1980

Glacial geology of the southern Flathead Valley Montana

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Recommended Citation

Stoffel, Keith L., "Glacial geology of the southern Flathead Valley Montana" (1980). *Graduate Student Theses, Dissertations, & Professional Papers*. 7426.
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GLACIAL GEOLOGY OF THE SOUTHERN FLATHEAD VALLEY, MONTANA

by

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B.S., University of Illinois, 1974

Presented in partial fulfillment of the
requirements for the degree of

Master of Science

UNIVERSITY OF MONTANA

1980

Approved by:

Chairman, Board of Examiners

Dean, Graduate School

Date April 15, 1980

5-25

ABSTRACT

Stoffel, Keith L., M.S., Spring, 1980 Geology

Glacial Geology of the Southern Flathead Valley, Montana

Director: Robert R. Curry Robt R. Curry

The Flathead lobe of the Cordilleran ice sheet deposited glacial drift in the southern Flathead Valley of Montana. Previous workers used geomorphic evidence to identify three Pleistocene glacial drift units in the valley: Mission till, St. Ignatius till, and Jocko diamictons. The goal of this study was to use sedimentary petrologic studies and field mapping to define the stratigraphy of the glacial drift units and to correlate the stratigraphic units with established glacial chronologies.

Thirty-nine samples of southern Flathead Valley glacial sediments were analyzed for their grain size properties by means of hydrometer and sieve analyses. Clay mineralogy of the drift units was determined by x-ray diffraction methods. Representative samples of each stratigraphic unit were examined to define the lithologic composition of their sand fractions. Results show that grain size properties, clay mineralogic composition, and sand fraction lithologies are all similar for each stratigraphic unit studied.

Field evidence, radiocarbon dating, and relative age dating indicate that Mission till is the youngest of the three stratigraphic units studied. A $>$20,380 year B.P. radiocarbon date from the front of the Mission moraine suggests that "late" Mission till is middle to late Wisconsinan (early Pinedale) in age. "Earlier" Mission till was apparently deposited by more extensive ice of the same glaciation.

Soil development and surface geomorphology indicate that St. Ignatius till is significantly older than Mission till. Complex field relationships complicate the age estimation of the St. Ignatius till, but evidence for deposition during early Wisconsinan time is given.

Field and laboratory data produced indicate that the Jocko diamictons are glacial tills, which represent the oldest (pre-Wisconsinan) glaciation in the region. Age, extent, and source area of the ice depositing the Jocko diamictons have not been determined, therefore correlation with other glacial chronologies remains speculative.

ACKNOWLEDGMENTS

I extend my warmest appreciation to Dr. Robert Curry, who as my advisor provided guidance and encouragement throughout all phases of the study. I would also like to thank my committee members Dr. Graham Thompson and Dr. John Donahue for their helpful discussions and review of the manuscript. Richard Galster and the Seattle District of the U.S. Army Corps of Engineers provided funding for the radiocarbon dates. And of course, thanks to Dorothy, for infinite support and inspiration.

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CHAPTER I

BACKGROUND AND OBJECTIVES

Introduction

Numerous times during the Pleistocene epoch, the growth of glaciers in two distinct accumulation areas in British Columbia led to the development of the Cordilleran ice sheet. Ice accumulating in the Coast Range of western British Columbia, and glaciers growing in the Canadian Rockies along the Albert-British Columbia border coalesced in the lower mountainous region between these two massive mountain ranges (Figure 1). This coalescence of piedmont glaciers produced an enormous ice mass, the Cordilleran ice sheet, which advanced southward through southern British Columbia and terminated in the northwestern United States (Figure 2). Along the Canadian Pacific coast, the glaciers flowed downslope from their western Coast Range accumulation centers and flowed directly into the sea to form extensive floating ice shelves. Cordilleran ice flowing eastward from the Canadian Rocky Mountain accumulation basins reached the plains of Alberta, where it encountered the Laurentide ice sheet, moving slowly southwestward (Figure 2). Along its southern margin, the thinning Cordilleran ice sheet diverged into numerous lobes, each of which occupied a major mountain valley in northern Washington, Idaho, or Montana (Figure 3). The westernmost and most extensive of these lobes was the Puget lobe of western Washington (Easterbrook, 1976). Other

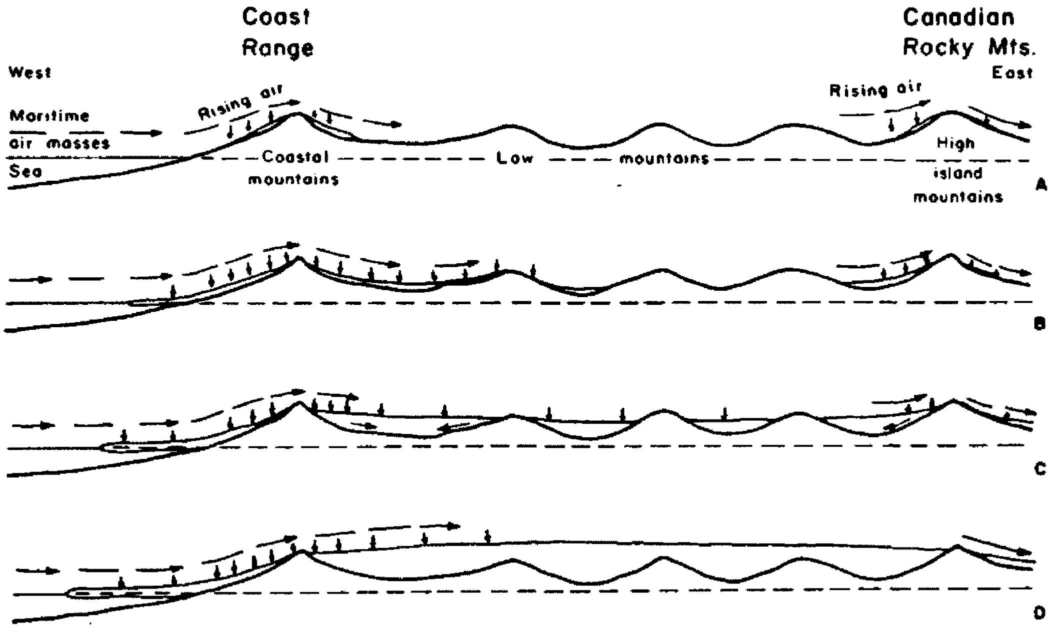


FIGURE 1. Diagrammatic sections showing development of the Cordilleran ice sheet. (after Flint, 1971)

A. Development of glaciers in mountain valleys
B. Coalescence of valley glaciers to form trunk glaciers in intermontane areas
C. Development of mountain ice sheet
D. Maximum ice sheet phase

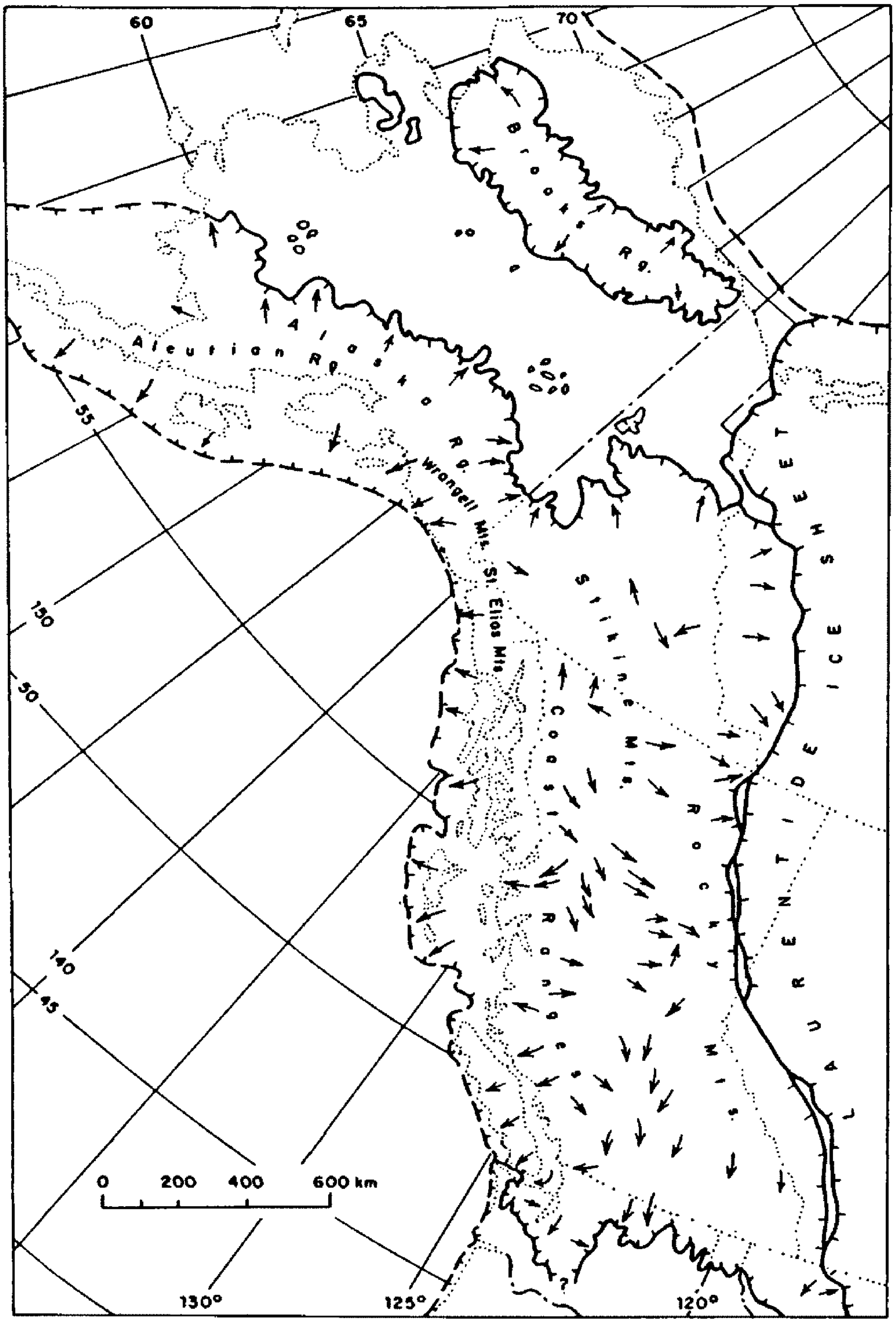


FIGURE 2. Sketch map of the Cordilleran ice sheet.
(after Flint, 1971)

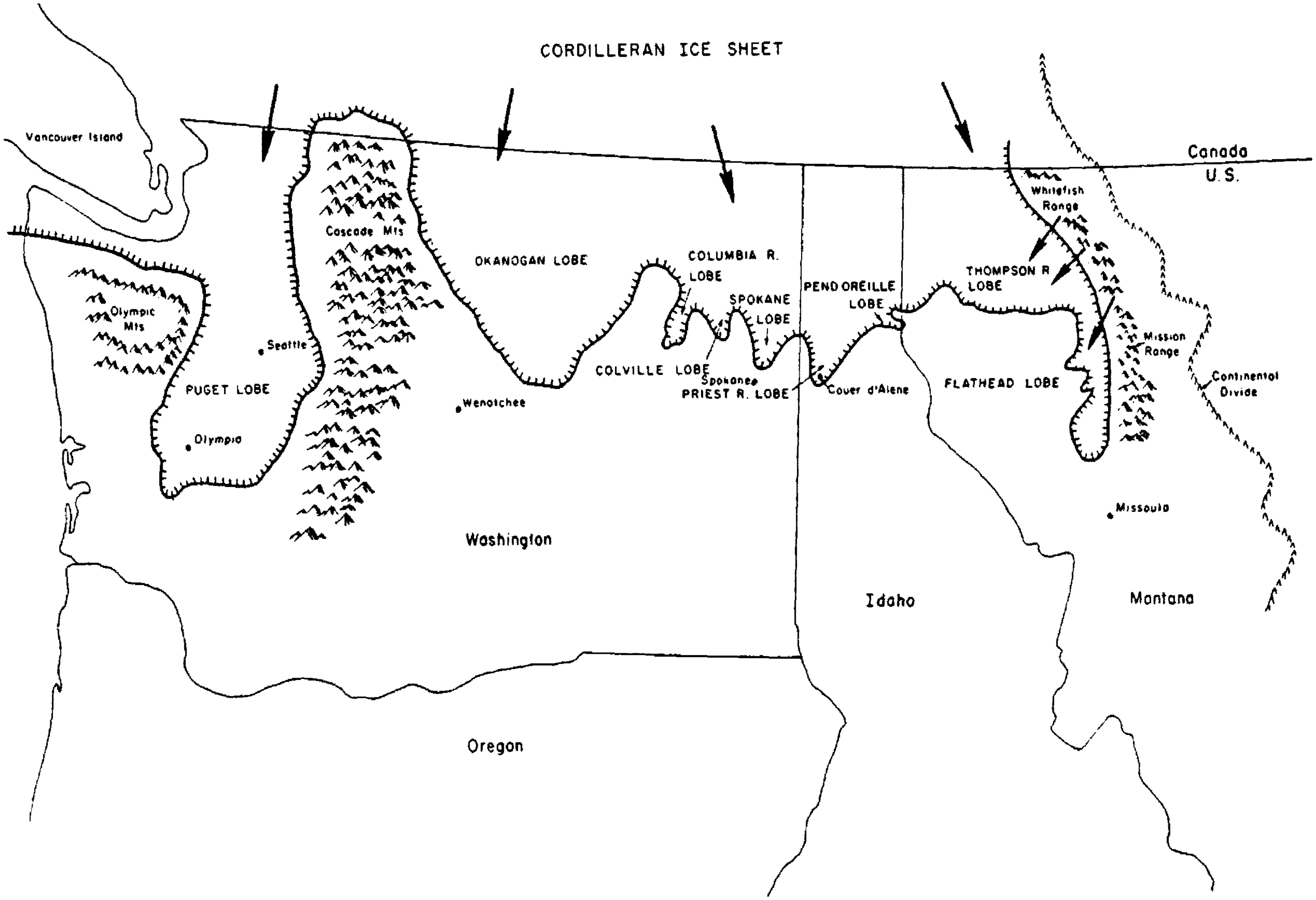


FIGURE 3. Map of the Cordilleran ice sheet in the northwestern United States

lobes east of the Cascade Range in Washington flowed out of their confined mountainous valleys and spread out onto the Columbia Plateau (Richmond and others, 1965). Still others in Idaho and Montana terminated within their valleys (Weis, 1965). The easternmost lobe of the Cordilleran ice sheet, the Flathead lobe in northwestern Montana, was of the last type, grinding to a halt within the Rocky Mountain Trench.

This thesis examines the geologic record of glacial drift deposited in the southern Flathead Valley of Montana, and correlates it with the Cordilleran, Rocky Mountain and mid-continent glacial chronologies. The objective of this study was three-fold: to investigate the glacial deposits in detail, to define the stratigraphy of the drift units, and to establish an absolute chronology and local nomenclature for the drift units.

General Geographic and Geologic Setting

Physiography. The southern Flathead Valley lies in the northern Rocky Mountain physiographic province. Northwest-trending mountain ranges and intermontane valleys dominate this uplifted, maturely dissected, and heavily glaciated region (Figure 4). The largest of these intermontane valleys, the Rocky Mountain Trench, extends for tens of miles through southern British Columbia and northwestern Montana. Near its southern limit, the Rocky Mountain Trench is divided into two segments by the Mission Mountain Range (Figure 4). The Swan River Valley occupies the eastern branch, while the southern Flathead Valley occupies the western segment.

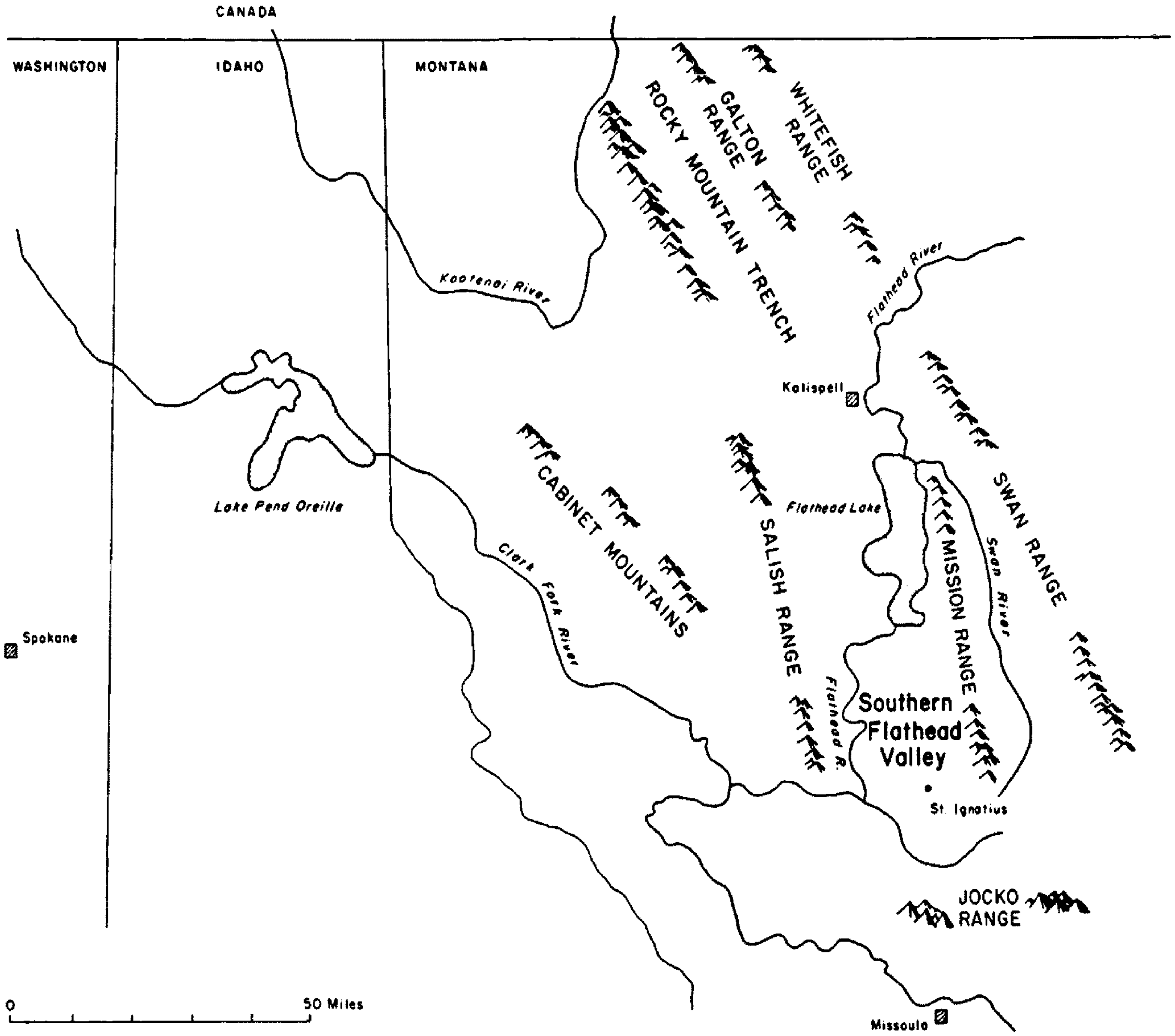


FIGURE 4. Location map of the southern Flathead Valley, Montana

South of Flathead Lake, the southern Flathead Valley is surrounded by mountains and varies from twelve to twenty miles in width (Figures 4 and 5). On the east, the valley is bounded by the precipitous front of the Mission Range. On the south, low bedrock hills separate the southern Flathead Valley from the Jocky Valley, which is bounded along its southern edge by the Jocko (or Rattlesnake) Range. The Salish Range rises gradually out of the western portion of the Flathead Valley.

Most of the southern Flathead Valley lies near 3,000 feet in elevation. However, scattered bedrock knobs reach altitudes as high as 4,000 feet and the elevation of the Flathead River in the southwestern portion of the valley is as low as 2,500 feet, giving the valley a considerable amount of relief.

Geology. Precambrian Belt Series metasediments comprise nearly all of the exposed bedrock in northwestern Montana. These Belt metasediments are predominantly argillites, quartzites, and impure limestones, deposited in a broad, shallow basin during the Precambrian (Harrison and others, 1974). Discontinuous igneous intrusive bodies as much as 1,000 feet thick intrude the sediments. These Precambrian intrusive sills, dikes, and stocks are predominantly metadiorite in composition (Johns, 1970). Both the Precambrian sediments and intrusives were metamorphosed and deformed during the late Mesozoic Laramide orogeny. Igneous bodies of late Mesozoic age also intrude the Belt rocks. These stocks and sills are distinguishable from the

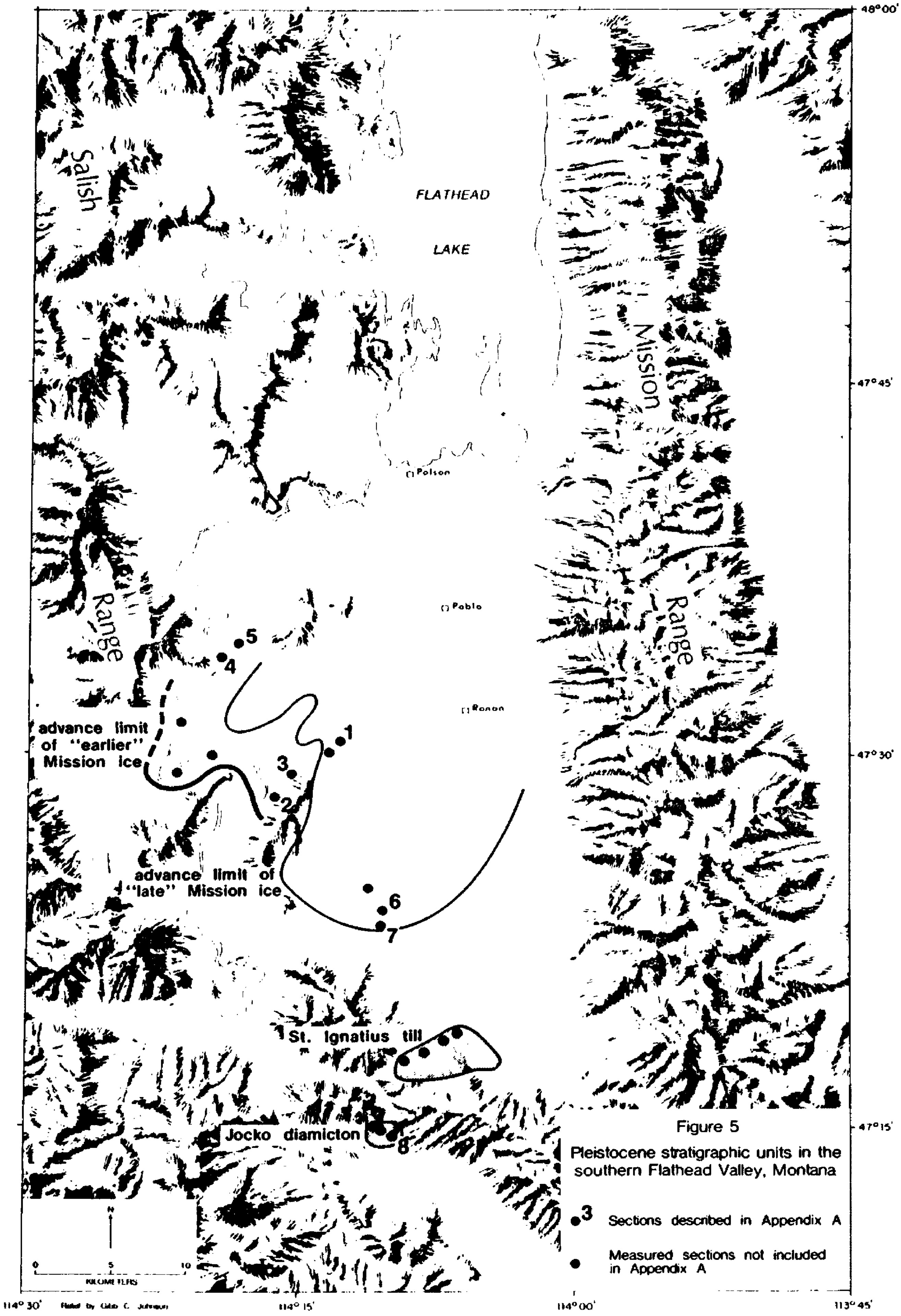


Figure 5

Pleistocene stratigraphic units in the southern Flathead Valley, Montana

●3 Sections described in Appendix A

● Measured sections not included in Appendix A

Precambrian intrusives by their granitic, quartz dioritic, or quartz monzonitic composition (Johns, 1970). Normal faults of Tertiary and Quaternary age commonly offset the Belt rocks and Mesozoic intrusives.

