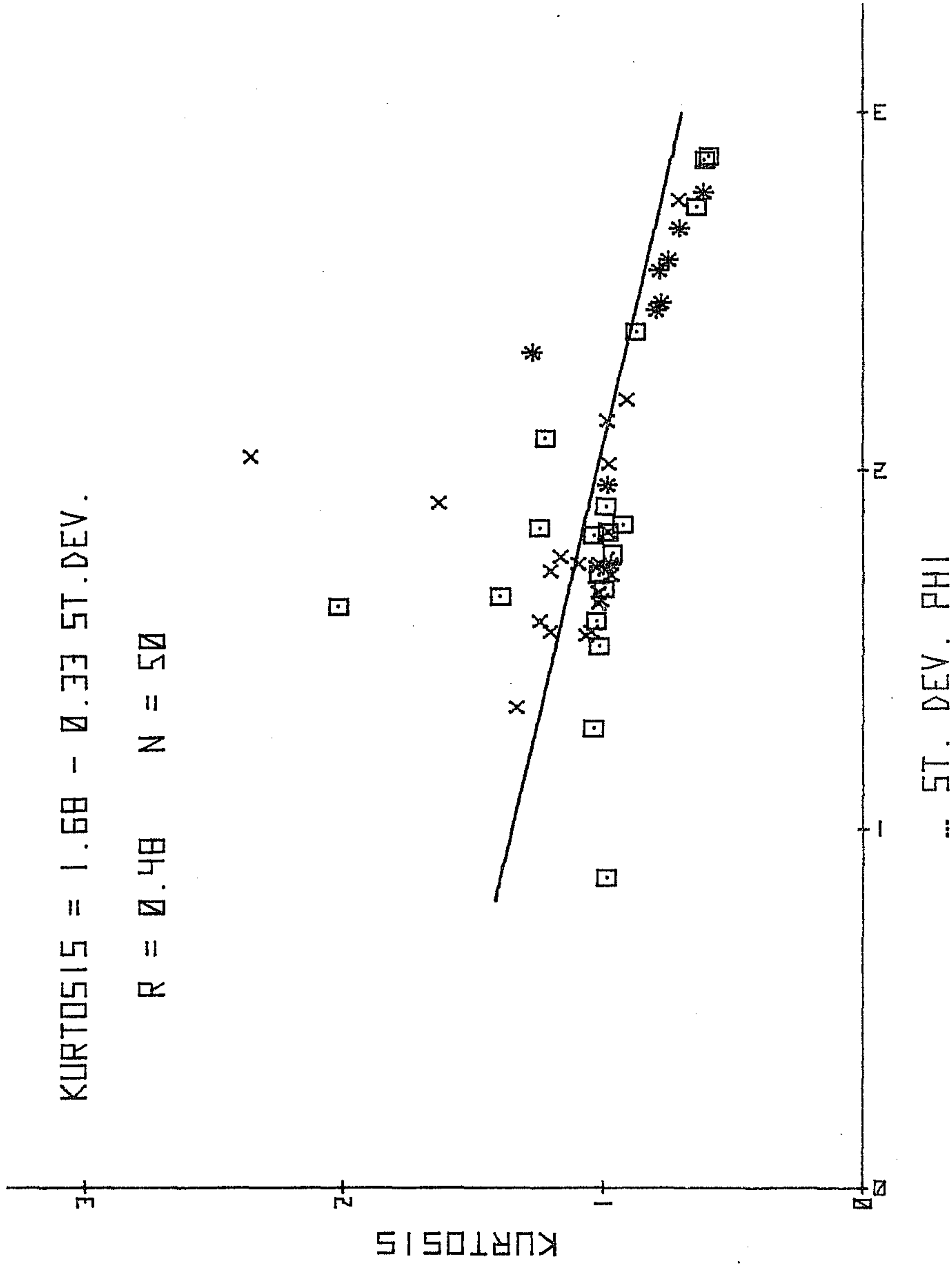

Fig. 31. The relationship of graphic kurtosis to standard deviation of $\bar{X}_\phi$ for the particle size distributions of Lake Winnipeg off-shore sediments. X = south basin; * = narrows; ☐ = north basin.