Numerous times during the Pleistocene epoch, an enormous ice mass, the Cordilleran ice sheet, flowed southward out of British Columbia into the United States. Along its southern margin, the thinning ice mass diverged into numerous distinct lobes (Richmond and others, 1965). One such lobe, the Flathead lobe, pushed southeastward down the Rocky Mountain Trench. Approximately fifty miles south of the Canadian border, it flowed into the northern Flathead Valley, where it was joined by ice flowing out of the Galton, Whitefish, and Swan Ranges (Witkind, 1978) (Figures 3 and 4). Maximum ice thickness along the international border reached 5,000 feet, but rapid thinning of the ice to the south reduced the maximum thickness to only 2,500 feet near Kalispell, Montana (Alden, 1953).

Contemporaneous with the advance of the Flathead lobe, the Purcell lobe of the Cordilleran ice sheet flowed through the Purcell Trench in northern Idaho, to the vicinity of Sandpoint, Idaho (Richmond and others, 1965). There, it blocked the drainage of the Clark Fork River, impounding an enormous lake, Glacial Lake Missoula, upstream from the ice dam. At its highest stand (4,150 feet), Glacial Lake Missoula covered an area of 3,000 square miles and reached a maximum depth of 2,000 feet (Alden, 1953). Formation of this lake during each glacial maximum is suspected, but lack of absolute dating control of the lacustrine sediments has led to great debate about the Lake Missoula chronology.

Previous Work

Numerous studies of the glacial geology of the Flathead lobe of the Cordilleran ice sheet in western Montana have been undertaken. The principal workers have been Elrod (1903), Nobles (1952), Alden (1953), Richmond (1965), and Richmond and others (1965). Work has consisted primarily of descriptions of the morphology of the glacial features.

Elrod identified and named the Mission moraine, Nobles mapped the entire Flathead Valley and named the St. Ignatius moraine, and Alden briefly examined all major exposures of glacial deposits in the valley in his reconnaissance study of the glacial geology of western Montana. Richmond examined the glacial drift deposited by local alpine glaciers in western Montana and correlated it with the chronology of other Rocky Mountain alpine glacial deposits. Richmond and others (1965) described the major glacial features laid down by the western Montana Flathead lobe of the Cordilleran ice sheet and discussed them in light of the chronology of Cordilleran glacial events. Most of these workers assigned Pleistocene age names (Bull Lake, Pinedale, Illinoisan, Wisconsinan, etc.) to the glacial drift units, however, since no detailed stratigraphic studies were made, considerable doubt remained about the correct relationships and ages of the deposits.

Most of the studies dealt with the glacial drift in the Flathead Valley almost purely from a morphological standpoint. There had been no attempt made to carefully define the stratigraphy of the till and associated glacial units. In addition, there was no dating upon which to establish an absolute chronology for the glacial sediments. Thus, much speculation existed concerning the age of the glacial deposits in the valley.

Methods of Investigation

Field mapping and sedimentary petrologic studies were employed in this investigation, to define the stratigraphy of Pleistocene glacial units in the southern Flathead Valley. It was anticipated that once the stratigraphy of the glacial deposits was established and a glacial chronology was outlined, correlation of the Flathead Valley sediments with other known glacial chronologies could be made.

Field work included systematic sampling and mapping of pertinent outcrops of glacial drift in the southern Flathead Valley (Figure 5). Exposures were described in detail and samples were taken for laboratory analyses. Descriptions of the degree of soil development on various drift units were made, in order to estimate the relative ages of the deposits. Where seemingly sufficient organic material was found, it was collected for radiocarbon dating.

Textural analyses were performed to obtain the grain sizes of the constituent clastic particles. The sieving method was used to determine the relative propertions of clastic particles coarser than 4ϕ (.0625 mm) in diameter, and the hydrometer method was employed to analyze the grain sizes of particles finer than 4 Ø. Grain size distribution curves were then drawn to calculate the values of mean grain size, sorting, skewness, and texture of the sediments. The mineralogy of the glacial drift units was defined by x-ray diffraction of clay minerals and microscopic examination of sand-size particles.

CHAPTER II

GLACIAL CHRONOLOGIES

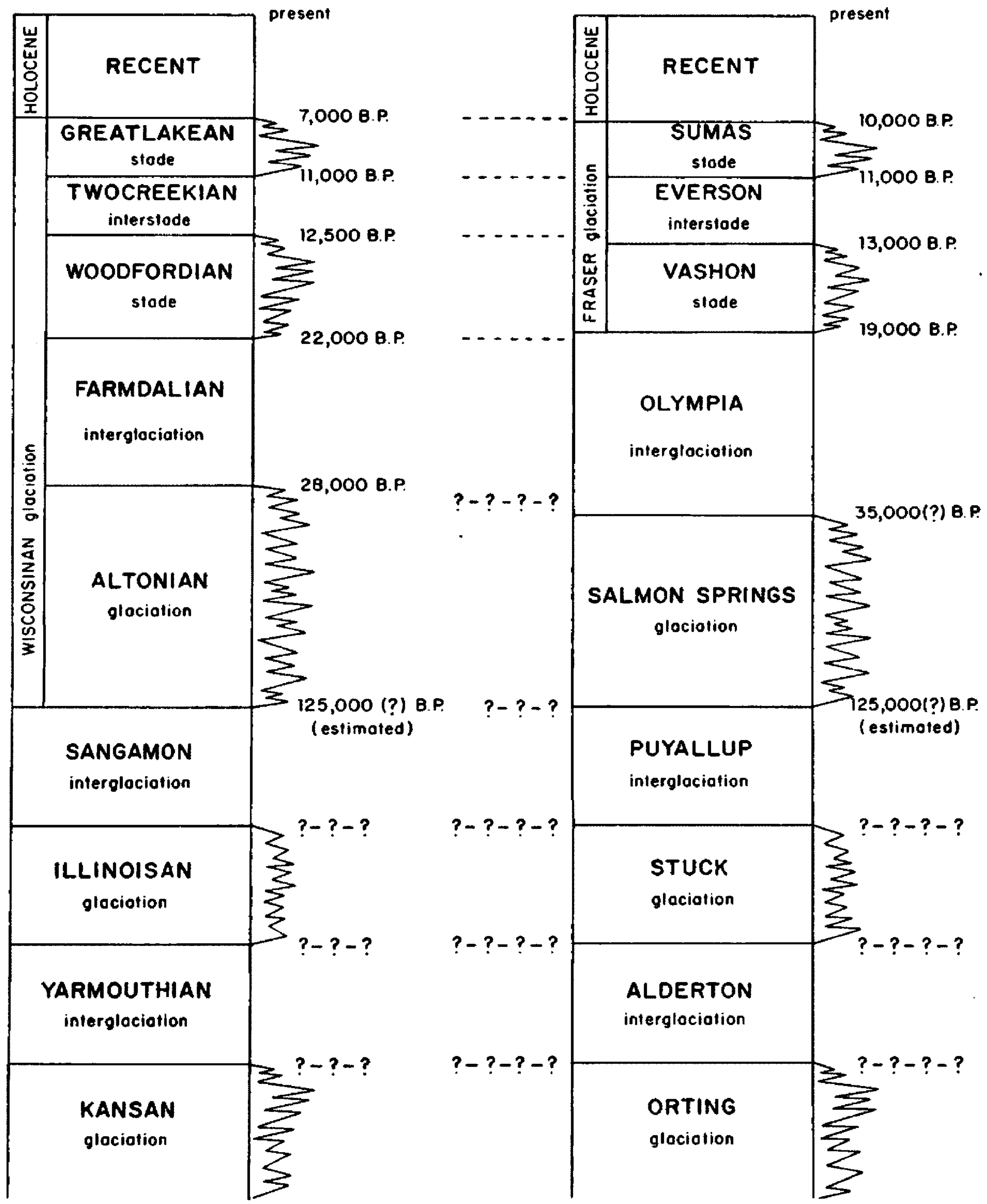
Glacial Chronology of the Cordilleran Ice Sheet

General discussion. Numerous times in the past, the growth of glaciers in the mountains of British Columbia has resulted in the formation of the Cordilleran ice sheet. The glacial record of southern British Columbia and the northwestern United States verifies the subsequent advance of the ice into these regions. Along its southern margin, the Cordilleran ice mass diverged into numerous distinct lobes (Figure 3). Study of the glacial drift laid down has been used to establish a four-part glacial chronology. At present, it appears as though the chronology of glacial events of the Cordilleran ice sheet is closely correlative with the mid-continent glacial chronology, resulting from the advances of ice masses generated within the Keewatin and Labradoran ice centers in the interior of Canada (William, 1970).

Despite the extremely large surficial area covered by the Cordilleran ice sheet, relatively few studies of the glacial drift have been undertaken in the United States. The most studied of the Cordilleran glacial deposits are located in the Puget Lowland of western Washington, the Okanagan Valley of north-central Washington, and the Purcell Trench of southern British Columbia and northern Idaho. This chapter concentrates on the chronology of the Puget Sound region, because it apparently contains the most complete record of Cordilleran ice advances and is presently the best understood. Based upon previous work and their own observations, Crandell and others (1958) established a sequence of four glaciations separated by nonglacial intervals in western Washington. Subsequent work by numerous people has led to constant revision of this chronology. Even today, controversy continues. The tentatively accepted glacial chronology of the Cordilleran ice sheet is outlined in Figure 6. In this chapter, some of the evidence which has led to the establishment of this Cordilleran chronology is presented and correlation with the glacial chronology of the mid-continent is made (Figure 6).

Orting glaciation. Glacial drift of the first apparent Cordilleran ice advance is found only in the southeastern portion of the Puget Lowland, where river bluffs expose nearly 200 feet of interstratified proglacial outwash and glacial till (Crandell and others, 1958). The entire unit is oxidized to a light yellowish-brown, and individual stones within the till have brown iron oxide coatings and are often extremely friable. More than 15 percent of the rock types found in the Orting glacial till are from northern provenances, indicating a northern source area for the ice inundating the Puget Lowland (Crandell and others, 1958). Orting glacial drift has been found as far south as Sumner, Washington, located along the Cascade Mountain front, bordering the Puget Lowland to the east. The age or Orting

FIGURE 6. Correlation of Cordilleran and Mid-continent glacial chronologies



CORDILLERAN AND MID-CONTINENT GLACIAL CHRONOLOGIES

GENERALIZED MID-CONTINENT CHRONOLOGY

GENERALIZED NORTHWESTERN CORDILLERAN CHRONOLOGY

(After Willman and Frye, 1970)

(Numerous sources)

glaciation is uncertain, but the strongly developed soil and decomposition of stones suggest an early Pleistocene age. No firm correlation with other glacial chronologies can be drawn.

Alderton interglaciation. Climatic change brought an end to the initial Cordilleran ice advance, and the ice retreated northward toward the British Columbia accumulation areas. During this interglacial period, streams and rivers, draining mainly to the north in the Puget Lowland, deposited interbedded sand, silt, and clay on extensive floodplains of aggrading streams. No record of this event has been found in any other locality occupied by Cordilleran ice. Pollen analyses of peat beds within the Alderton sediments record a climatic warming trend from early post-glacial time (Crandell and others, 1958). The lower portions of these peat horizons are dominated by Engelmann spruce and fir, suggestive of a cool, moist climate. The upper parts of the peat are dominated by Douglas fir and alder, indicative of climatic conditions comparable to those present today in the southern Puget Lowland. Age of the Alderton interglaciation is also uncertain, but it must represent an old Pleistocene event.

Stuck glaciation. Stuck drift represents the second apparent major glaciation of the Puget Lowland. Glacial till and outwash of Stuck drift are found immediately overlying the interglacial sediments of the Alderton Formation (Crandell and others, 1958). As in the glacial till of the older Orting glaciation, more than 15 percent of the pebbles in the Stuck drift are of northern derivation, indicative of a Cordilleran source for the ice in the lowland. When not buried by younger sediments, the glacial drift of the Stuck glaciation displays a well developed soil. However, since sediments of the Puyallup interglaciation were immediately deposited upon most Stuck drift, the absence of a deep weathering profile is usually characteristic. No intervening weathering or erosion occurred prior to the deposition of the interglacial sediments. Based upon its degree of weathering and stratigraphic position, the Stuck till is believed to be time-equivalent to deposits of the Illinoisan glaciation of the mid-continent.

At present, Stuck(?) drift has been recognized in only two other localities occupied by Cordilleran ice. On the southern end of Whidbey Island in Puget Sound, just northwest of Seattle, up to 60 feet of outwash sand and gravel underlie 40 feet of gray compact glacial till. This unit, the Double Bluff drift, contains pebble lithologies which suggest a British Columbia provenance (Easterbrook and others, 1967). Based upon its stratigraphic position beneath a major nonglacial sedimentary unit, Easterbrook has suggested that the Double Bluff drift is correlative with the Stuck drift in the southeastern Puget Lowland. The possibility also exists that it is younger in age, and may be correlative with the middle Pleistocene Salmon Springs glaciation. Also, in the Purcell Trench of southern British Columbia, a strongly developed soil on glacial till has been observed (Fulton, 1968).

Since the age of this deposit is beyond the limit of radiocarbon dating, stratigraphic assignment of this unit cannot be made with certainty. It may represent drift of the Stuck glaciation or of the younger Salmon Springs glaciation.

Puyallup interglaciation. Strong soil development on Stuck drift took place during the Puyallup interglaciation, while southern British Columbia and the northwestern United States were free of ice (Fulton, 1968). The Cordilleran ice sheet had once again melted and retreated back to its accumulation centers in the mountains of British Columbia. As previously mentioned, in portions of the Puget Lowland, fluvial and lacustrine sediments were deposited on top of the Stuck drift soon after retreat of the ice. These sediments of the Puyallup interglaciation very closely resemble those of the older Alderton interglaciation previously discussed.

Pollen assemblages obtained from peat beds within the Puyallup sediments record a climatic warming from the base of the unit toward the top (Crandell and others, 1958). Peat immediately above Stuck till is dominated by pine, with minor amounts of Engelmann spruce, suggestive of forests of the Hudsonian vegetation zone. This represents the cool and moist climatic conditions prevailing immediately after retreat of the Cordilleran ice, during early Puyallup interglacial time. Douglas fir, hemlock, and alder dominate the peat from the middle of the Puyallup sediments, representing a warm, dry climate similar to that in the Puget Lowland today. The pollen record of the uppermost Puyallup sediments once again is rich in Engelmann spruce and pine, suggesting a return to a cool and moist climate. This return to cooler and more moist conditions was probably synchronous with the buildup of Cordilleran ice prior to the Salmon Springs glaciation.

On Whidbey Island in Puget Sound, 200 feet of interbedded peat-bearing sand, silt, and clay are exposed. Easterbrook and others (1967) suggest that the sediments represent floodplain deposition by aggrading streams. This interglacial unit, the Whidbey Formation, also contains a pollen record which indicates an early interglacial cool climate, which ameliorated to a maximum similar to the present day climate in the Puget Lowland. Stratigraphic position and pollen records suggest correlation between the Whidbey Formation and the Puyallup Formation of the southeastern part of the lowland (Easterbrook, 1969).

The Puyallup interglaciation may be the time-equivalent of the mid-continent Sangamon interglaciation. It is estimated to have ended somewhere in the vicinity of 100,000 (?) years B.P., when ice of the Salmon Springs glaciation advanced into the region. Other areas of Cordilleran ice occupancy also record the Puyallup interglacial event. In the Okanagan Valley of southern British Columbia, interglacial sediments underlie drift of the Salmon Springs glaciation (MacAulay, 1972). In this locality, the sediments have been assigned to the "Okanagan interglaciation", which is most likely correlative with the Puyallup interglaciation of the Puget Lowland.

Salmon Springs glaciation. With deteriorating climatic conditions, rebuilding of the Cordilleran ice sheet and subsequent readvance occurred. This Cordilleran advance is known as the Salmon Springs glaciation. Salmon Springs drift is normally a compact, unoxidized to slightly oxidized till, and in most exposures only a single glacial till unit is identifiable. However, in the southern Puget Lowland, up to four feet of peat and volcanic ash separate the Salmon Springs drift into two distinct till units (Crandell and others, 1958). Four radiocarbon dates from this peat horizon yielded ages beyond the limit of radiocarbon dating (Easterbrook, 1969). Pollen analysis of this organic horizon has identified a pollen assemblage dominated by pine and fir. This assemblage represents a cool, moist climate (Crandell and others, 1958). This climatic interpretation, coupled with the lack of soil development between the two till units, suggests at least two minor glacial advances of the Salmon Springs glaciation.

On Whidbey Island, Possession drift consists of as much as 80 feet of gray compact glacial till overlying the Whidbey Formation. This drift unit is extremely discontinuous and patchy throughout the Puget Sound area. It consists of only one till unit, with no interglacial sediments present. A radiocarbon date from the Possession drift unit indicates an age of more than 40,000 years B.P. (Easterbrook and others, 1967). The stratigraphic position above the Whidbey Formation suggests a Salmon Springs equivalent, if the Whidbey Formation is indeed the Puyallup equivalent.

Numerous radiocarbon age dates from most of the major Cordilleran ice lobes suggest that Salmon Springs ice had retreated from the region by approximately 35,000 years B.P. If so, then Salmon Springs drift must be correlative with the Altonian substage of Wisconsinan glaciation in the mid-continental United States (Frye and others, 1968). Unfortunately, this 35,000 year B.P. date is extremely close to the limit of radiocarbon dating (37,000 years by conventional methods). Recently most of these dates have become suspect. A more detailed discussion of this problem follows this summary of Cordilleran chronology.

Olympia interglaciation. With moderating climatic conditions, the Cordilleran ice sheet once again withdrew from the region. This event marks the Olympia interglaciation, which is correlative with the Farmdalian interglaciation of the mid-continent. As previously mentioned, the interpretation of radiocarbon dates obtained from Olympia sediments as led to confusion concerning the age of the beginning of this interglacial period. Although the age of return to interglacial conditions is unknown, it is certain that it terminated in the northern regions approximately 24,000 years B.P. (Armstrong and others, 1965). Naturally, the period of ice-free conditions was much longer along the southern margin of the Cordilleran ice sheet than further to the north, where Salmon Springs ice persisted longer and Fraser glaciation ice returned sooner. Along the southern margins, ice-free conditions lasted at least as long as 20,000 years (35,000 years B.P. to 15,000 years B.P.) (Armstrong and others, 1965).

The Olympia interglaciation is represented in the geologic record by moderately deep soil development on Salmon Springs drift (Fulton, 1968), and by abundant fluvial deposits laid down in aggrading stream environments (Armstrong and others, 1965). Pollen analyses from associated peat units in the Puget Lowland suggest that the climate was cool and moist throughout the interglacial period (Easterbrook, 1969). Apparently, climatic conditions comparable to today did not exist during Olympia time. Other similar interpretations have been made in southern British Columbia (Armstrong, 1965).

Fraser glaciation. The Fraser glaciation, which records the last major buildup and advance of the Cordilleran ice sheet, is correlative with the "classical" Wisconsin recognized in many other glaciated regions of the world (Frye and others, 1968). While ice persisted in the Cordilleran accumulation centers throughout Fraser time, the numerous lobes along the southern extent of the ice sheet recorded two glacial advances separated by a minor ice retreat (Easterbrook, 1969). Numerous reliable radiocarbon age dates have been used to establish the chronology of Fraser glaciation events.

Evidence of buildup and advance of the Cordilleran Ice Sheet is found in the Puget Lowland glacial record, where a proglacial outwash sand, the Esperance Sand, rests on Olympia Interglacial sediments. This diachronous, lithostratigraphic unit invaded the northern reaches of the region first slowly encroaching to the south. The earliest known occupany in the north is slightly more than 20,000 years B.P.

(Clague, 1977). Accompanying the southward march of the Esperance Sand was the Cordilleran Ice Sheet, entering the Fraser Lowland of British Columbia nearly 19,000 years B.P. (Fulton, 1971). Once the ice had flowed southward far enough to block the drainage of the predominantly northward-flowing streams (south of the Strait of Juan de Fuca), a huge proglacial lake formed. Thus, in the southern stretches of the Puget Lowland, lacustrine sediments are found sandwiched between Olympia interglacial and Esperance Sand (outwash) deposits (Mullineaux, 1965). Eventually, Cordilleran ice overrode the entire sequence, depositing Vashon till throughout the lowland.

Vashon glacial ice persisted in the region until 13,000 years B.P. (Esterbrook, 1966). At this time, a relatively minor retreat of the ice occurred, known as the Everson Interstade. Upon retreat of the ice to the north, the glacially depressed land was inundated by the sea, and glaciomarine drift was deposited in the Puget Lowland. As previously mentioned, the northern portions of the region remained buried by Cordilleran ice, indicative of a retreat of limited extent. Final readvance of the Cordilleran ice, termed the Sumas Stade, took place approximately 11,000 years B.P. and persisted until about 10,000 years B.P. (Fulton, 1971). Ice of the Sumas Stade maximum did not advance nearly as far south as during the Vashon Stade maximum, only advancing to just south of the U.S.-Canadian border. Thus, the age of the last occupancy of the Cordilleran ice in the region is significantly older in the southern portions of the region than in the northern reaches (13,000 years B.P. near Seattle compared to 10,000 years B.P. in the Fraser Lowland of southern British Columbia).

Discussion of Cordilleran chronology problems. Some recent studies have given rise to controversy concerning the previously outlined chronology of the Cordilleran ice sheet. Of immediate concern is the timing of mid-Wisconsinan glacial events. As the principal critics, Fulton (1971), Clague (1978), and Allen (1979), have questioned the age of the Salmon Springs glaciation. Fulton (1971, 1968) has shown that lowland areas in British Columbia, which must have been inundated by any major Cordilleran ice mass, were continuously ice-free from at least 60,000 years B.P. until the onset of Fraser glaciation around 24,000 years B.P. Clague (1978) produced paleoclimatic data from deep sea cores and terrestrial biostratigraphic and lithostratigraphic evidence to support the claim for this lengthy nonglacial interval in southern British Columbia and northern Washington. Alley (1979) produced additional evidence from southern Vancouver Island for ice-free conditions from greater than 51,000 to approximately 21,000 years B.P. Thus, these authors maintain that the Salmon Springs glaciation ended not later than 60,000 years B.P., and is of early Wisconsinan age. They suggest that nonglacial conditions persisted throughout mid-Wisconsinan time.

Although this proposed chronology is in direct conflict with the established mid-continent glacial chronology, it is recognized that growth of the Pleistocene glacier complex was controlled by climatic factors vastly different from those of the Laurentide ice sheet of the central interior of Canada. Just as at the present time, Pleistocene temperature and precipitation regimes of the Cordillera were strongly influenced by Pacific oceanic conditions. Reduced air temperatures and warm surface waters in the northeastern Pacific were probable requirements for the growth of glaciers in British Columbia (Clague, 1978). It is possible that these conditions were not met during mid-Wisconsinan time, while the Laurentide ice sheet in the Canadian interior grew and advanced far south into the United States.

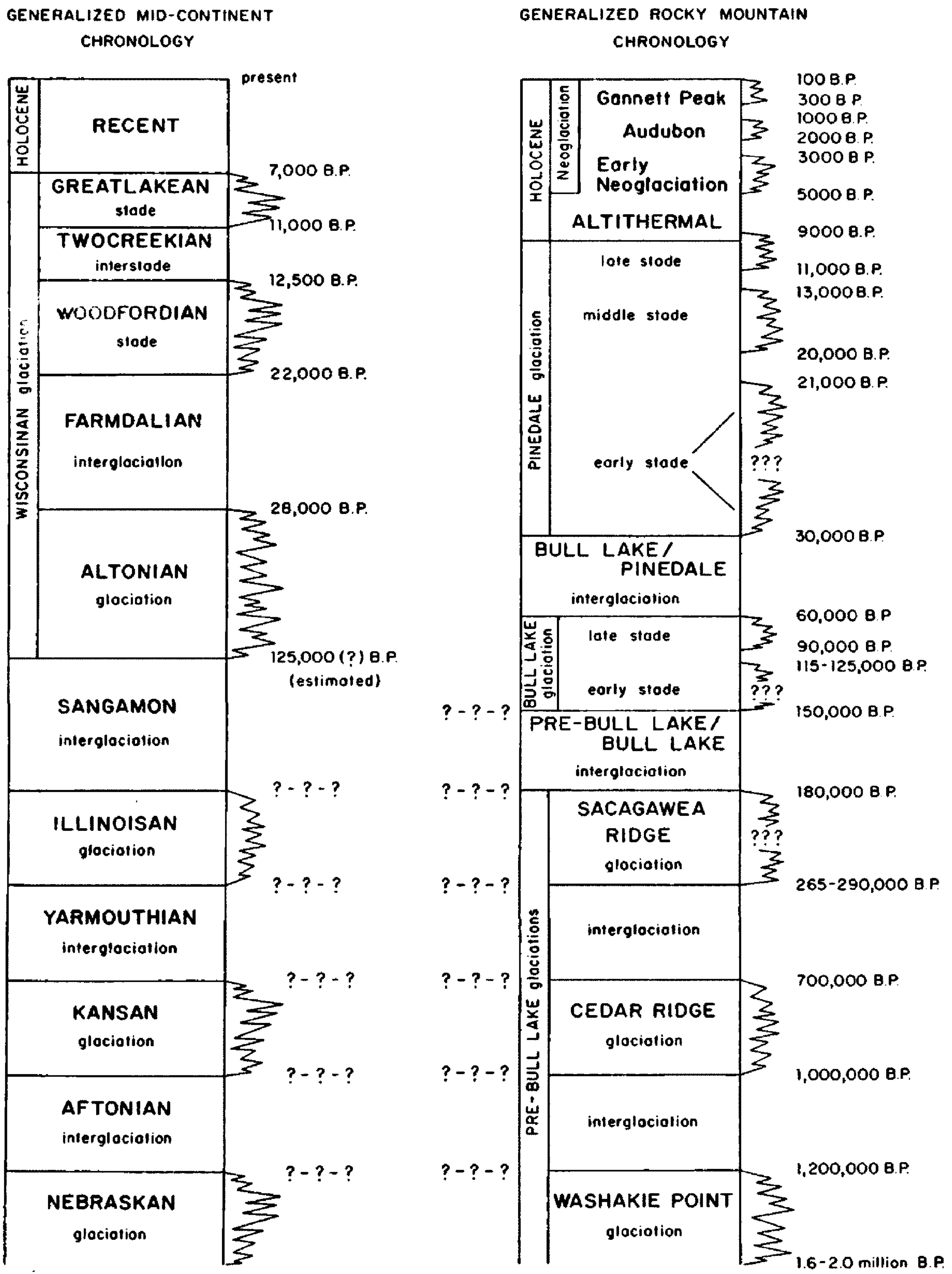
With the aid of numerous radiocarbon age dates, the late Wisconsinan glacial history of the Cordilleran ice sheet is clear. The general correlation with mid-continental glacial events cannot be questioned. However, upon reaching the limit of conventional radiocarbon age dating (37,000 years B.P.), the reliability of presently accepted stratigraphic relationships deteriorates rapidly. Much of the early to middle Pleistocene chronology of the Cordilleran ice sheet is based upon extremely limited exposures, in some cases merely a single outcrop. Stratigraphic relationships are, at very best, unclear. Correlation with other established glacial chronologies is therefore questionable. When considering pre-Olympia events in the Cordilleran chronology, it should be kept in mind that the climates of other sectors of glaciated North America are controlled by different ocean bodies and air circulation patterns. "Detailed synchroneity of glacial events on a continental scale are therefore unlikely" (Clague, 1978).

Rocky Mountain Glacial Chronology

Introduction. The following Rocky Mountain glacial chronology is given, since ice derived from local alpine glaciations is known to have merged with the Flathead lobe of the Cordilleran ice sheet (Witkind, 1978). Pleistocene ice accumulation in mountain ranges surrounding the Flathead Valley did result in the growth of extensive valley glaciers (Alden, 1953), but evidence for their coalescence into a piedmont lobe in the southern Flathead Valley has not been found. Correlation of the Rocky Mountain chronology with the Cordilleran chronology cannot be made with certainty, since the Cordilleran and Rocky Mountain ice complexes may have been temporally out of phase. This section is a brief summary of the Rocky Mountain glacial chronology.

General discussion. At least five major Pleistocene glaciations have been recognized in the Rocky Mountains. Glacial conditions were separated by nonglacial episodes of varying durations. In both the last (Pinedale) and penultimate (Bull Lake) glaciations, multiple glacial advances were separated by interstadial retreats. Glaciation in the southern and central Rockies was restricted to individual valley glacier systems, while in the northern Rockies glaciation was so heavy that local ice caps formed in some ranges. The inception of a warm and dry period, known as the Altithermal interval, brought an end to the latest Pinedale glaciation. The Rocky Mountains were ice-free during the Altithermal maximum. Following the Altithermal period, climatic deterioration resulted in renewed local cirque

CORRELATION OF ROCKY MOUNTAIN
AND MID-CONTINENT GLACIAL CHRONOLOGIES



(After Willman and Frye, 1970)

(Numerous sources)

FIGURE 7. Correlation of Rocky Mountain and Mid-continent glacial chronologies

glaciation. Three episodes of post-Altithermal cirque glaciation are recognized in the Rocky Mountains, which are collectively known as the Neoglaciation (Benedict, 1973).

Pre-Bull Lake glaciations. Very strong weathered glacial drift, void of morainal topography and located on high interstream divides, was first described in the Wind River Mountains of western Wyoming. Similar deposits subsequently found throughout the Rocky Mountains have been assigned to pre-Bull Lake glaciations (Richmond, 1965).

Flat to very gently rolling topography is characteristic of pre-Bull Lake glacial deposits. Smeared on high interstream divides, these deposits are commonly found above the limits of younger glaciations. Pre-Bull Lake drift is characterized by intensely weathered cobbles and boulders. Crystalline and volcanic rocks are very highly decomposed and friable. Highly soluble rocks, such as carbonates, are not found in the weathered drift, even when they are abundant in the parent material. This intense weathering of soluble rock types has resulted in the concentration of highly resistant rocks at the surface of weathered pre-Bull Lake drift (Richmond, 1965).

Since pre-Bull Lake glaciers were the first to scour the thick soils of the pre-glacial bedrock surface, even fresh pre-Bull Lake drift contains a much greater amount of weathered bedrock than do the younger glacial deposits. Incorporation of the thick soil into the ice has also resulted in a greater proportion of silt and clay in pre-Bull Lake tills, giving them an overall finer-grained character (Richmond, 1965).

Geologists recognize three pre-Bull Lake glaciations in the Rocky Mountains (Richmond, 1970). They are, from oldest to youngest, the Washakie Point glaciation, the Cedar Ridge glaciation, and the Sacagawea Ridge glaciation. At their type locality in the Wind River Mountains, three lithologically distinct tills representing these glaciations are separated by strongly developed soil horizons. At other localities within the Rockies, identification of pre-Bull Lake deposits is complicated by lithologic monotony and the absence of one or more of the paleosols.

The strongly developed paleosols between pre-Bull Lake tills suggest major nonglacial periods between glaciations. The duration of ice-free conditions during the pre-Bull Lake interglaciations can be estimated by the thickness of the pre-Bull Lake soil horizons, which are three to four times thicker than post-glacial soils forming in the Rockies today. Thick pre-Bull Lake paleosols found high in the Rockies are indicative of complete deglaciation of the mountains during pre-Bull Lake interglaciations (Richmond, 1965).

Recent work in Yellowstone National Park (Richmond, 1976) has provided some absolute age dates for pre-Bull Lake glaciations (Figure 7). Richmond suggests correlation of approximately 1.6-2.0 million year old glacial tills (interbedded with radiometrically dated tuffs and flows) with deposits of the Washakie Point glaciation in the Wind River Mountains. Approximately 1.2 million year B.P. Pearlette-like volcanic ash beds in interglacial alluvium overlying older glacial gravels date the end of the Washakie Point glaciation prior to that time (Richmond, 1970).

An approximately 1.0 million year B.P. loess (believed to represent glacial conditions) beneath a Pearlette tuff records a stade of the Cedar Ridge glaciation (Richmond, 1976). A 700,000 year old volcanic ash bed (related to the Bishop Tuff in California) on Cedar Ridge glacial deposits record the conclusion of that glaciation prior to 700,000 years B.P. (Richmond, 1970).

A 150,000-170,000 year old glacial till and an approximately 266,000 year old till are believed to be the result of two distinct advances of the Sacagawea Ridge glaciation (Richmond, 1976). Further evidence for these two advances are found in Yellowstone Park, where 180,000 and 290,000 year old glaciolacustrine sediments have been described (Richmond, 1970).

These three Rocky Mountain glaciations are presumed correlative with the Nebraskan, Kansan, and Illinoisan glaciations of the mid-continent (Richmond, 1970) (Figure 7). Since the radiometrically dated glacial stratigraphy in Yellowstone Park cannot presently be firmly correlated with the type sections of the pre-Bull Lake glaciations in the Wind River Range of Wyoming, these correlations are tentative.

Pre-Bull Lake/Bull Lake interglaciation. A major interglaciation characterized by deep, intensive weathering and thick soil formation followed the last pre-Bull Lake (Sacagawea Ridge) glaciation. The date of the end of the Sacagawea Ridge glaciation is uncertain, but potassium-argon dates from interglacial sediments suggest that the pre-Bull Lake/Bull Lake interglacial began at least 180,000 years B.P. It lasted until sometime in the vicinity of 120,000-130,000 years B.P., when ice of the early stade of the Bull Lake glaciation advanced (Richmond, 1970). Richmond correlates the Rocky Mountain Sacagawea Ridge/Bull Lake interglaciation with the Sangamon interglaciation of the mid-continent.

Bull Lake glaciations. At the type locality in the Wind River Mountains of Wyoming, Bull Lake glaciation deposits are characterized by broad, smooth, and gently sloping moraines (Richmond, 1965). Two or three sets of Bull Lake moraines are commonly found in the Rockies, suggesting at least two, and probably three Bull Lake glacial advances. Further support for three Bull Lake glaciations is given by three sets of outwash-veneered terraces at three distinct elevations in the Rocky Mountains (Richmond, 1965).

Broad, gently sloping, and widely breached moraines are characteristic of Bull Lake age drift. Few end moraines retain lakes and lateral moraines are generally highly dissected by streams. Kettles are commonly filled with sediment and no longer contain water, while those that do are usually swampy. Cobbles and boulders at the surface of Bull Lake drift are nearly always iron-stained and commonly exhibit weathering rinds. Highly decomposed and friable cobbles like those of pre-Bull Lake deposits are rare. During the pre-Bull Lake glaciations, the pre-glacial bedrock surface was scoured clean, leaving only remnants of deeply weathered bedrock to be incorporated by Bull Lake ice. Thus, Bull Lake till contains a much smaller percentage of silt and clay than pre-Bull Lake drift and is noticeably coarser-grained (Richmond, 1965).

Obsidian-hydration and potassium-argon dating of Pleistocene sediments in Yellowstone Park have been used to establish a chronology of Bull Lake glaciation events. Obsidian-hydration techniques were used to date the age of percussion fractures in obsidian pebbles lodged in a till, presumably of early Bull Lake age. The average age of abrasion was calculated to be approximately 140,000 years B.P., with dates ranging from 130,000 to 155,000 years B.P. (Richmond, 1976). Evidence for a glaciation of similar age came from Richmond (1976), when he described a 150,000 year old glacial till sandwiched between dated rhyolite flows and pumice beds in Yellowstone Park. He considers the till to have been deposited by ice of the early stade of the Bull Lake glaciation (Figure 7). Since these reported dates from the early stade of the Bull Lake glaciation are in conflict with those from the conclusion of the Sacagawea Ridge/Bull Lake interglaciation, more work needs to be done to refine the timing of Pleistocene events between 120,000 and 150,000 years B.P.

Glacial tills dated at approximately 115,000-125,000 years B.P. (Richmond, 1976) and 120,000 years B.P. (Richmond, 1972) record an additional early stade Bull Lake ice advance in the Yellowstone Park region. Since this approximately 115,000-125,000 year B.P. ice advance is elsewhere indistinguishable from the 140,000-150,000 year B.P. advance, and since no evidence for nonglacial conditions separating the two advances has been found, the 115,000-125,000 year B.P. advance is assigned to the early stade of the Bull Lake glaciation along with the older advance.

Radiometric age dates from flows and tuffs interbedded with glacial sediments bracket the age of the late stade of the Bull Lake glaciation between approximately 60,000 and 90,000 years B.P. (Richmond, 1976, 1972). Tills from two distinct ice advances, one around 70,000 years B.P. and the other around 90,000 years B.P., are separated by nonglacial sediments approximately 80,000 years old (Richmond, 1972). Since this nonglacial episode was apparently of short duration (about 10,000 years), it is considered to represent an interstadial event separating two ice advances of the late stade of the Bull Lake glaciation.

Richmond believes that the late and early stades of the Bull Lake glaciation in the Rocky Mountains represent distinct glacial advances separated by a nonglacial interval of sufficient duration (20,000 to 30,000 years) to produce a mature zonal soil. He correlates the Bull Lake glaciations with the older tills of the Altonian Substage of the Wisconsinan glaciation in the mid-continent (Richmond, 1970). Since evidence for glaciations between 30,000 and 60,000 years B.P. has not been found in the Rocky Mountains, there are apparently no Rocky Mountain glaciations correlative with the mid-continent glaciations occurring in the last half of the Altonian Substage of the Wisconsinan (Richmond, 1970) (Figure 7).

Bull Lake nonglacial intervals. The antiquity of Bull Lake glacial drift is evident from the mature zonal soil developed on the surface of Bull Lake sediments. A similar strongly developed paleosol is commonly found between the drift units of the early and late stades of the Bull Lake glaciation. The soil formed during the approximately 80,000 year B.P. interstadial is found only in scattered localities in the Rocky Mountains (Richmond, 1972). However, three Bull Lake age paleosols of equal development have been found intercalated with alluvial sediments in the San Juan Mountains of Colorado, and with loess deposits on the Columbia Plateau of Washington (Richmond, 1965).

Bull Lake paleosols are more strongly developed than Pinedale soils, but less well developed than pre-Bull Lake soils. This suggests that nonglacial conditions separating Bull Lake glaciations were of longer duration than Pinedale glaciation interstadials, but of shorter duration than pre-Bull Lake interglaciations. Since Bull Lake soils have been observed in high altitude cirques and summit areas as far north as Glacier National Park in Montana, it is believed that the Rockies were completely ice-free during at least one Bull Lake nonglacial interval (Richmond, 1965).

Pinedale glaciations. Renewed climatic deterioration resulted in the buildup and advance of glaciers in the Rocky Mountains. Deposits of this last major glacial episode were first recognized in the Wind River Range of Wyoming (Blackwelder, 1915). Subsequent work throughout the Rockies has produced evidence for multiple glacial stades interrupted by interstades of short durations. Pinedale moraines are most often found up-valley from older Bull Lake moraines, but in scattered localities Pinedale ice breached Bull Lake moraines (Richmond, 1965). Sets of moraines representative of the two oldest Pinedale advances are most often found in close proximity of each other, while the youngest Pinedale moraine often occupies a position much further up-valley.

Fresh constructional morphology of rough, hummocky moraines characterizes Pinedale glaciation deposits. End moraines of the late Pinedale stades commonly retain glacial lakes, while moraines of the older Pinedale advances are often narrowly breached by erosion and seldom dam lakes. Pinedale glaciation lateral moraines are normally only slightly modified by erosion. Most Pinedale glacial kettles are well preserved and still contain water. Pinedale sediments are characterized by abundant fresh boulders, and fresh till is generally less compact and more coarse grained than the older glacial deposits. Highly decomposed rock fragments are rare (Richmond, 1965).

Since few absolute age dates have been obtained from Pinedale drift in the Rocky Mountains, the chronology of Pinedale glaciation events is poorly defined. Nevertheless, stratigraphic relationships, paleosols, relative age dating, and a few absolute age dates have been used to subdivide the Pinedale glaciation into three stades: the early, middle, and late stades.

Two ice advances have been recognized in the early stade of the Pinedale glaciation. Obsidian-hydration dating techniques were used to date the age of glacial abrasion of obsidian pebbles in the oldest Pinedale moraine in Yellowstone National Park. The average age of glacial abrasion was calculated to be approximately 30,000 years B.P., with dates ranging from 20,000 to 35,000 years B.P. (Pierce and others, 1976). This date records the first ice advance of the early stade. A 23,150 ± 1,000 year B.P. radiocarbon date from shoreline sediments of a high stand of glacial Lake Bonneville in Utah, records the maximum of a second ice advance during the early stade (Richmond, 1965). Richmond believes that the early stade terminated around 21,000 years B.P., when a slight climatic amelioration resulted in a minor ice retreat (Richmond, 1970).

Dates from the middle stade of the Pinedale glaciation are scarce. The middle stade apparently began around 20,000 years B.P., when the glaciers readvanced (Richmond, 1970). Little is known about the chronology of events between 20,000 and 13,000 years B.P. It is known that the glaciers of the middle stade began receding no later than 13,000 years B.P. (Madole, 1976), and had reached their maximum position of retreat prior to 12,000 years B.P. (Richmond, 1970). This 12,000 year B.P. date is derived from Glacier Peak ash (from western Washington), which is commonly found between drift units of the middle and late stades of the Pinedale glaciation (Richmond, 1965).

The late stade of the Pinedale glaciation is represented by two or three minor ice readvances between about 9,000 and 11,000 years B.P. (Richmond, 1970). Supporting evidence comes from the Colorado Rockies, where Benedict (1973) dated a late stade advance between 9,000 and 10,000 years old. Currey (1974) also provided evidence for this late Pinedale advance in the Wind River Mountains of Wyoming, when he established the pre-Neoglacial age of the Temple Lake moraine.

Weak azonal soils separate glacial drift units of the Pinedale glaciation. Richmond (1965) suggests that the dark gray iron-stained nature of these interstadial soils is indicative of a cool and wet environment. Maximum ice retreat between the early and middle stades was only a few kilometers, representing only a slight amelioration of the climate. Retreat of as much as 25 kilometers (15 miles) occurred during the middle/late interstade, reflecting a slightly warmer and drier climate (Richmond, 1965).

Altithermal interval. Following final retreat of the Pinedale ice around 9,000 years B.P., the climate once again ameliorated. This period is known as the Altithermal interval, a nonglacial period during which time the glaciers of the Rocky Mountains in the United States melted completely and disappeared (Richmond, 1965). This interval is represented in the geologic record by a weakly developed zonal soil on

Pinedale glaciation deposits (Mahaney and Fahey, 1976). The true degree of development of this soil can only be observed in areas glaciated during the Neoglacial period, where the immature zonal soil is found between PVnedale and Neoglacial deposits. Other areas exhibit slightly stronger soil development, reflecting ice-free conditions since the retreat of the late Pinedale ice. The Altithermal interval spanned the period between approximately 5,000 and 9,000 years B.P., reaching its maximum sometime between 6,000 and 7,500 years B.P. (Benedict, 1973).

Neoglaciation. A group of moraines found in many Rocky Mountain cirque basins, represent three minor glacial advances which have taken place in post-Altithermal time. These advances, spanning the last five thousand years, are collectively known as the "little ice age" (Matthes, 1939). Neoglacial moraines are high and rough, and support little to no vegetation. The till is very fresh, quite sandy, and very boulderly (Miller and Birkeland, 1974). Recent workers, using relative age dating techniques, have outlined the following Neoglacial history.

Early Neoglacial stage (Temple Lake?). This advance, formerly named the Temple Lake stade of Neoglaciation, was originally defined from the Temple Lake moraine in the Wind River Mountains of Wyoming (Richmond, 1965), but recent workers have produced evidence for the pre-Neoglacial age of that moraine (Currey, 1974; Miller and Birkeland, 1974). Nevertheless, these same workers have described a set of moraines immediately up-valley from the Temple Lake moraine, which they have assigned to the earliest Neoglacial ice advance. These findings have complicated usage of the Temple Lake nomenclature, which now requires revision. Future stratigraphic usage of the name Temple Lake could be either 1) the name used to designate a late pre-Neoglacial ice advance represented by the Temple Lake moraine (late stade of the Pinedale), or 2) the name used to designate the earliest Neoglacial ice advance in the Rocky Mountains. Since this issue is presently unresolved, this earliest Neoglacial ice advance will simply be referred to as the Early Neoglacial stade. Deposits from this advance are widespread throughout the Rocky Mountains. In the Rocky Mountains of Colorado, this ice advance is known as the Triple Lakes advance. There, radiocarbon age dates bracket the Early Neoglacial stade between 3,000 and 5,000 years B.P. (Benedict, 1973).

Audubon stade. Moraines of this intermediate-age Neoglacial advance are found in many cirque basins of the Colorado Rockies. Similar deposits have recently been described in the Wind River Mountains of Wyoming (Miller and Birkeland, 1974). Named by Mahaney (1972), the Audubon stade replaced the Arikaree terminology of previous usage. Using radiocarbon control, lichenometry, and boulder weathering studies, Benedict (1973) determined the age of the Audubon stade to range from approximately 1,000 to 2,000 years B.P.

Gannett Peak stade. The youngest Neoglacial advance is named for moraines at the foot of Gannett Glacier in the Wind River Mountains of Wyoming (Richmond, 1965). Moraines of this advance are widespread throughout the Rocky Mountains. Numerous workers (Benedict, 1973; Richmond, 1965) have determined that the Gannett Peak ice advance occurred betwen 100 and 300 years B.P.

Correlations. Correlation of the Rocky Mountain glacial chronology with the mid-continent glacial chronology is given in Figure 7. Numerous absolute age dates from the two regions suggest a rough synchroneity of glacial advances. Pleistocene events greater than 37,000 years B.P. (the limit of conventional radiocarbon dating) can only be crudely correlated, since absolute age dates are available only from the Rocky Mountain region. Correlation of the older sediments is based upon relative age dating methods. One exception to this rule is the occurrence of the Pearlette Ash in both the Rocky Mountain Cedar Ridge and the mid-continental Kansan glacial drifts, permitting direct temporal correlation.

As a general rule, many of the alpine glacial advances appear to have slightly preceded the "continental" ice advances, since the alpine glacial systems were more dynamic and reacted more quickly to climatic change. This out-of-phase relationship of alpine and continental ice masses is well documented in the Cascade Range and surrounding lowlands in Oregon and Washington (Easterbrook, 1969). However, this temporal relationship of alpine and "continental" ice sheet advances has yet to be proven in the Rocky Mountain region. All that can be said at present is that direct correlation of the Rocky Mountain and Cordilleran glacial deposits is questionable, and cannot be made with certainty.

CHAPTER III

FIELD OBSERVATIONS

Utilizing the mapping of previous workers, a field reconnaissance of Mission till, St. Ignatius till, and Jocko diamictons was completed. Representative exposures of each stratigraphic unit were described and systematically sampled (Figure 5 and Appendix A). Descriptions of the surficial landforms and degree of soil development were made for each unit, in order to estimate the relative ages of the deposits. Where sufficient organic material was found, it was collected for radiocarbon dating. The following is a summary of field observations for each stratigraphic unit.

Mission Till

Mission till is well exposed in numerous places along the Mission moraine. The moraine, located just north of Post Creek, extends from the big bend of the Flathead River on the west side of the valley, to the Mission Mountains on the east side of the valley (Figure 5). The majority of the surface of the Mission moraine is dominated by a fresh, constructional topography (characterized by glacial kettles filled with water), moderate soil development, and the lack of an integrated drainage pattern.

Evidence for the deposition of "late" Mission till by a thin ice sheet is found near Round Butte, where two broad, subdued moraines of

Mission till indicate that Round Butte (400 feet high) divided the "late" Mission ice sheet into two small lobes.

A portion of the Mission moraine along the Flathead River bluffs, lies beyond the advance limit of the "late" Mission ice (Figure 5). These thick (at least 120 feet) sections of Mission till, which could not have been deposited by ice as thin as the "late" Mission ice, record either 1) deposition by ice of an earlier glaciation, or 2) deposition by ice of an earlier stand of the same glaciation depositing "late" Mission till. Thick (up to 75 feet) lacustrine deposits cover the "earlier" Mission till surface, and prohibit any age estimation based upon soil development or surficial integration pattern. "Earlier" Mission till apparently composes the majority of the thickness of the Mission moraine, even in the areas covered by "late" Mission till. "Late" Mission till is probably just a thin veneer spread upon the surface of "earlier" Mission till.

Nowhere in the southern Flathead Valley has a soil or erosional horizon been found between "late" and "earlier" Mission tills. This suggests that both tills were deposited by ice of the same glaciation. The "late" Mission till probably records deposition during recession of the "earlier" Mission ice. Evidence for a composite age of the Mission moraine (Curry and others, 1977) has not been found.

All unweathered Mission till exposed is massive, yellowish-brown (10 YR 5/4) to brown (10 YR 5/3), strongly calcareous, and a silty clay loam. "Late" and "earlier" Mission tills do not differ in appearance. In places, especially along the Flathead River bluffs, thin (less than two feet thick) lenses of poorly sorted cobbly gravel give the Mission till a distinct layering. These horizontal gravel lenses are often laterally continuous for as much as one mile. They probably represent periods of increased melting, and perhaps even episodes of minor ice retreat. Above and below the gravel lenses, tills are identical. No paleosols or erosional horizons are found anywhere in the Mission till sequence.

Glaciolacustrine and glaciofluvial sediments are commonly interbedded with Mission till. The texture of the lacustrine beds varies from silty clay to fine sandy silt. Most lacustrine sediments contain scattered dropstones. Glaciofluvial beds are not common in exposures low in the Mission moraine, but become fairly abundant near the top. The fluvial sediments are characteristically moderately sorted, medium to coarse-grained sands and poorly sorted sandy gravels.

A mature zonal soil is developed on the surface of the "late" Mission till (Figure 8). The depth of soil development averages around four feet, with the soil thinning toward the mountains on the east. The A_1 horizon ranges from about 10 inches thick near the Flathead River, to about 20 inches thick adjacent to the Mission Mountains. Depth of carbonate leaching ranges from 15 to 30 inches, with a valley center average of about 20 inches (Nobles, 1953). This increase in soil thickness reflects the increase in rainfall toward the mountains, due to the orographic influence of the Mission Range.

FIGURE 8. Soil profile on Mission Till.

Location: 3/4 mile north of Ninepipe Power Station
Vegetation: grassland
Landscape: hummocky morainal topography of the Mission moraine
Slope: on crest of small hummock
Aspect: south-facing
Parent Material: "late" Mission till

Horizon	Depth	Munsell color (moist)	Texture	Structure	Reaction	Roots	Boundary	Density	CO_3
A_1	0-12"	10YR 3/2 very dark grayish-brown	gravelly loam	weak, fine, crumb	7.0	fine, abundant	irregular, transitional	low	non-calc.
$B_{t_{ca}}$	12-36"	10YR 5/4 yellowish-brown	gravelly clay loam	moderate, fine, ang. blocky	7.5	fine, few	smooth, transitional	moderate	mod. calc.
B_3	36-48"	10YR 5/4 yellowish-brown	gravelly silt loam	strong, coarse, ang. blocky	7.5	none	wavy, transitional	high	strongly calc.
C_1	48"+	10YR 5/4 yellowish-brown	gravelly silt loam	massive	7.5	none	--------	high	strongly calc.

Moderate soil development, unfilled glacial kettles, and the lack of an integrated drainage pattern, all suggest that at least the surface of the Mission moraine is not of great antiquity. An absolute age date from the Mission moraine was obtained by radiocarbon dating organic material dispersed throughout Mission glaciofluvial sediments. These fluvial sands, sandwiched between tills near the top of the Mission moraine at Dublin Gulch (Appendix A), record the maximum stand of "late" Mission ice (Figure 9). The organics were dated at greater than 20,380 years B.P. The infinite date was the result of insufficient organic material and the silty nature of the organics collected.

Descriptions of seven pertinent sections of Mission till (Figure 5) are presented in Appendix A. Laboratory data from these seven Mission till sample localities are also presented in the other appendices.

St. Ignatius Till

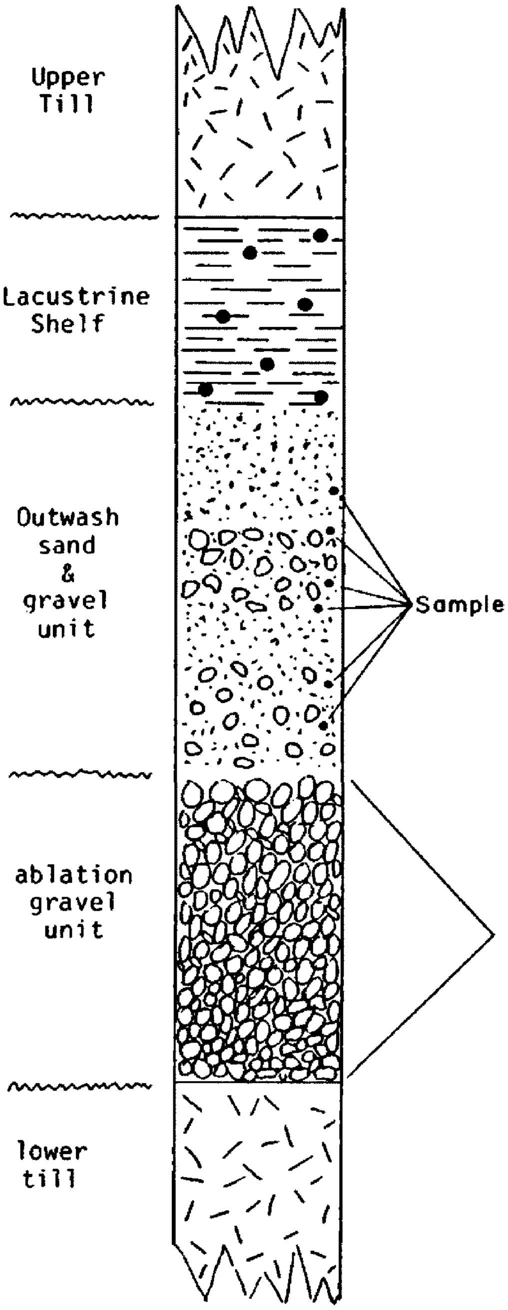
Exposures of St. Ignatius till are limited to shallow road cuts along Ravalli Hill. The till extends easterly from the crest of Ravalli Hill to the Hills southeast of the town of St. Ignatius (Figure 5). It occurs as a thin veneer covering Precambrian Belt bedrock. In places, bedrock is exposed at the surface. The surface has a well integrated drainage pattern, which could be affected by the shallowness of the bedrock.

Nowhere in the southern Flathead Valley is more than five feet of St. Ignatius till exposed. The till is slightly calcareous and

Sample # UM-77-1

Dublin Gulch Highway Section   >20,380 years B.P.

SW SW SW Section 20, Twp 19N Rge 20W
Charlo, Montana 7.5 min Quad
(outcrop located at intersection of highway and railroad tracks)



~4.0 m buff sandy silt till; calcareous

30-50 cm massive light buff lacustrine silt with dropstones; contains thin lenses of festoon-type cross-bedded sands; A continuous cross-bedded sand layer occurs just above the contact with the gravel unit below; cross-beds generally dip south.

20 cm brown well-sorted, medium to coarse grained sand; some gravel; clean and openwork.

40 cm Brown coarse sand and gravel, rounded to subrounded; contains rounded clay balls; clean and openwork; organics common.

In middle of this unit occurs a 5 cm thick brown fine-medium grained sand with trace gravel; cross-beds dip south; organics common.

50 cm Brown coarse sand and gravel; with abundant large cobbles, especially near base. Rounded to subrounded; rounded clay balls; clean openwork; no bedding evident. Grades eastward into a dirty matrix supported cobbly gravel.

Buff sandy silt till; calcareous. Thickness unknown.

All of the organic material was collected from the outwash-type sand & gravel unit interpreted to be a Kame terrace deposit.

FIGURE 9. Description of the radiocarbon-dated Dublin Gulch Highway section

yellowish-brown (10 YR 5/4). Exposed St. Ignatius till is a silty clay loam, however the original texture of the parent material is unknown, since fresh, unaltered St. Ignatius till was not found. No glaciolacustrine or glaciofluvial sediments were found associated with the St. Ignatius till.

Depth of soil development on the St. Ignatius till is poorly defined, since fresh, unaltered till was not observed. Thickness of the A_1 soil horizon ranges from 12 to 20 inches along Ravalli Hill, similar to the A_1 horizon thickness on the "late" Mission till. However, the textural B horizon (zone of eluviation) extends to at least 60 inches in depth, and could be significantly deeper (Figure 10). Depth of leaching of carbonate on the St. Ignatius till ranges from 30 inches on Ravalli Hill to more than 40 inches adjacent to the Mission Range, with an average of 34 inches (Nobles, 1953). Thus, soil development on the St. Ignatius till is significantly greater than on the "late" Mission till. The deeper soil development and more developed drainage pattern on the St. Ignatius till suggest that the till is significantly older than the "late" Mission till.

Jocko Diamictons

The Jocko diamictons are best exposed in a small bluff at the junction of the Jocko River and Valley Creek (Figure 5). They are also found at scattered localities throughout the northern Jocko Valley, where outcrops are thin and of limited lateral extent. The diamictons

FIGURE 10. Soil profile on St. Ignatius Till.

Location: Ravalli Hill summit
Vegetation: grassland
Landscape: hummocky morainal topography of St. Ignatius till
Slope: on crest of small hummock
Aspect: south-facing
Parent material: St. Ignatius till

Horizon	Depth	Munsell color (moist)	Texture	Structure	Reaction	Roots	Boundary	Density	CO_3
A_1	0-6"	10YR 3/2 very dark grayish-brown	silty clay loam	weak, fine, crumb	7.0	fine, few	wavy, transitional	low	non-calc.
B_t	6-48"	10YR 5/4 yellowish-brown	gravelly silty clay	moderate, fine, subang. blocky	7.5	fine, v. few	smooth, transitional	moderate	non-calc.
B_t	48-60"+	10YR 5/4 yellowish-brown	gravelly silty clay	moderate, medium, subang. blocky	7.5	none	---------	high	weakly calc.
	covered below 60"								

are massive, noncalcareous, brown (10 YR 5/3) to yellowish-brown (10 YR 5/4) and strongly oxidized throughout. Pebbles and cobbles are more abundant than in either the Mission or St. Ignatius tills.

At the Valley Creek section, two till-like units are interbedded with lacustrine (?) silt beds and fluvial (?) gravels. Glacial Lake Missoula sediments rest unconformably upon the uppermost Jocko silt unit. Olive-green Tertiary (?) sands and silty clays are exposed at the base of the section. This section is cut by normal faults, with offsets up to one foot. The faults cannot be traced upward beyond the base of the uppermost till-like unit. Lignitic wood fragments are common in the Tertiary (?) sediments at the base of the section and are scattered throughout the diamictons above. The lignitic wood also occurs as a thin (5 cm thick) horizon within a silt bed between Jocko diamictons.

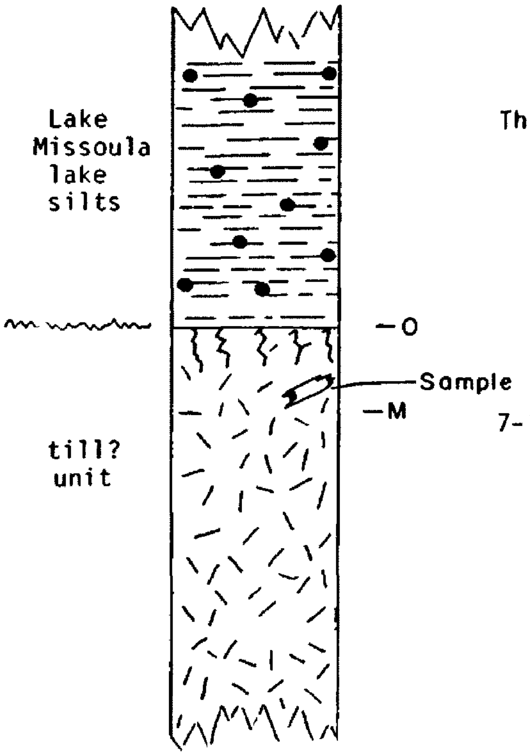
Glacial Lake Missoula sediments mantle much of the northern Jocko Valley, prohibiting any age estimation of the Jocko diamictons by the degree of development of drainage integration patterns. The strong oxidation and carbonate leaching of the bulk of the Valley Creek section is indicative of a substantially greater age for the Jocko diamictons than for either the Mission or St. Ignatius tills. This is also suggested by an absolute age date from a lignitic wood fragment found within the upper diamicton (Figure 11). It was radiocarbon dated at greater than 37,000 years B.P., the limit of conventional radiocarbon dating. A detailed description of the Jocko diamictons at the Valley Creek section is included in Appendix A.

Sample # UM-77-2

>37,000 years B.P.

Valley Creek Section

SW NE SW Section 8, T17N R20W
Arlee, Montana 15 min Quad
(at junction of Valley Creek and Jocko River)



Thickness Unknown

Tan, varved lacustrine silt with dropstones; unoxidized; calcareous; a few large chunks of wood occur scattered through this unit, which were not used in dating.

7-10 m

Brown clayey silt with abundant angular to rounded gravel; oxidized to a bright orange-brown color; unit could be till; Abundant wood fragments occur scattered randomly throughout this unit; this wood is found as tiny bits scattered through the matrix as well as larger squared-off chunks; wood for dating was taken from near the top of this unit.

FIGURE 11. Description of the radiocarbon-dated Valley Creek section

CHAPTER IV

LABORATORY OBSERVATIONS

Lab Methods

Sedimentary petrologic analyses were employed in this study, in an attempt to "fingerprint" Pleistocene stratigraphic units in the southern Flathead Valley. The lab techniques used are outlined here., data is presented, and a discussion of results is offered. Lab tests performed include grain size analyses (both sieve and hydrometer methods), clay mineralogy by x-ray diffractometry, and microscopic examination of sand size particles.

Grain size analyses. Grain size analyses were performed using sieving and hydrometer methods. The sieving procedure employed is a modification of those outlined by Bowles (1970) and Folk (1968). It is an accurate, easily reproducible, and reliable method. The procedure followed for hydrometer analyses is given by Bowles (1970). One representative hydrometer analysis data sheet (Figure 12) and one representative sieve analysis data sheet (Figure 13) are presented, to illustrate how the grain size data were obtained.

Grain size distribution curves. Sieve and hydrometer data were used to produce a grain size distribution curve for each sample. In order to facilitate the reading of statistical parameters, the data were plotted as a cumulative curve. Grain diameters were plotted on

GRAIN SIZE ANALYSIS - HYDROMETER METHOD Data Sheet

Sample No. DGH - 7

Location Dublin Gulch Highway Section

Date of testing 3-10-79

Hydrometer no. 152H G_s of solids 2.65 a= 1.00

Dispersing agent Calgon Amount 125 ml

Zero correction +6 units at 4% Meniscus correction +1 unit

Weight of soil, W_s 48.78 g

Date	Time of reading	Elapsed time, min.	Temp., °C	Actual Hyd. reading Ra	Corr. Hyd. reading Rc	% Finer	Hyd. Corr. only for meniscus, R	L	$\frac{L}{t}$	K	D, mm	D, φ
4-1-79	4:17	START	—	—	—	—	—	—	—	—	—	—
"	4:18	1	20	39.5	33.5	68.7	40.5	9.65	9.65	.0137	.0426	4.55
"	4:19	2	20	37.5	31.5	64.6	38.5	10.0	5.00	.0137	.0306	5.03
"	4:21	4	20	36	30	61.5	37	10.2	2.55	.0137	.0219	5.51
"	4:25	8	20	35	29	59.5	36	10.4	1.30	.0137	.0156	6.00
"	4:32	15	20	33.5	27.5	56.4	34.5	10.6	0.707	.0137	.0115	6.44
"	4:47	30	20	31	25	51.3	32	11.1	0.370	.0137	.00833	6.91
"	5:17	60	19.5	27.5	21.3	43.6	28.5	11.6	0.193	.01375	.00604	7.37
"	6:17	120	19	25	18.7	38.3	26	12.0	0.100	.0138	.00436	7.84
"	8:17	240	18.5	22	15.6	32.0	23	12.5	.0521	.0139	.00317	8.30
"	12:17	480	18	19	12.5	25.6	20	13.0	.0271	.0140	.00230	8.76
4-2-79	4:17	1440	17.5	15	8.4	17.2	16	13.7	.00951	.0141	.00138	9.50
4-3-79	4:17	2880	17.5	14	7.4	15.2	15	13.8	.00479	.0141	.000976	10.00

R_c = R_{actual} − zero correction + C_T % finer = $R_c(a)/W_s$ $D = K\sqrt{L/t}$

FIGURE 12. Representative hydrometer analysis data sheet.

GRAIN SIZE ANALYSIS - MECHANICAL

Data Sheet

Sample No. DGH-7

Location Dublin Gulch Highway Section

Date of testing 4-3-79

Weight of dry sample 212.50 g

Weight of sample after wet sieving 55.82 g

Weight loss from wet sieving 156.68 g

Sieve no.	Diam., Ø	Wt. retained	% retained	% passing
10	-1.0	25.87	12.17	87.83
18	0.0	6.73	3.17	84.66
35	1.0	5.42	2.55	82.11
60	2.0	5.05	2.38	79.73
120	3.0	5.38	2.53	77.20
200	3.75	5.11	2.40	74.80
pan	—	1.82	—	—
		55.38 g		

Weight loss = 0.44g

= 0.79% error

% passing = 100 − ∑ % retained

FIGURE 13. Representative sieve analysis data sheet.

the abscissa (arithmetic scale) in ϕ units. Cumulative percent frequency was plotted on the ordinate (probability scale).

Percentages of gravel, sand, silt, and clay were calculated from each curve, and recorded as *texture*. The gravel percentage given is the percent of the entire sample. Sand, silt, and clay percentages given are exclusive of the gravel-size material present; they total 100 percent when added together.

Statistical parameters have been calculated for each grain size distribution curve. Following is a short discussion of each paramater used, including graphic mean (M_z), graphic standard deviation (σ_G or σ_I), and graphic skewness (S_{k_G} or S_{k_I}). Equations and tables are from Folk (1968).

Graphic Mean (M_z). The graphic mean is the best graphic measure of the average grain size of a sediment sample. It is superior to the median (ϕ_{50}), because it is calculated from three points on the grain size curve, rather than just one. Thus, calculations of mean size by measuring the median are not very satisfactory in strongly skewed curves. The graphic mean is a standard measure of grain size used in sedimentary petrologic studies.

$$M_z = (\phi_{16} + \phi_{50} + \phi_{84})/3$$

Graphic Standard Deviation (σ_G) or Inclusive Graphic Standard Deviation (σ_I . The standard deviation is a measure of the uniformity or *sorting* of a sediment. The inclusive graphic standard deviation (σ_I) is the best measure of sorting, because it embraces 90 percent of the distribution curve.

$$\sigma_I = (\phi_{84} - \phi_{16})/4 + (\phi_{95} - \phi_5)/6.6$$

It was calculated whenever possible. However, most of the samples studied in this project contained so much clay and/or gravel, that the values of ϕ_5 and/or ϕ_{95} were not obtained. Therefore, it was necessary to use the graphic standard deviation (σ_G), which covers only 68 percent of the curve.

$$\sigma_G = (\phi_{84} - \phi_{16})/2$$

It is still a good measure of sorting, which is commonly used in sedimentological analyses. A classification of sediment sorting devised by Folk (1968), is given below: it was employed in this study.

σ_I (or σ_G)
under 0.35ϕ, very well sorted
0.35 - 0.50ϕ, well sorted
0.5 - 0.71ϕ, moderately well sorted
0.71 - 1.00ϕ, moderately sorted
1.00 - 2.00ϕ, poorly sorted
2.00 - 4.00ϕ, very poorly sorted
over 4.00ϕ, extremely poorly sorted

Graphic Skewness (S_{k_G}) or Inclusive Graphic Skewness (S_{k_I}).

The graphic skewness is an indicator of the amount of asymetry of the distribution curve. In essence, it is a measure of the amount of displacement of the median (ϕ_{50}) from the graphic mean (M_z). Thus, graphic skewness is a measure of the amount of excess fine material (positive skewness) or excess coarse material (negative skewness) present in the sediment. Since most skewness occurs in the tails of the distribution curves, use of the inclusive graphic skewness (S_{k_I}) is preferable.

$$S_{k_I} = (\phi_{16} + \phi_{84} - 2\phi_{50})/2(\phi_{84} - \phi_{16}) + (\phi_5 + \phi_{95} - 2\phi_{50})/2(\phi_{95} - \phi_5)$$

However, as previously mentioned, values of ϕ_5 and/or ϕ_{95} were generally not obtained in this study, so that the graphic skewness (S_{k_G}) was used for most samples.

$$S_{k_G} = (\phi_{16} + \phi_{84} - 2\phi_{50})/\ (\phi_{84} - \phi_{16})$$

Although not as encompassing as the inclusive graphic skewness, the graphic skewness is still a useful parameter, which is commonly used in sedimentary petrologic studies. Folk's classification of skewness, based upon values of S_{k_I} (or S_{k_G}) was used in this thesis to assign skewness descriptions to the sediments. Folk's classification is given below.

S_{k_I} (S_{k_G}) from +1.00 to +0.30, strongly fine-skewed
+0.30 to +0.10, fine-skewed
+0.10 to - 0.10, near symmetrical
-0.10 to -0.30, coarse-skewed
-0.30 to -1.00, strongly coarse-skewed.

Discussion of grain size distribution curves. Thirty-nine samples of glacial drift from the southern Flathead Valley were analyzed for their grain size properties. Twenty samples were glacial till, eleven were glaciolacustrine, four were glaciofluvial, and four were diamictons. All grain size distribution curves are presented in Appendix B. Figure 14 is a terniary diagram of the grain size properties of the glacial units studied.

Mission till. Seventeen samples of Mission till were analyzed. The average texture of representative samples of the silty clay loam

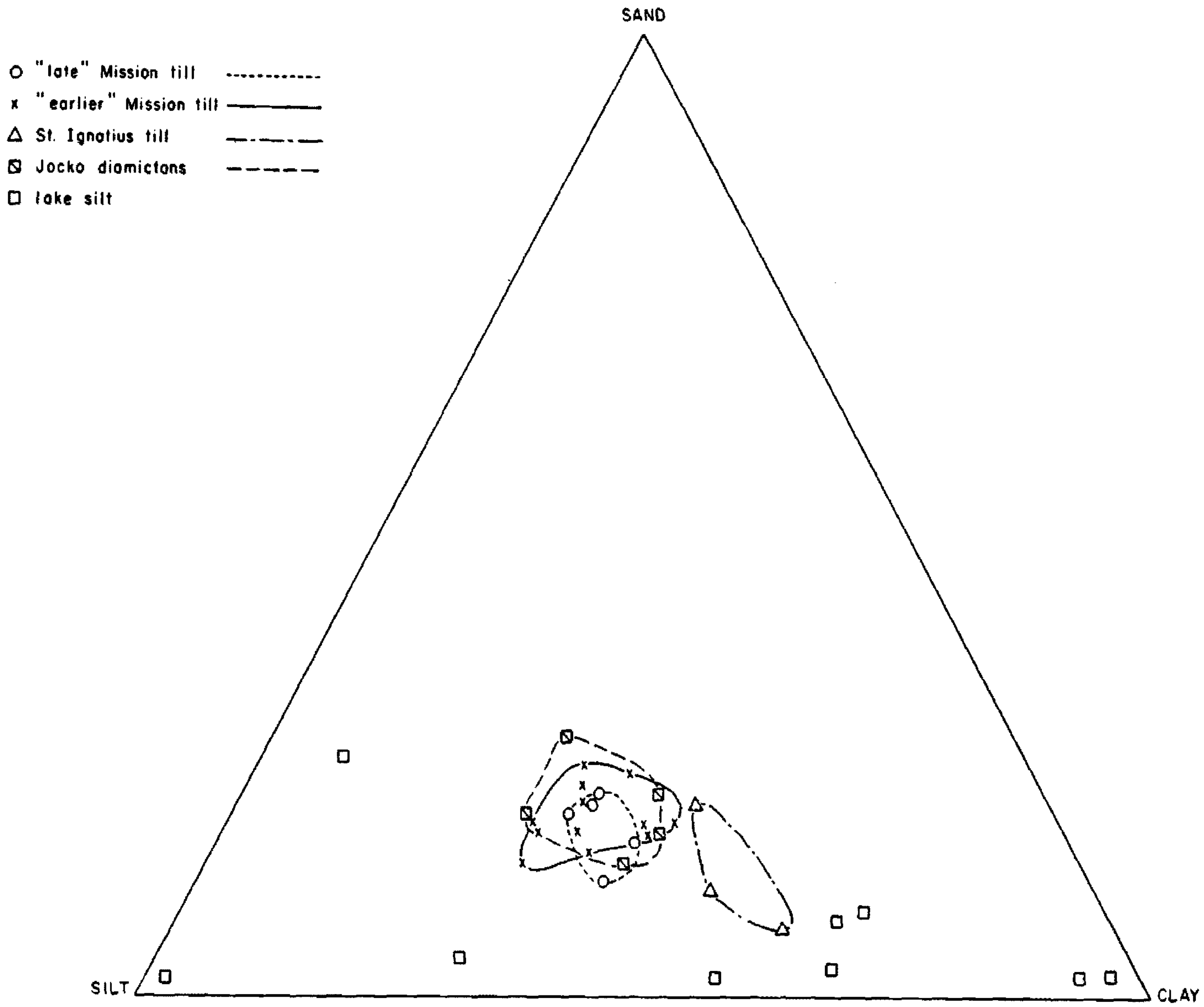


FIGURE 14. Terniary diagram of grain size properties of glacial sediments in the southern Flathead Valley

Mission till is 13 percent gravel/18 percent sand - 46 percent silt - 36 percent clay, with the average mean grain size of 5.47 ϕ (medium-grained silt). Sorting (σ'_G) of all Mission tills analyzed ranges from 3.30 ϕ to 5.65ϕ, indicative of very poor to extremely poor sorting. Textures differ little from sample to sample (Figure 14) and "late" and "earlier" Mission tills could not be differentiated by grain size analyses.

The texture of the Mission till results from the overriding of both proglacial outwash and lacustrine sediments by Mission ice. Negative skewness values for all Mission tills analyzed are indicative of the excess coarse material present, presumably derived from the overriding of proglacial outwash by the Mission ice. Three samples of Mission till (FRF-17, CCC-2, and MCC-3) are slightly coarser than the other samples, containing more silt and less clay (12/17-53-30). All three siltier tills rest directly upon lacustrine silt beds, suggesting that their siltier textures result from local incorporation of lake silts into the tills.

St. Ignatius till. Three samples representative of St. Ignatius till were analyzed. This clay loam till averages 15 percent gravel/ 12 persent sand - 36 percent silt - 52 percent clay, with an average mean grain size of 6.45 ϕ (fine-grained silt). σ'_G values between 5.85ϕ and 6.13ϕ are indicative of extremely poor sorting. As in the Mission till, negative skewness values are indicative of excess coarse material present.

The higher clay content of the St. Ignatius till (Figure 14) could reflect finer-grained parent material, but since all samples of the till are from the textural B soil horizon, the greater clay content probably relfects clay illuviation from the surface. No completely unweathered St. Ignatius till is exposed in the southern Flathead Valley, preventing the analysis of fresh, unaltered till.

Jocko diamictons. The Jocko diamictons analyzed are texturally similar to the Mission till (Figure 14). The silty clay loam Jocko diamictons average 15 percent gravel/16 percent sand - 43 precent silt - 41 percent clay, with an average mean grain size of 5.420 (medium-grained silt). As in the Mission and St. Ignatius tills, σ_G values between 3.380 and 6.500 are indicative of very poor to extremely poor sorting, and negative skewness values reflect the incorporation of glaciofluvial sediments into the till. One sample of Jocko diamicton (VC-9) is significantly coarser-grained than the other Jocko diamictons analyzed (27/23-44-29). Since the sample was taken from very strongly oxidized diamicton near the top of the uppermost till-like unit, its coarser texture may be the result of illuviation of clay from the matrix.

Glaciolacustrine and glaciofluvial sediments. Grain size analyses were performed on lacustrine sediments interbedded with Mission till and Jocko diamictons. No similar sediments were found associated with the St. Ignatius till. Mean grain size, texture, and sorting of the lake sediments vary considerably (Figure 14). Textures range from nearly pure clay (0/2-3-95; sample FRF-12) to sandy silt with virtually no clay (0/25-67-8; sample DGH-2). Mean grain size ranges from 3.80Ø (coarse silt; sample MCC-2) to 8.82Ø clay; sample CCC-4). All of the lake sediments are poorly to very poorly sorted, with σ_G values from 1.15Ø to 3.55Ø. Most are fine-skewed.

Grain size analyses were also performed on glacioflvial sediments interbedded with Mission till. No similar fluvial sediments were found within the St. Ignatius till, and fluvial sediments in the Jocko diamictons were too altered to make an accurate grain size analysis. All Mission glaciofluvial sediments are predominantly gravel, with a matrix of variable grain size. Gravel composed 45 to 78 percent of the samples. Sand composition ranges from 36 to 90 percent of the matrix, while silt and clay composes from 10 to 64 percent of the matrix. The mean grain size of the fluvial sediments is approximately -1.44Ø (granule-size). Sorting of the sediments range from poor (σ_G = 1.77Ø) to very poor (3.23Ø), while positive skewness values reflect excess fine material present.

Conclusions. Mission till, St. Ignatius till, and Jocko diamictons cannot be differentiated by grain size analyses. The texture and mean grain size of Mission till and Jocko diamictons are extremely similar and not distinctive. St. Ignatius till analyzed is finer-grained, but samples are from the textural B soil horizon, which probably do not fully reflect the texture of the parent material. Lacustrine sediments interbedded with Mission till and Jocko diamicton are too variable to be diagnostic, and glaciofluvial sediments are only available from the Mission till, prohibiting comparison with similar sediments in the St. Ignatius till and Jocko diamictons.

Clay mineralogy. X-ray diffraction of clay minerals was used in an attempt to "fingerprint" the glacial units in the southern Flathead Valley. It was anticipated that drift units of different glacial advances might contain distinctive mineralogies, resulting from the incorporation of unique sediments or bedrock types.

Clay minerals present in the glacial deposits of the southern Flathead Valley include illite, smectite, chlorite, mixed-layer clay, and possibly kaolinite. Quartz and calcite peaks are also present in the diffraction patterns of the less than 2 micron clay fraction. Clay minerals were identified using the criteria outlined by Carroll (1970). Since kaolinite peaks were not differentiated from chlorite peaks, their presence is designated chlorite-kaolinite(?) in the discussion.

Following is a discussion of the clay mineralogic composition of each stratigraphic unit studied. Diffraction patterns of samples representative of each unit are presented in Appendix C.

Mission till. X-ray diffraction patterns were obtained from twenty-one samples of Mission till and associated lacustrine sediments. Little variation occurs in the clay mineralogic composition of the Mission tills. Nineteen of the twenty one samples analyzed are nearly identical. They contain approximately equal proportions of illite and chlorite-kaolinite (?), with a lesser amount of smectite. Most samples also contain minor amounts of quartz and calcite. Some contain very small amounts of mixed-layer clay.

The two samples which do show minor compositional variation are samples DGL-5 (from the top of the Mission moraine along Dublin Gulch) and FRF-17 (from the base of the bluffs along the Flathead River). Both are glacial tills. These samples also have approximately equal proportions of illite and chlorite-kaolinite (?), but do not contain smectite. A possible explanation for the lack of smectite in these samples may be that both tills are slightly coarser-grained than the majority of Mission tills. Since smectite is a very fine-grained mineral, and since the clay fraction in these samples is coarser, smectite does not appear in the diffraction patterns.

The clay mineralogic composition of Mission till reflects the source material overridden by Mission ice. Illite and chlorite-kaolinite(?) are major components of the Precambrian Belt metasediments (Maxwell, 1964). Quartz and calcite are also derived from the quartzites and limestones of the Belt rocks. The smectite present in most samples of Mission till was apparently derived by incorporation of Tertiary sediments into Mission ice. A sample of Tertiary(?) sediments (FRF-9) exposed along the Flathead River was analyzed to determine its mineralogic composition. As suspected, the matrix of this talus breccia is dominantly smectite.

The uniformity of all samples analyzed, from scattered localities and varying depths within the Mission moraine, prohibits differentiation of "late" and "earlier" Mission tills by clay mineralogy. Diffraction patterns of representative Mission tills are presented in Appendix C.

St. Ignatius till. As previously mentioned, the St. Ignatius till is poorly exposed along the hills south and southwest of the town of St. Ignatius. It occurs as a thin veneer of till on top of Precambrian Belt bedrock. For this reason, samples of fresh, unaltered St. Ignatius till were not available for analysis. The samples analyzed for clay mineralogic composition were of the least weathered St. Ignatius till exposed. X-ray diffraction patterns of four samples of St. Ignatius till were obtained. Two patterns are presented in Appendix C.

All samples of St. Ignatius till contain approximately equal proportions of illite and chlorite-kaolinite(?), as in the Mission till. Shallow, highly weathered samples of St. Ignatius till (SIT-3 and SIT-4) (Appendix C) contain a comparable amount of smectite to that found in weathered Mission till (DGH-3). Slightly oxidized samples of St. Ignatius till (SIT-1 and SIT-2) (Appendix C) contain smectite in amounts comparable to that in unweathered Mission till. The slightly higher amount of smectite, and the lack of calcite in some St. Ignatius till samples may result from slightly greater weathering.

Source material incorporated into the ice of the St. Ignatius advance must have been the same as that of the Mission advance. Illite, chlorite-kaolinite(?), quartz, and calcite were derived from Precambrian Belt metasediments. Tertiary sediments supplied smectite.

Differentiation of the Mission and St. Ignatius tills cannot be made using clay mineralogic studies. Incorporation of similar materials by both Mission and St. Ignatius ice, has given them similar clay mineralogic compositions.

Jocko diamictons. Four samples of Jocko diamictons and one sample of associated lacustrine(?) silt were analyzed for their clay mineral composition. All samples of diamicton are strongly oxidized, while the lake(?) silt (sample VC-7 , from between diamictons) at the Valley Creek section is oxidized only along joints. The bulk of this lake(?) silt is unweathered.

As in Mission and St. Ignatius tills, sample VC-7 contains approximately equal proportions of illite and chlorite-kaolinite(?) (Appendix C). Smectite occurs in an amount comparable to that of fresh Mission till. Quartz is a minor component; calcite is absent.

Patterns of the strongly oxidized diamictons all confirm the presence of illite and chlorite-kaolinite(?), albeit in small amounts. The dominant clay mineral in the oxidized diamictons is smectite.

The illite and chlorite-kaolinite(?) present in the diamictons and lake(?) silt were probably derived from Precambrian Belt rocks. Some of the smectite in the Jocko diamicton was presumably derived from Tertiary sediments, while some is the product of weathering. The similarity of clay mineral composition of the unweathered Jocko lake(?) silt and Mission till is striking. This suggests that the original clay mineral composition of the Jocko diamictons, before weathering, was similar to the Mission till. The increased smectite in the Jocko diamictons could be due to weathering. It is also possible that fresh, unoxidized Jocko diamictons could contain a greater relative amount of smectite than the Flathead Valley tills, which would be indicative of the incorporation of more Tertiary sediments into the Jocko diamictons than in either the Mission or St. Ignatius tills.

The clay mineralogic suite of the Jocko diamictons does indicate that they were deposited by a transporting medium capable of incorporating both Precambrian Belt rocks and Tertiary sediments. The clay mineral suite cannot be used to reconstruct the source area of the diamictons, since Belt rocks and Tertiary sediments are found in every direction from the outcrops of Jocko diamictons in the northern Jocko Valley.

Microscopic Examination of Sand Fraction

At the outset of the study, it was hoped that heavy mineral analyses might also be an aid in "fingerprinting" Pleistocene stratigraphic units. Upon completion of sieving, examination of the sand fraction revealed only a minor amount of heavy minerals present, an amount insufficient for heavy mineral analysis. Thus, a microscopic examination of sand lithologies was substituted for heavy mineral analysis. Since the fine sand fraction contained only rock fragments and quartz, a coarse sand size fraction was chosen for examination. The larger grain size also made lithologic identifications simpler. Grain lithologic counts were made, using the particles remaining on the #18 mesh screen (U.S.

Standard Sieve size). Counts were made on eleven representative samples; seven from Mission till, two from St. Ignatius till, and two from Jocko diamictons. Approximately 300 grains were counted for each sample.

The rock types recognized in the deposits of the southern Flathead Valley are grouped into seven categories: 1) gray-brown argillaceous limestone; 2) tan sandstone; 3) yellowish-white quartzite and argillite; 4) green quartzite and argillite; 5) gray quartzite and argillite; 6) purple and purplish-red quartzite; and 7) purple and purplish-red argillite. All lithologies are from the Precambrian Belt Series metasediments, with the possible exception of the tan friable sandstone. It may have been derived from Tertiary sediments underlying glacial sediments on the floor of the southern Flathead Valley.

The following is a summary of the lithologies present in the sand fraction of Mission till, St. Ignatius till, and Jocko diamictions. Individual sample data is given in Appendix D.

Mission till. All of the grains examined in Mission till are fresh and unoxidized. Many limestone grains have an etched appearance, but etched limestone occurs in fresh Mission till as well, indicating that at least some etching is pre-glacial. Two of the till samples examined were from "late" Mission till, and five were from "earlier" Mission till. The two Mission units could not be differentiated by lithologic composition of sand grains.

The predominant lithologic group present in most samples of Mission till is the dark gray quartzite and argillite. Most of the grains in this group are highly calcareous argillite, with quartzite only composing about 10 percent of the gray lithologic group. Gray quartzite and argillite grains range from 20 percent - 31 percent in abundance.

Nearly as abundant as the gray quartzites and argillites are grains of the tan friable sandstone. It is easily recognized by its rounded shape, non-calcareous nature, and micaceous glitter. It ranges from 16 percent - 25 percent in abundance in the Mission till.

Another lithologic group quiet abundant in Mission till is the yellowish-white quartzite and argillite. Approximately 80 percent of the grains in this group are quartzite. Color ranges from clear to white to yellow; all grains are non-calcareous. Abundance ranges from 9 percent to 21 percent.

Purple and purplish-red quartzites, and purple and purplish-red argillites occur in approximately equal amount in the Mission till. While the quartzites are non-calcareous, the argillites are slightly to moderately calcareous. Quartzites range from 3 percent to 14 percent in abundance in the total sample, while argillites compose from 5 percent - 13 percent of the Mission till.

Gray brown argillaceous limestone grains compose about 10 percent of the grains in Mission till. The patchy distribution of argillaceous material within the limestone gives the carbonate an etched appearance, due to increased weathering along the highly calcareous sections of the grains. Much of the argillite in the gray argillite and quartzite group may have originally been within argillaceous limestone fragments, thus derived from limestone lithologies. Limestone grains range from 7 percent - 15 percent in abundance in the Mission till.

Green quartzite and argillite ranges from 6 percent - 12 percent in abundance. Non-calcareous quartzite makes up only about 25 percent of the green lithologies, with the slightly calcareous argillite being far more abundant.

St. Ignatius till. Grain counts from St. Ignatius till are quite similar to those from Mission till. All of the lithologies previously described from the Mission till occur in the St. Ignatius till. Grain counts of all seven lithologic types, from samples of St. Ignatius till, fall within the range present in the Mission tills. Therefore the two stratigraphic units are indistinguishable based solely upon lithologic grain counts. Slight oxidation of limestone, sandstone, and some argillite grains occurs in the St. Igantius till, but the quartzites are virtually fresh and unoxidized..

The gray quartzite and argillite group is the most abundant (25%) in the St. Ignatius till, as it was in the Mission till. Tan sandstone is again the next most abundant lithology (18%). Purple and purplish-red argillite is slightly more abundant in St. Ignatius till than in Mission till. All other lithologies are similar in abundance to the Mission till.

Jocko diamictons. Although the relative percentages of the seven lithologic groups present in the Jocko diamictons are different from the Mission and St. Ignatius tills, grains of at least six of the seven groups are present. Limestone grains similar to those in the Mission and St. Ignatius tills do not occur (discussed below). Strong oxidation of argillite and sandstone grains is indicative of a prolonged period of weathering. Even the matrix of many quartzite grains is slightly oxidized, giving the grains a pitted appearance.

Gray quartzite and argillite grains compose just over 50 percent of the grains counted in the Jocko diamictons. The etched appearance of many of the gray argillite fragments identified in the Jocko diamictons suggest that they are remnants of the weathering and dissolution of the calcareous portions of the gray-brown argillaceous limestone. The presence of numerous etched cobbles and boulders in the Jocko diamictons supports this interpretation. Thus, the sand fraction of unweathered Jocko diamicton presumably contained all seven of the lithologic types found in the other southern Flathead Valley tills.

Green quartzites and argillites are less abundant in the Jocko diamictons than in the Mission and St. Ignatius tills, as are purple and purplish-red quartzites and argillites. Yellowish-white quartzites and argillites are just slightly less abundant in the Jocko diamictons, while tan friable sandstone fragments are as abundant as in the other Flathead Valley tills.

Conclusions. The sand fractions of Mission till, St. Ignatius till, and Jocko diamictons contain grains of seven lithologic groups, detrital components derived from Precambrian Belt rocks and Tertiary sediments. Similar sand fraction lithologic compositions prohibit the differentiation of "late" and "earlier" Mission tills. Nor can St. Ignatius till be distinguished from Mission till. Variations in the relative percentages of the lithologies present in the Jocko diamictons make it distinguishable from Mission and St. Ignatius tills. However, the relationship is complicated by the comparison of highly weathered Jocko diamictons to only slightly weathered Mission and St. Ignatius tills. Original unaltered Jocko diamictons presumably had sand fraction lithologic compositions comparable to those of the Mission and St. Ignatius tills.

CHAPTER V

CONCLUSIONS AND CORRELATION WITH ESTABLISHED CHRONOLOGIES

Conclusions

Sedimentary petrologic laboratory studies were used to "fingerprint" Pleistocene stratigraphic units in the southern Flathead Valley. Mission till, St. Ignatius till, and Jocko diamictons could not be differentiated by grain size analyses, clay mineralogy, or microscopic examination of sand grain lithologies.

Field evidence and relative age dating techniques show that Mission till is the youngest of the three stratigraphic units studied in the southern Falthead Valley. St. Ignatius till is older and Jocko diamictons are oldest. Field observations indicate that Mission till was deposited by two distinct stands of ice (Figure 5). Moderate soil development, a fresh glacial kettle topography, and a non-intergrated drainage pattern all indicate that "late" Mission till is young. Stratigraphic relationships suggest that "late" Mission till was deposited by ice of a recessional phase of the ice which deposited "earlier" Mission till. Deeper soil development and a better developed surface drainage pattern on St. Ignatius till, show that it is significantly older than Mission till. Strong oxidation and deep weathering of a thick section of Jocko diamictons indicate that the diamictons are substantially older than either Mission or St. Ignatius tills.

The association of striated pebbles, silt and gravel beds within the Jocko diamictons, the clay mineralogic composition, and the great variation of sand and gravel lithologies, all suggest that the Jocko diamictons are glacial tills. They record an old ice advance from an undefined source area. Jocko diamictons could have been deposited by ice of the Flathead lobe of the Cordilleran ice sheet, by ice from alpine glaciers in the Mission or Jocko Ranges, or by ice from a glacier originating on Squaw Peak to the southwest (Figures 4 and 5).

Correlation With Established Chronologies

Radiocarbon dates obtained in this study have failed to delineate the absolute ages of the three stratigraphic units studied. Therefore, correlation with other established glacial chronologies remains tentative.

The age of "late" Mission till in the southern Flathead Valley is fairly well defined by geomorphic criteria and an open-ended radiocarbon date. The youthful constructional topography on the surface of the Mission moraine, combined with a >20,380 year B.P. date from near the top of the moraine, suggest deposition of "late" Mission till during the last major glaciation. Correlation with Easterbrook's (1969) Vashon stade of the Fraser glaciation in western Washington seems likely. Correlation with Richmond's (1965) 23,150 ± 1,000 B.P. Rocky Mountain ice advance of the early stade of the Pinedale glaciation is also suggested, but correlation with Pierce's (1976) 30,000 year B.P. early Pinedale advance cannot be ruled out. Synchroneity with early Woodfordian (William, 1970) mid-continental glaciation is suspected.

The absence of paleosols and unconformities in the Mission till sequence suggest that "earlier" Mission till was deposited by ice of the same Cordilleran ice advance which deposited "late" Mission till. However, lack of absolute age dates and surficial geomorphic criteria prohibit verification. It remains possible that the Mission moraine is a composite moraine composed of tills deposited during more than one glaciation, as suggested by Curry (1977), although no evidence was found to support this theory.

A more mature land surface and stronger soil development both suggest that St. Ignatius till is significantly older than Mission till. It is difficult to estimate the relative age of the St. Ignatius till, since much of the surface in the area covered by St. Ignatius till was apparently reworked by Glacial Lake Missoula floodwaters. While the flat to gently rolling topography characteristic of the St. Ignatius till suggests correlation with pre-Bull Lake glaciations, the lack of a deep soil profile and intense weathering of cobbles and boulders, plus the presence of carbonate cobbles imply a younger age. For these reasons, the age of the St. Ignatius till is believed to correspond with Richmond's (1976) early stade of the Bull Lake glaciation (Figure 7) and/or to Easterbrook's (1969) Salmon Springs glaciation, as revised by Fulton (1971), Clague (1978), and Alley (1979) (Figure 6). These glaciations correspond to early Wisconsinan (Altonian) glaciations on the mid-continent (Willman, 1970).

Strong oxidation and moderate weathering of clasts in the Jocko diamictons are indicative of their antiquity. It is apparent that the Jocko diamictons are substantially older than the infinite radiocarbon date of >37,000 years B.P. obtained from a lignitic wood fragment from the base of the uppermost Jocko diamicton. However, no evidence is available to allow estimation of the absolute age of the Jocko diamictons. It is obvious that the Jocko diamictons are pre-Wisconsinan (pre-Bull Lake) in age, but correlations with other pre-Wisconsinan (or pre-Bull Lake) glaciations would be purely speculative.

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APPENDIX A

DETAILED DESCRIPTIONS OF REPRESENTATIVE FIELD SECTIONS

(See Figure 5, page 8)

SECTION 1

East end of Lower Crow Reservoir.
SW SE SW Section 7, Twp 20N, Rge 20W.

2.0 m	silty clay loam till; yellowish-brown (10YR5/4); strongly calcareous; massive; etched carbonate pebbles abundant.	Sample LCR-4
10cm	silty clay; brown (10YR 5/3); massive	
20m	very fine sand; brown (10YR 5/3); well sorted; cross-beds sip southeasterly	Sample LCR-3
1.5m	gravel; dark yellowish-brown (10YR 4/4); clean and openwork; strongly calcareous; minor medium-gravel sand lenses interbedded; cross-beds in sand lenses dip south.	Sample LCR-2
?	silty clay loam till; brown (10YR 5/3); strongly calcareous; massive; etched carbonate pebbles common.	Sample LCR-1

Base of Section

SECTION 2

Junction of Crow Creek and Flathead River.
SE SE SW Section 21, Twp 20N, Rge 21W.

10.0m	silty clay loam till; yellowish-brown (10YR 5/4); strongly calcareous; massive; etched carbonate pebbles common.	Sample MCC-1
7.5m	very fine sand; brown (10YR 5/3); strongly calcareous; interbedded with thin lenses of silty clay; cross-beds in sand dip south and west.	Sample MCC-2
?	silty clay loam till; yellowish-brown (10YR 5/4); strongly calcareous; massive.	Sample MCC-3

Base of Section

SECTION 3

Crow Creek Canyon
NW SE SE Section 21, Twp 20N, Rge 21W.

0.5m	fine gravel to cobbles; clean and openwork; fair to poor sorting; subrounded to subangular; contains lenses of well sorted cobbles.	
1.0m	silty clay; brown (10YR 5/3); varved; contains dropstones	
3.0m	silty clay loam till; yellowish-brown (10YR 5/4); strongly calcareous; massive	Sample CCC-5
1.0m	silty clay; brown (10YR 5/3) strongly calcareous; massive; occasional dropstone.	Sample CCC-4
1.0m	gravel; dark yellowish brown (10YR 4/4); clean and openwork gravel as above.	Sample CCC-3
3.0m	silty clay; brown (10YR 5/3); strongly calcareous; massive; occasional dropstone.	
2.0m	gravel; similar to above; cross-beds dip southwesterly.	
6.0m	silty clay loam till; yellowish-brown (10YR 5/4); strongly calcareous; massive.	Sample CCC-2
0.5m	stilty clay; brown (10YR 5/3); massive	
?	silt till; brown (10YR 5/3); contains discontinuous lenses of silty clay and poorly sorted gravel.	Sample CCC-1

- -

Base of Section

SECTION 4

Flathead River Bluff section.
SE SE NE Section 19, Twp 21N, Rge 21W.

2.5m	silty clay; brown (10YR 5/3); massive; scattered pebbles.	
~ 20.0m	silty clay loam till; yellowish-brown (10YR 5/4); strongly calcareous; massive.	Sample FRF-15
2.0m	silty clay; yellowish-brown (10YR 5/4); varved; contains dropstones.	Sample FRF-16
~ 20.0m	silty clay loam till; brown (10YR 5/3); strongly calcareous; massive	Sample FRF-17
1.5m	silty clay; brown (10YR 5/3); varved; contains scattered dropstones.	
~ 20.0m	silty clay loam till; yellowish-brown (10YR 5/4); strongly calcareous; massive.	Sample FRF-18

Base of Section

SECTION 5

Flathead River -- canyon section.
SW NE NW Section 20, Twp 21N, Rge 21W.

5.0m	silty clay; yellowish-brown (10YR 5/4); strongly calcareous; thin-bedded (5-10cm); contains striated pebble dropstones.	Sample FRF-10
6.0m	silty clay loam till; brown (10YR 5/3); strongly calcareous; massive.	Sample FRF-11
2.5m	clay; brown (7.5YR 5/4); thin-bedded; occasional dropstone.	Sample FRF-12
6.0m	silty clay loam till; brown (10YR 5/3); strongly calcareous; massive.	Sample FRF-13
2.0m	silty clay; brown (10YR 5/3); strongly calcareous; massive; occasional dropstone.	
1.5m	cobbly gravel; clean and openwork; poorly sorted; continuous horizon throughout the canyon.	
?	silty clay loam till; brown (10YR 5/3); strongly calcareous; massive.	Sample FRF-14

- -

Base of Section

SECTION 6

Dublin Gulch landslide section.
SE NW SW Section 20, Twp 19N, Rge 20W.

20cm	silt; dark grayish-brown; high organic content; soil development on loess.	
2.0m	clayey silt; reddish-brown (5YR 5/3); slightly calcareous; varves; contains abundant dropstones; contains a few thin (5-10) gravel lenses; base of soil in this unit.	Sample DGL-1
1.0m	interbedded fine sand and silt; brown (10YR 5/3); fine-grained sand contains cross-beds dipping to south; a thin (30cm) discontinuous till (?) lens lies within this unit, sample DGL-4 from the till (?).	Sample DGL-2 Sample DGL-4
70cm	cobbly, gravelly loam; poorly sorted mixture of pea gravel and cobbles in a sandy silt matrix; discontinuous; gran size coarsens toward base; dark yellow-brown (10YR 4/4); strongly calcareous.	Sample DGL-3
?	silty clay loam till; yellowish-brown (10YR 5/4); strongly calcareous; massive.	Sample DGL-5

Base of Section

SECTION 7

Dublin Gulch Highway and RR section.
SW SW SW Section 20, Twp 19N, Rge 20W.

4.0m	silty clay loam till; yellowish-brown (10YR 5/4); strongly calcareous; massive.	Sample DGH-1
30-50 cm	silt loam; brown (10YR 5/3); massive; contains thin lenses of festoon-type cross-bedded sands, cross-beds dip predominantly south; silt unit contains scattered dropstones.	Sample DGH-2
20cm	medium-grained sand; brown (10YR 5/3); well-sorted; contains scattered gravel; clean and openwork.	
40cm	coarse sand and gravel; brown (10YR 5/3); rounded to subrounded; also contains rounded clay balls; aand is clean and openwork; organic fragments are common.	
50cm	cobbly sand and gravel; brown (10YR 5/3); abundant large cobbles, especially near base; rounded to subrounded; clean and openwork; also contains rounded clay balls; no bedding evident; grades eastward into a dirty matrix - supported cobbly gravel (Sample DGH-5).	Sample DGH-5
?	silty clay loam till; yellowish-brown (10YR 5/4); strongly calcareous; massive; a 0-10 cm thick (discontinuous) oxidized zone occurs on the surface of this till, probably a groundwater effect; samples DGH-3 and DGH-6 from oxidized till samples DGH-4 and DGH-7 from unaltered till.	Sample DGH-3 Sample DGH-4 Sample DGH-6 Sample DGH-7

Base of Section

SECTION 8

Valley Creek section
SW NE SW Section 8, Twp 17N, Rge 20W

Normal faults, with as much as 0.5m of offset, occur in this section. These faults cannot be traced above the base of the upper diamicton.

?	*clayey silt*; brown (10YR 5/3); varved lacustrine silt with dropstones; unoxidized; calcareous; a few large chunks of wood scattered throughout the silt; this silt is presumably of Lake Missoula origin.	
0.0-2.0m	*clayey silt*; yellowish-brown (2.5Y 5/4); contains scattered cobbles and boulders; massive to faintly laminated; discontinuous poorly sorted gravel lenses scattered through the silt unit, silt is noncalcareous.	Sample VC-10
7.0-9.0m	*silty clay loam diamicton*; yellowish-brown (10YR 4.5/4); non-calcareous; contains abundant rounded to subangular gravel and cobbles; lignitic wood fragments scattered randomly throughout the diamicton; considerable relief on surface of this diamicton.	Sample VC-9 Sample VC-8
2.0m	*sandy silt*; light yellowish-brown (2.5Y 5.5/4); non-calcareous; massive; a 10cm thick gravel lens occurs in the middle of this unit; at the surface of this unit is a 10cm thick well-sorted, medium to coarse pea gravel.	Sample VC-7
1.5-2.0m	*silty clay*; yellowish-brown (10YR 5/4); non-calcareous; trace of gravel scattered throughout; a thin (5cm) but continuous marker bed of lignitic wood fragments occurs at the top of this unit; just below the wood horizon is a carbonate-cemented pea gravel.	Sample VC-6
75cm	*fine sand*; yellowish-brown (2.5Y 5/2); well sorted; non-calcareous.	Sample VC-5
50cm	*pea gravel*; poorly sorted with a sandy silt matrix; non-calcareous.	Sample VC-4

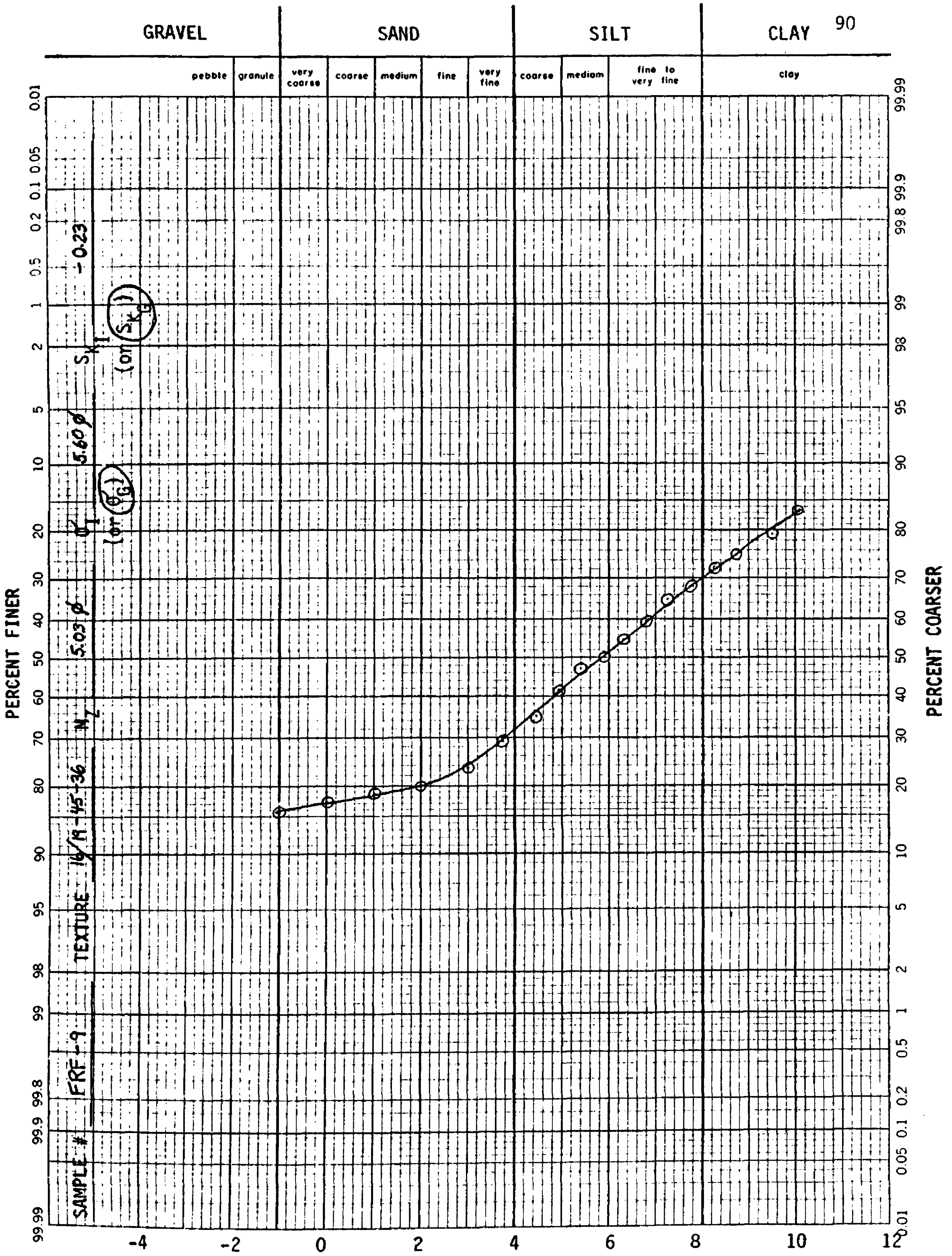
SECTION 8 (continued)

75cm	clayey silt; yellowish-brown (10YR 5/4) massive; non-calcareous.	Sample VC-3
2.0-2.5m	silty clay loam diamicton; brown (10YR 5/3); contains abundant gravel, pebbles and cobbles; strongly oxidized; clasts subangular to rounded; black lignitic wood fragments scattered throughout; non-calcareous.	Sample VC-2A Sample VC-2
1.0-2.0m	sandy silt; olive-gray (5Y 5/2); strong oxidation along joints, otherwise unaltered; lignitic wood fragments scattered throughout unit; noncalcareous	Sample VC-1
?	green sandy to clayey silt; massive; lignitic wood abundant; strongly oxidized; noncalcareous.	

Base of Section

APPENDIX B

GRAIN SIZE DISTRIBUTION CURVES



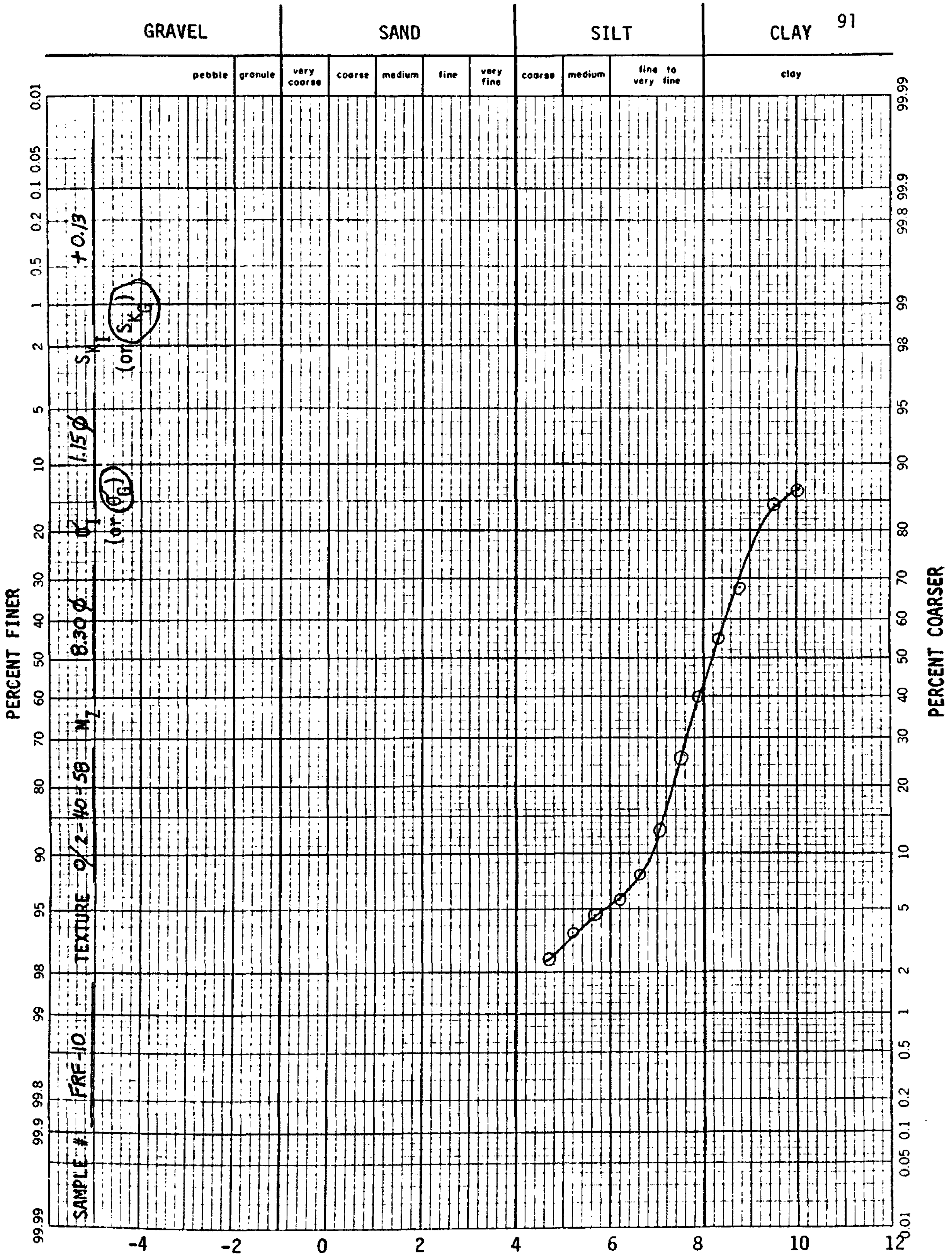
SAMPLE # FRE-9

TEXTURE 16/19-45-36

M_Z 5.03 φ

σ_I (or σ_G) 5.60 φ

Sk_I (or Sk_G) -0.23



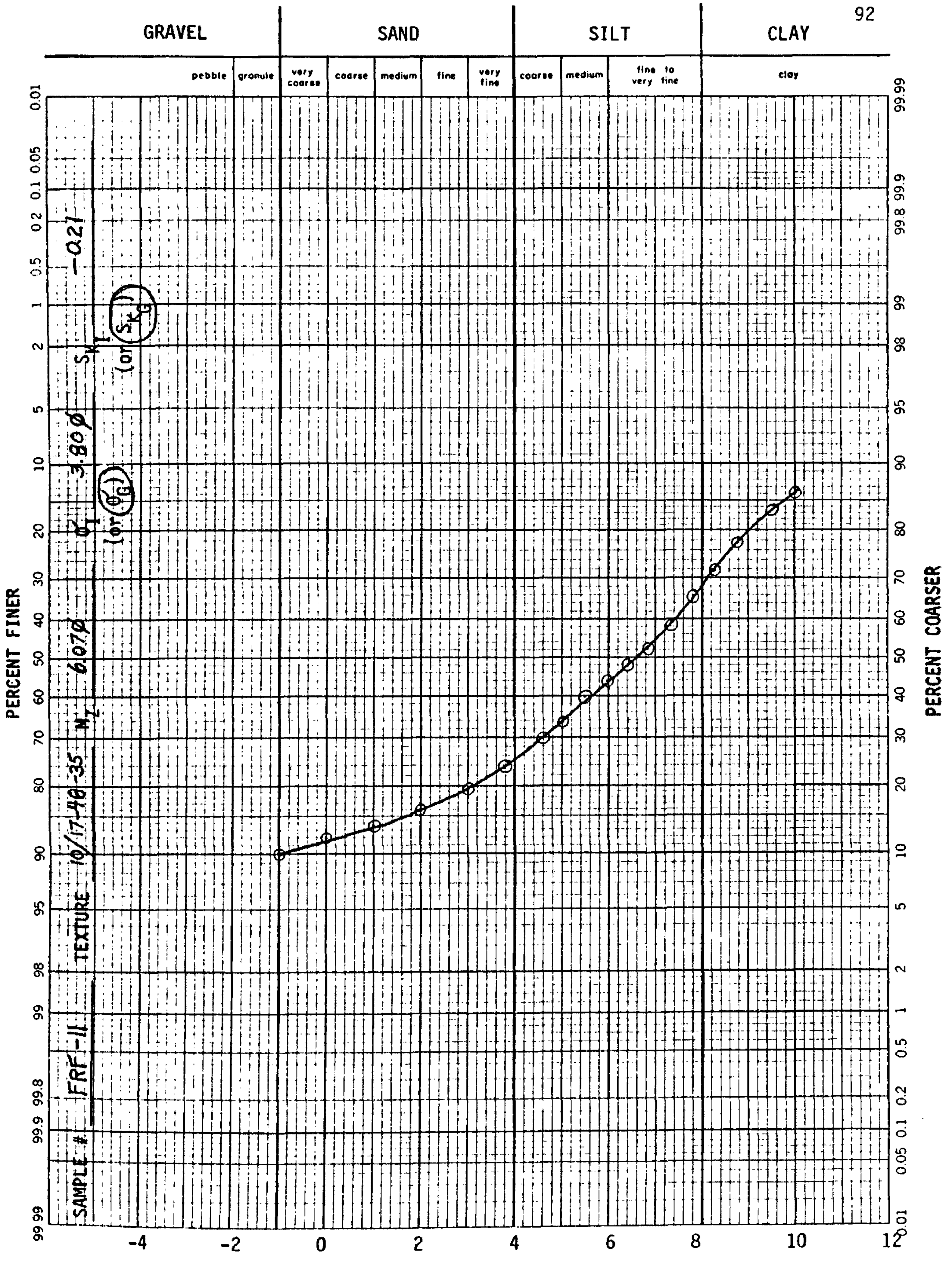
SAMPLE # FRF-10

TEXTURE 0/2-40-58

M_Z 8.30ϕ

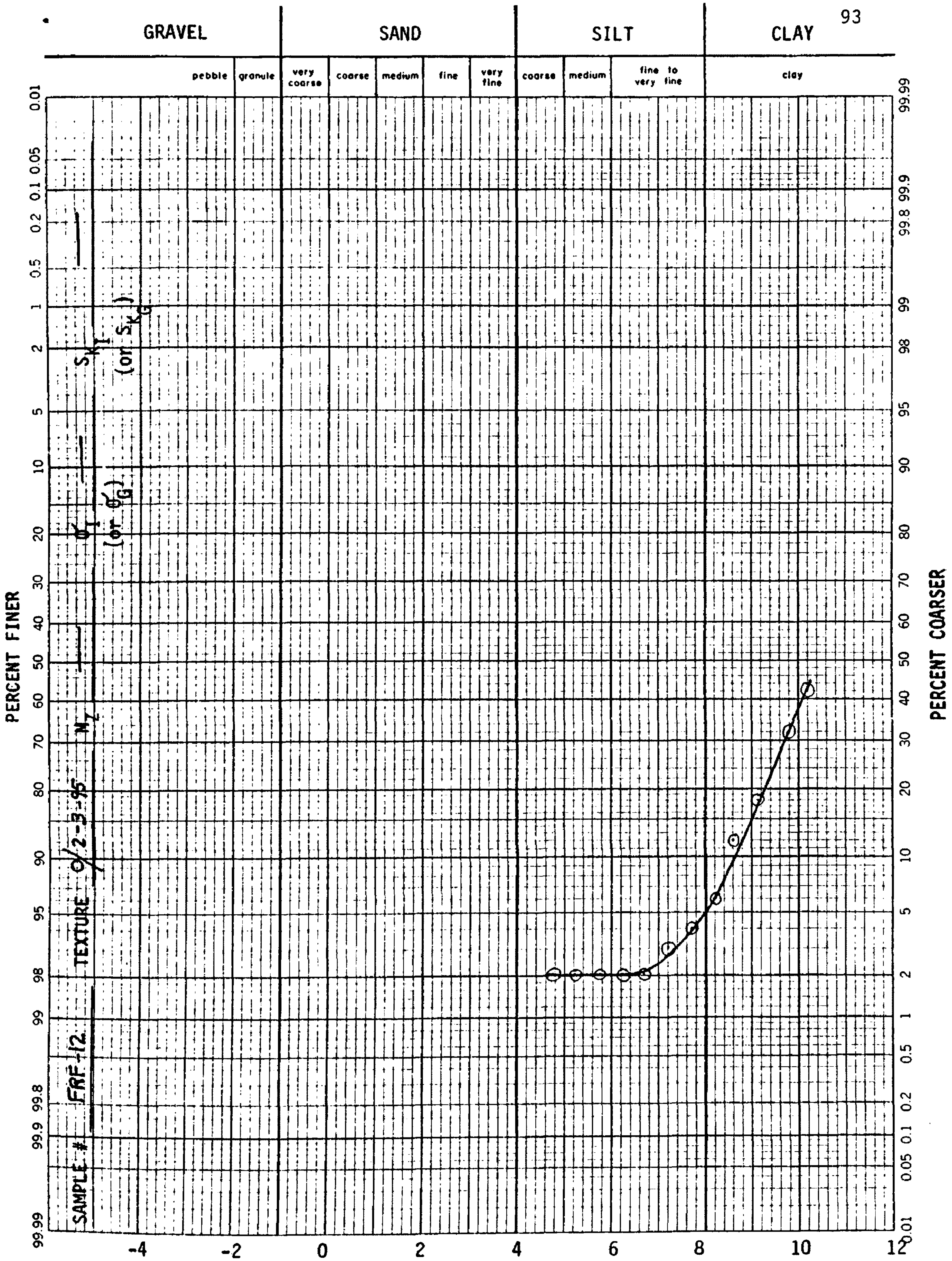
σ_I 1.15ϕ (or σ_G)

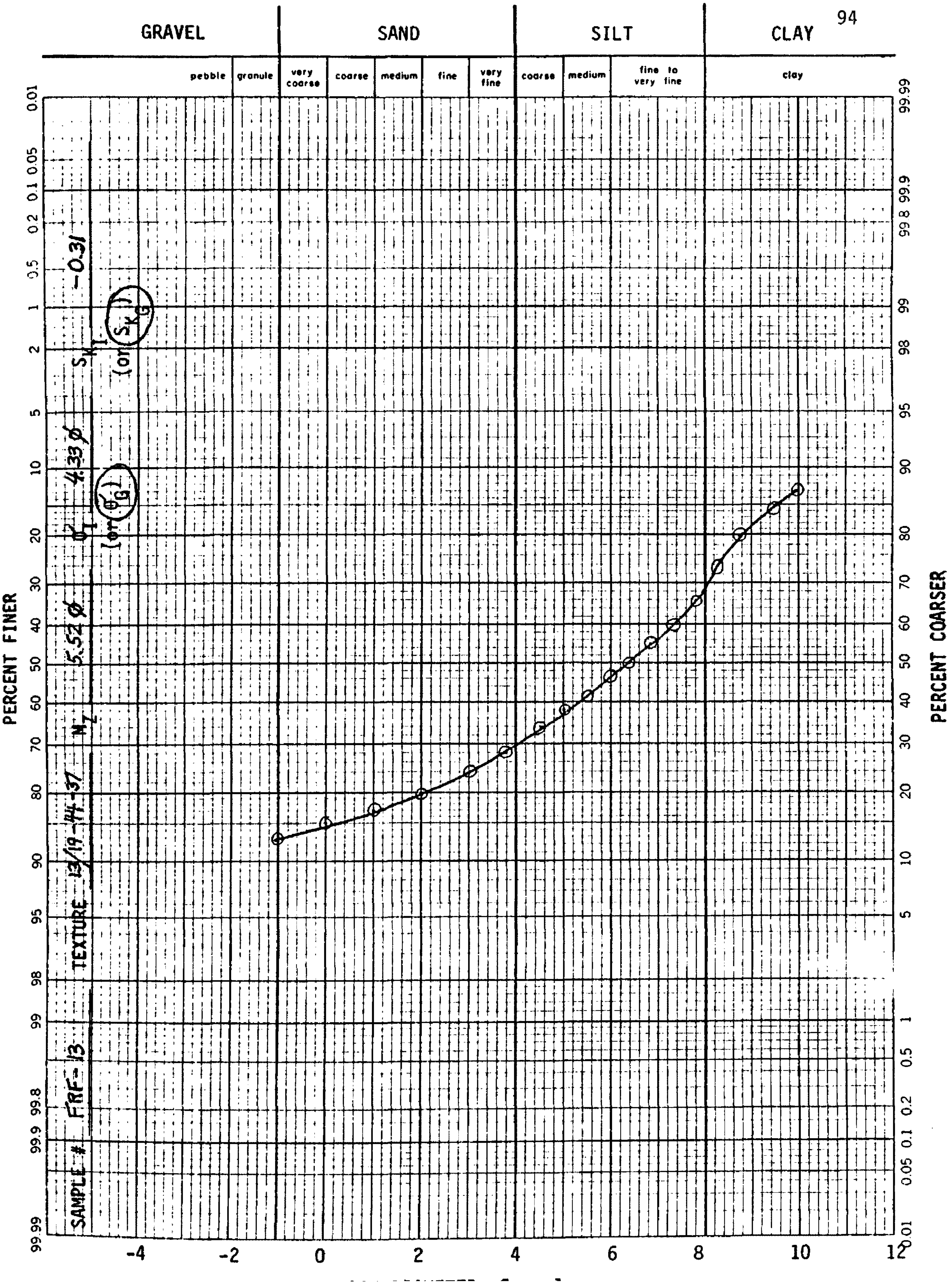
S_{K_I} +0.13 (or S_{K_G})



SAMPLE # FRF-11 TEXTURE 10/17-90-35 M_Z 6.07ø σ_I 3.80ø S_{K_I} -0.21

(or σ_G) (or S_{K_G})


GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12
SAMPLE # FRF-12
TEXTURE 0/2-3-95
M_Z
σ_I (or σ_G)
S_{K_I} (or S_{K_G})



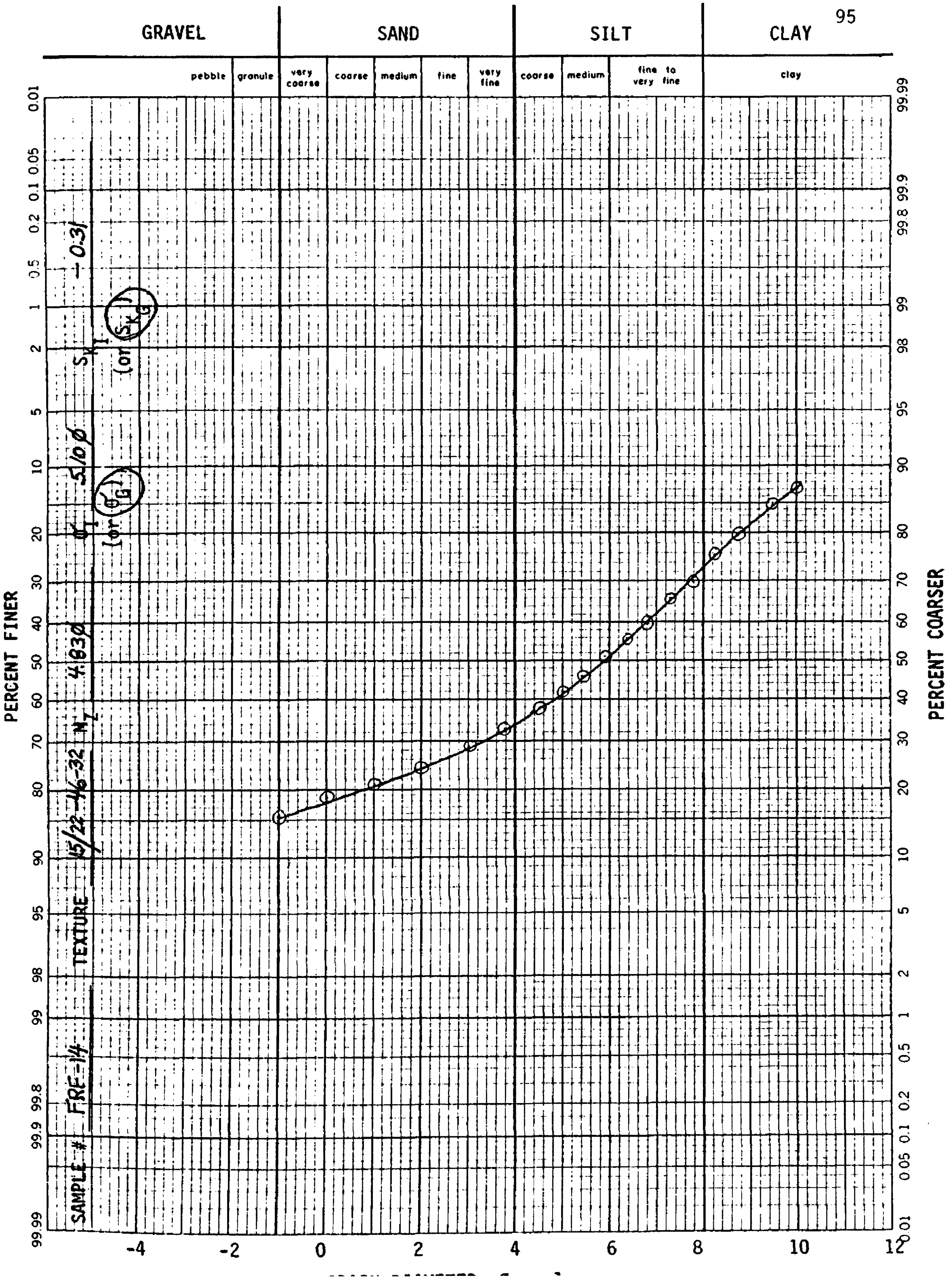
SAMPLE # FRF-13

TEXTURE 13/19-44-37

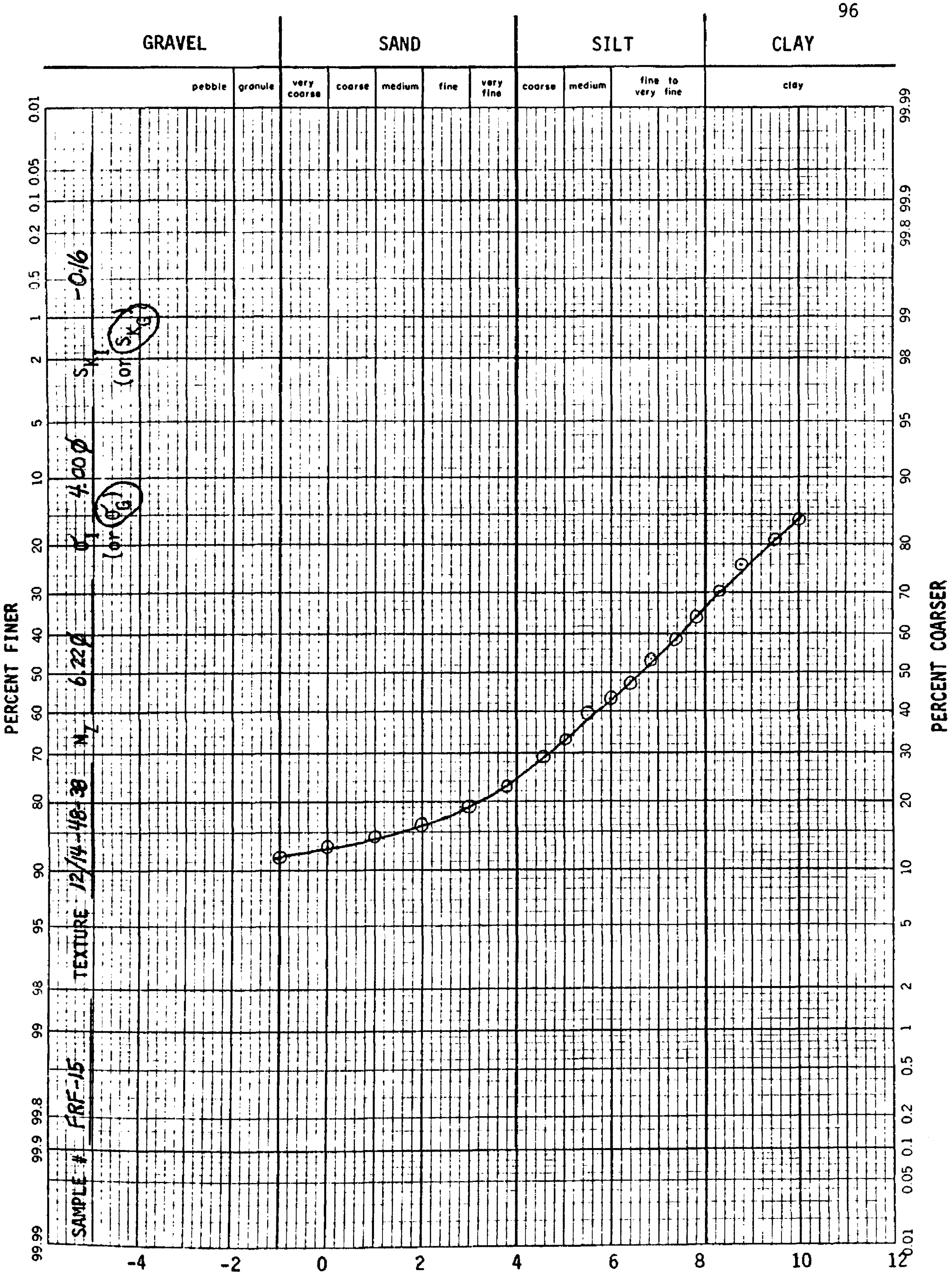
M_Z 5.52 Ø

σ_I 4.33 Ø (or σ_G)

S_{K_I} -0.31 (or S_{K_G})



SAMPLE # FRE-14 TEXTURE 15/22-46-32 M_Z 4.83ø σ_I (or σ_G) 5.10ø Sk_I (or Sk_G) -0.31



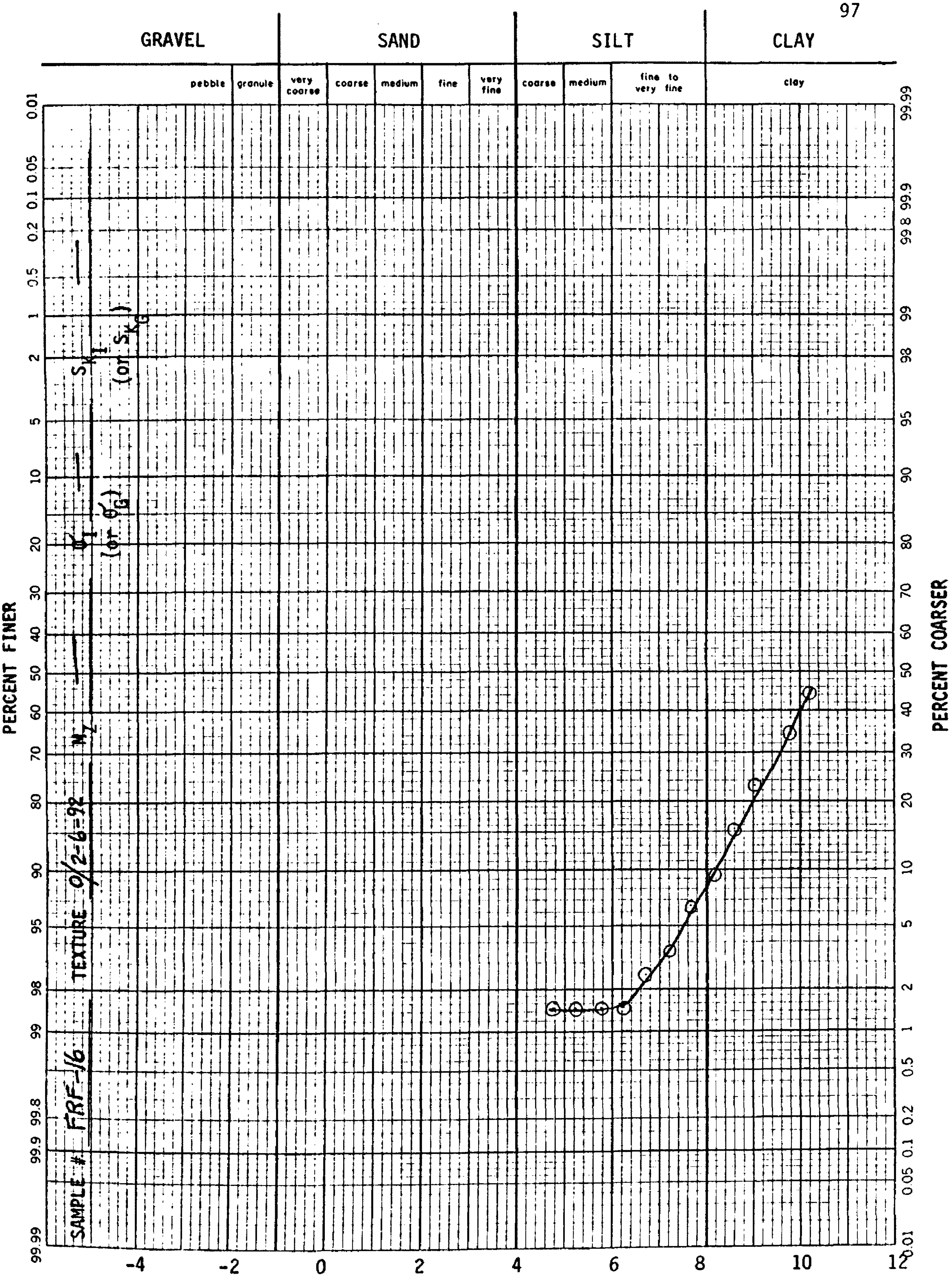
SAMPLE # FRF-15

TEXTURE 12/14-48-38

M_Z 6.22Ø

σ_I (or σ_G) 4.00Ø

Sk_I (or Sk_G) -0.16



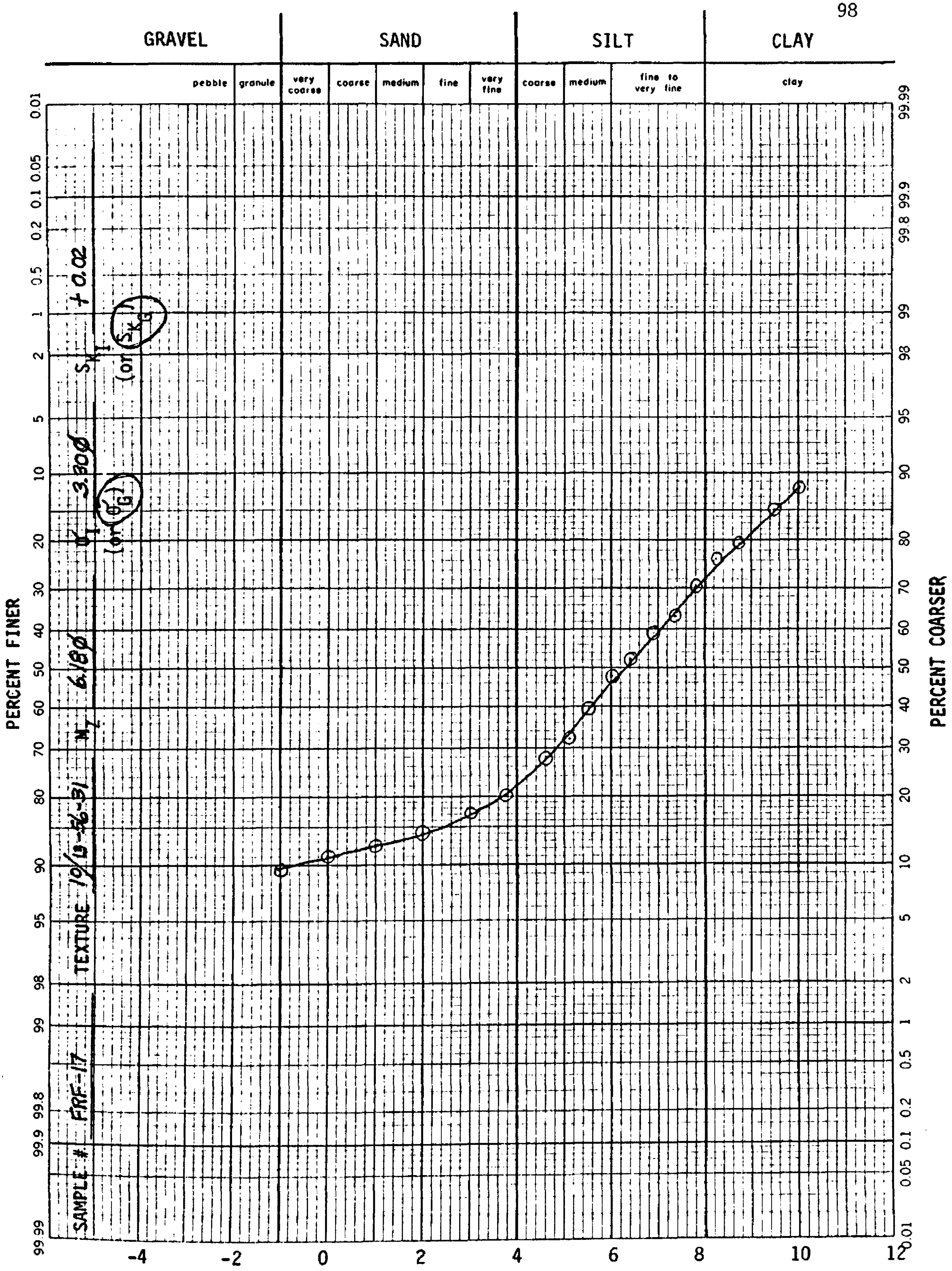
SAMPLE #: FRF-16

TEXTURE 0/2-6=92

M_Z ——

σ_I (or σ_G) ——

Sk_I (or Sk_G) ——



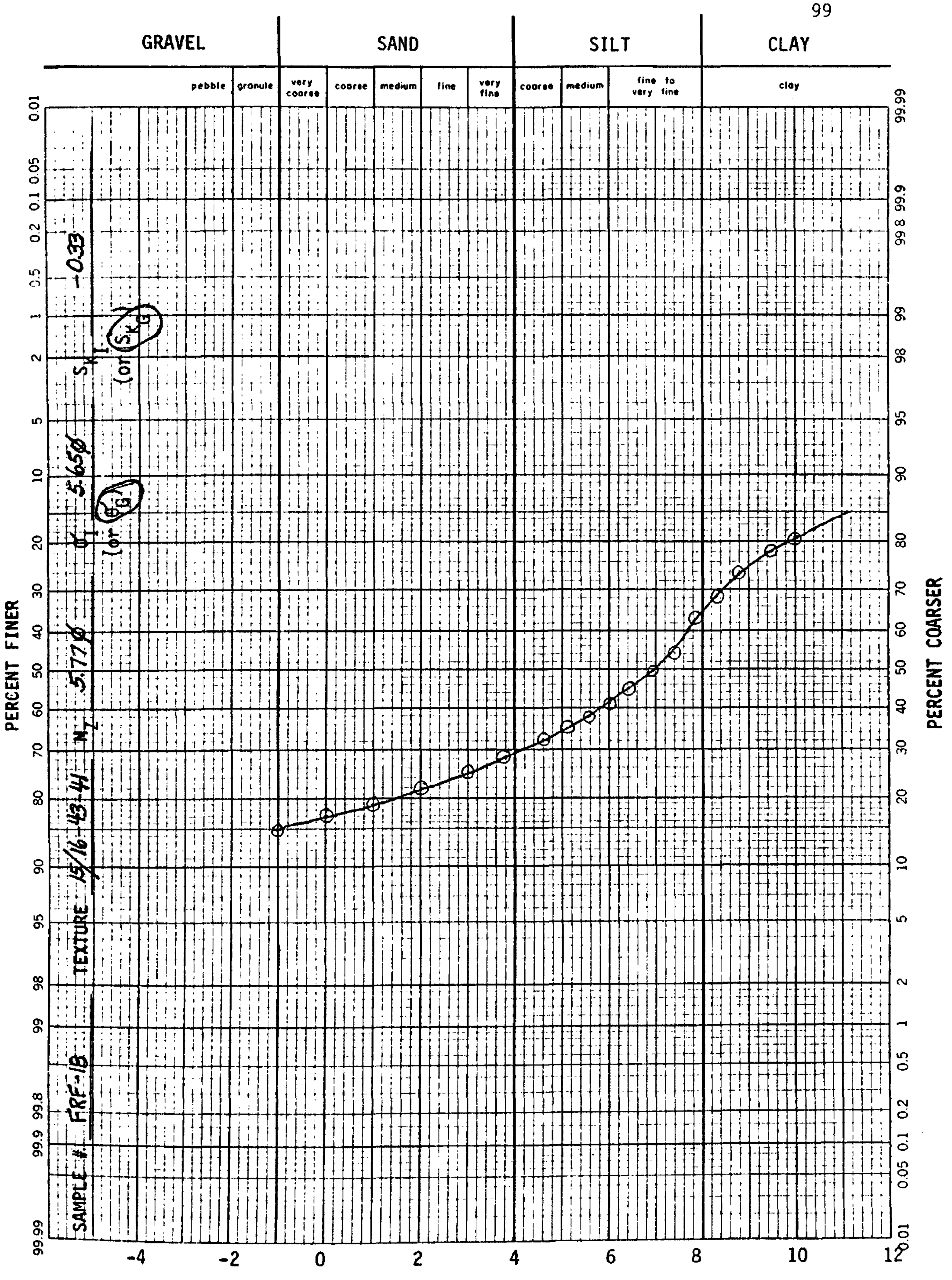
SAMPLE # FRF-17

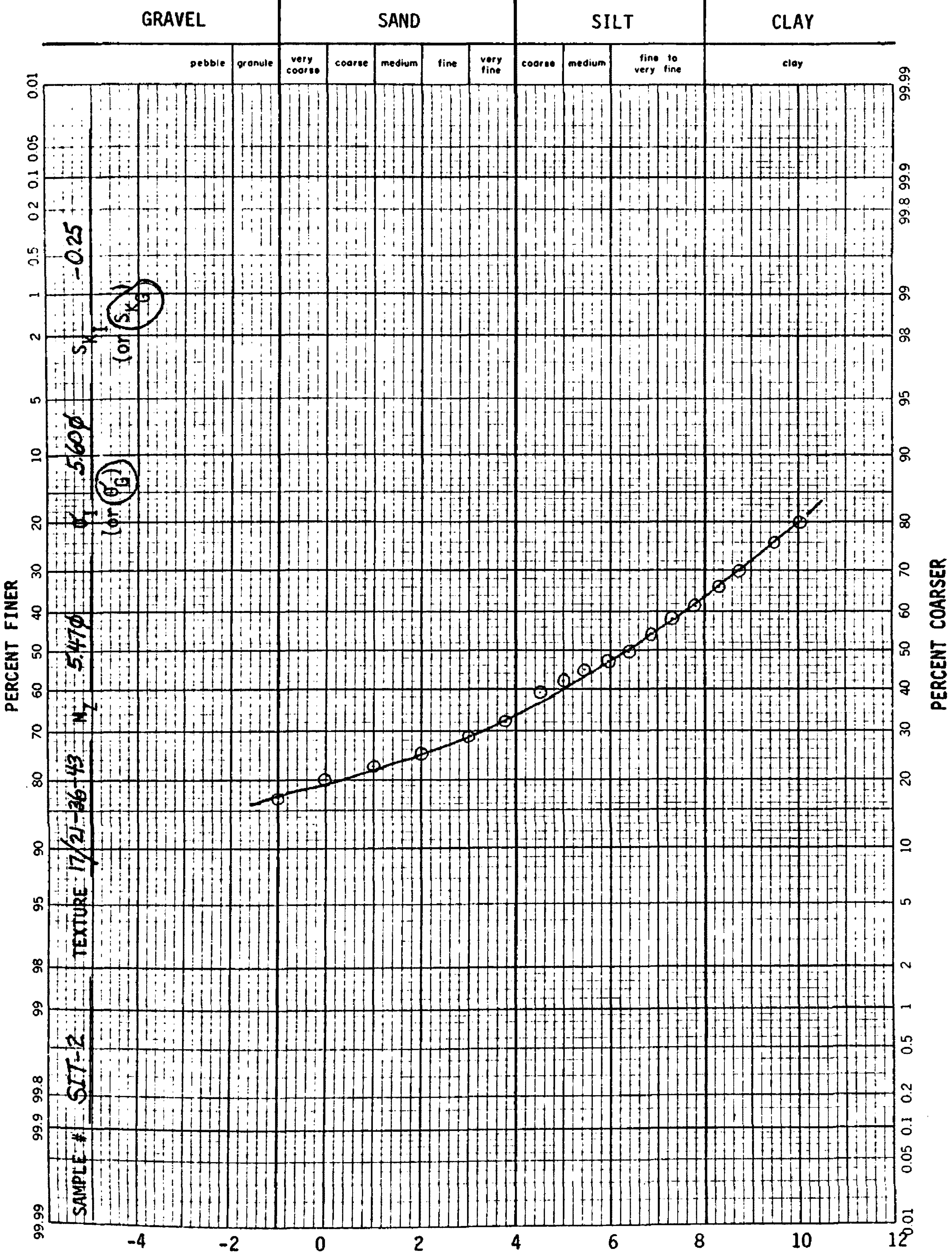
TEXTURE 10/13-56-31

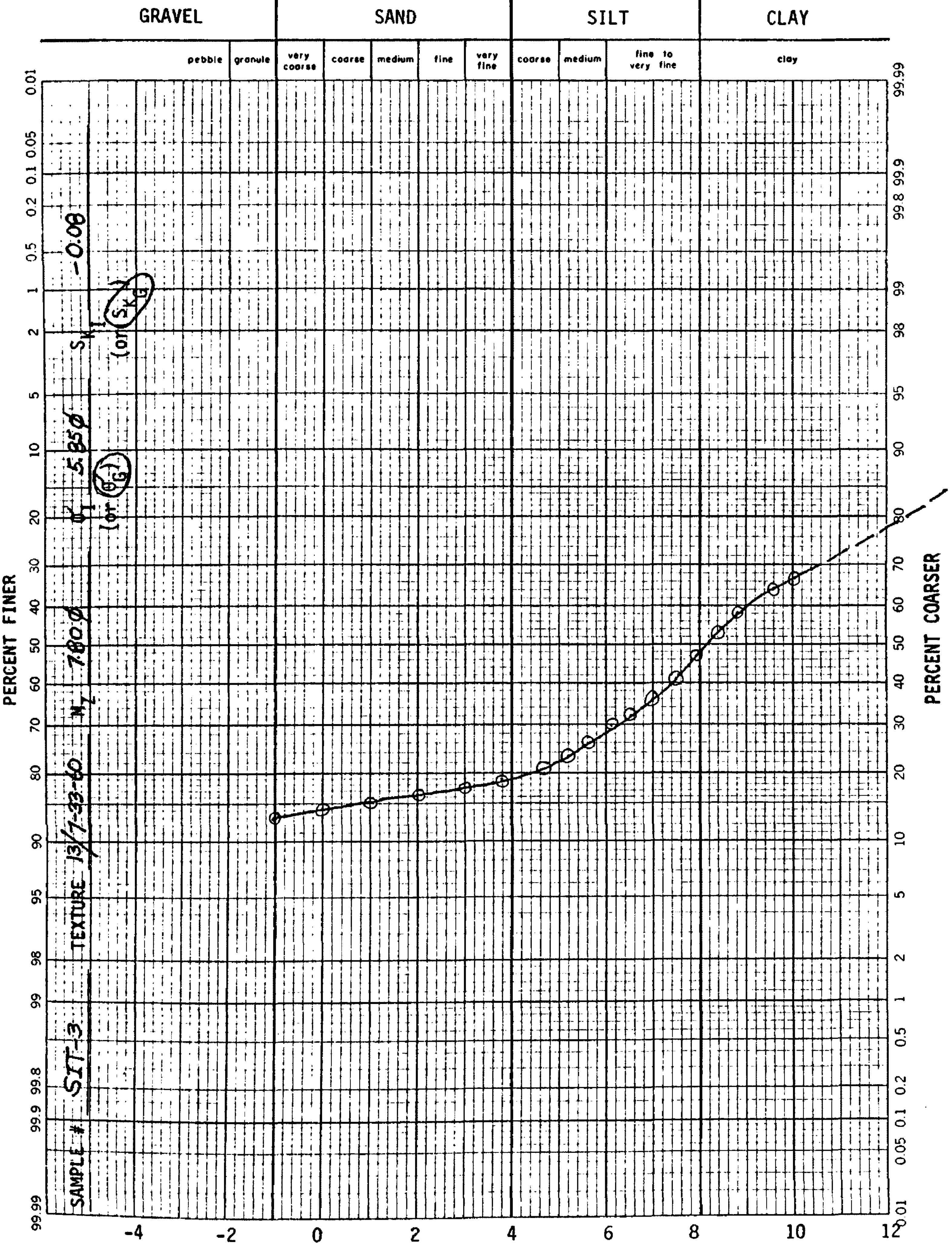
M_Z 6.18ϕ

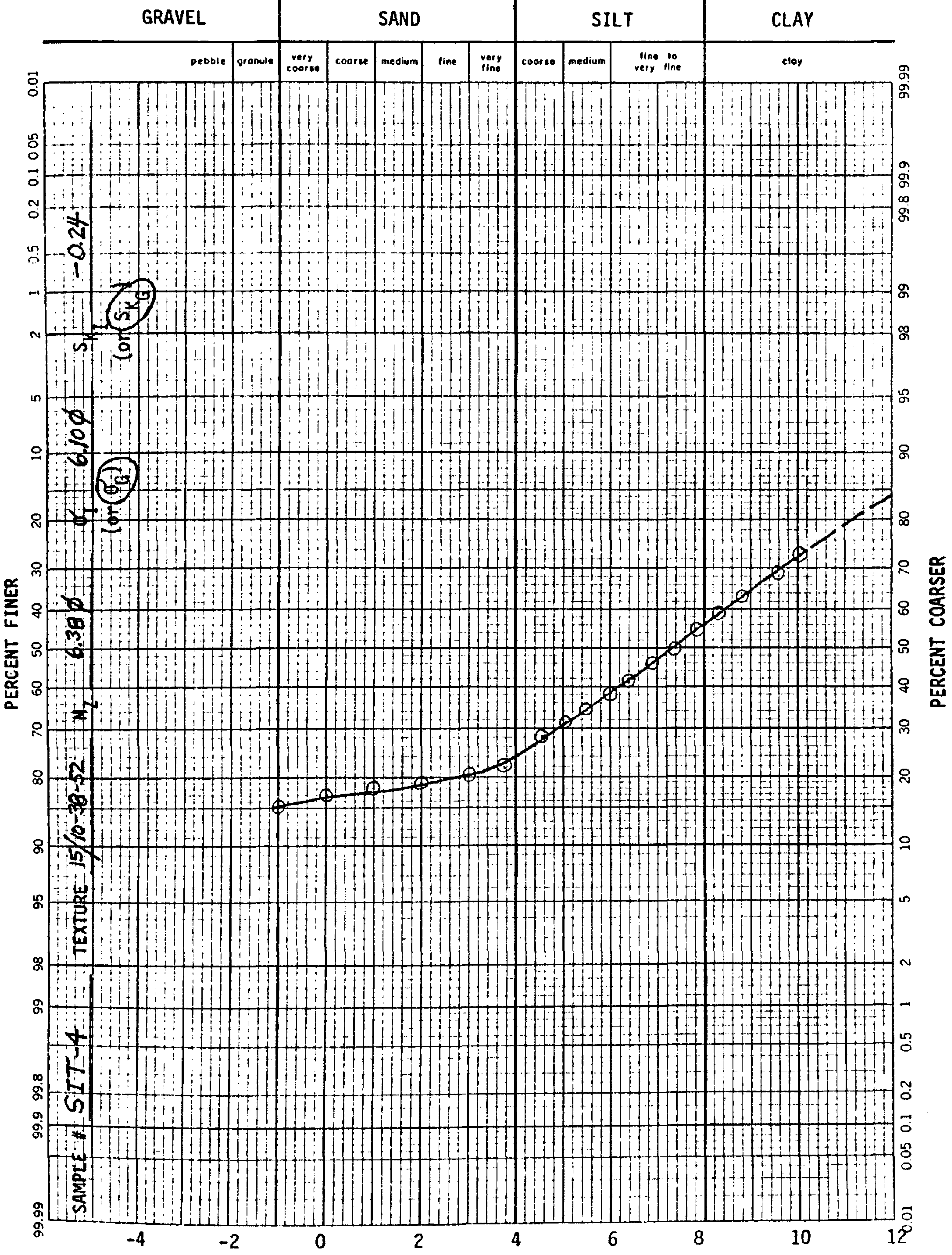
σ_I (or σ_G) 3.30ϕ

Sk_I (or Sk_G) +0.02


GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12
SAMPLE #. FRF-1B
TEXTURE 15/16-43-41
M_z 5.77∅
σ_I (or σ_G) 5.65∅
Sk_I (or Sk_G) -0.33


GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12
SAMPLE # SIT-2
TEXTURE 17/21-36-43
M_z 5.47φ
σ_I 5.60φ (or σ_G)
S_{k_I} -0.25 (or S_{k_G})


GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12
SAMPLE # SIT-3
TEXTURE 13/7-33-60
M_Z 7.80ϕ
σ_I 5.35ϕ (or σ_G)
Sk_I -0.08 (or Sk_G)



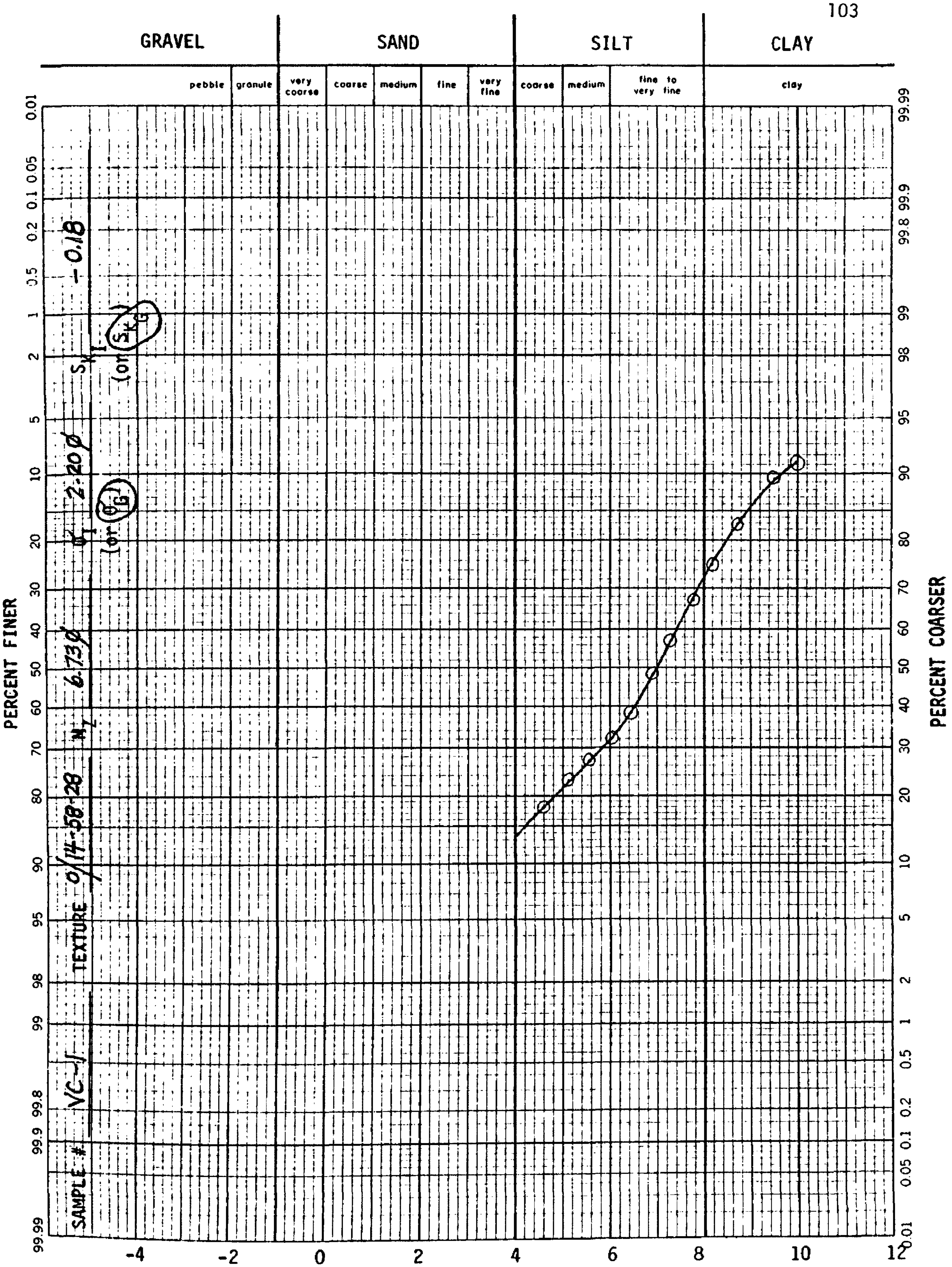
SAMPLE # SIT-4

TEXTURE 15/10-38-52

M_Z 6.38ϕ

σ_I 6.10ϕ (or σ_G)

Sk_I -0.24 (or Sk_G)



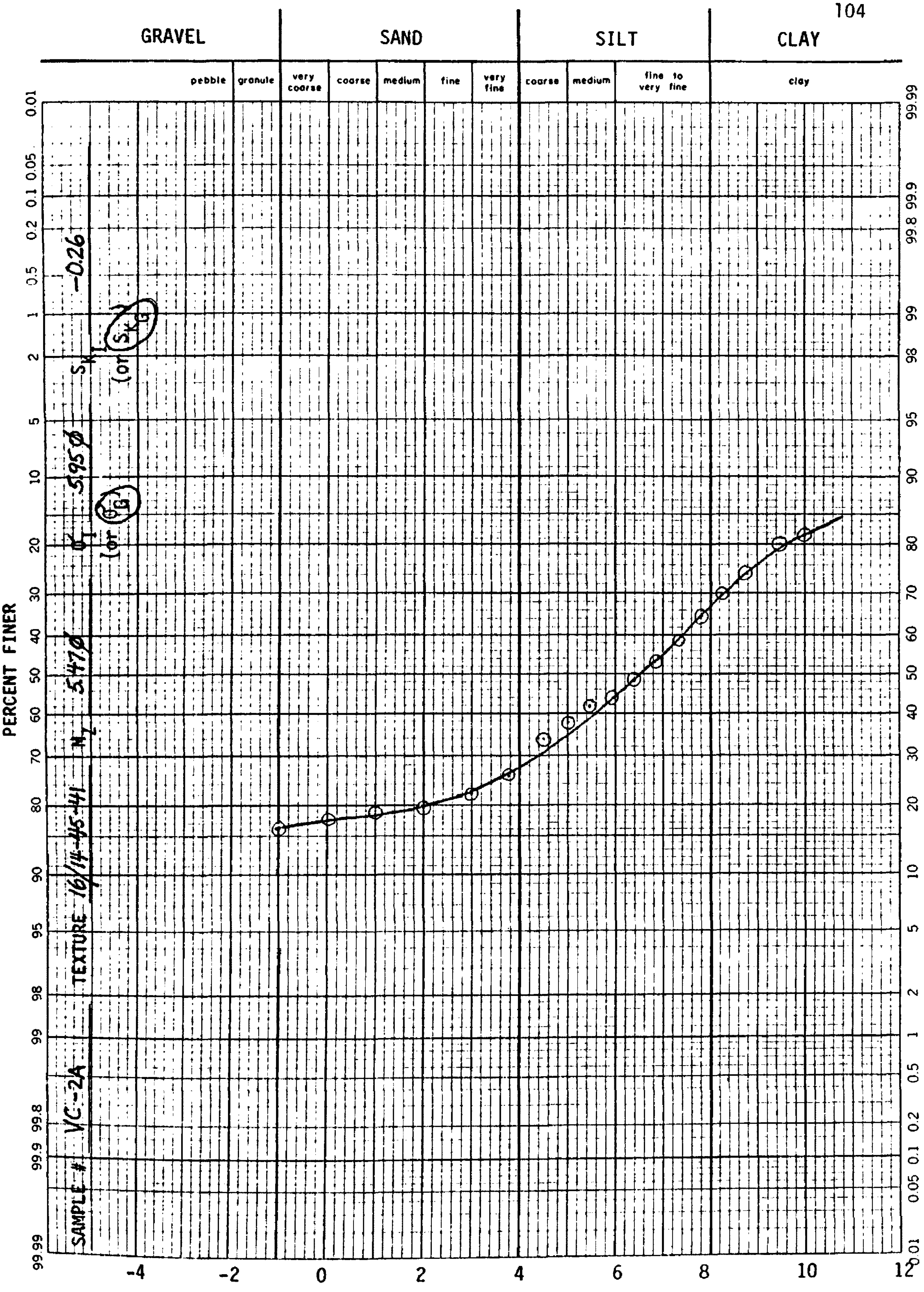
SAMPLE # VC-1

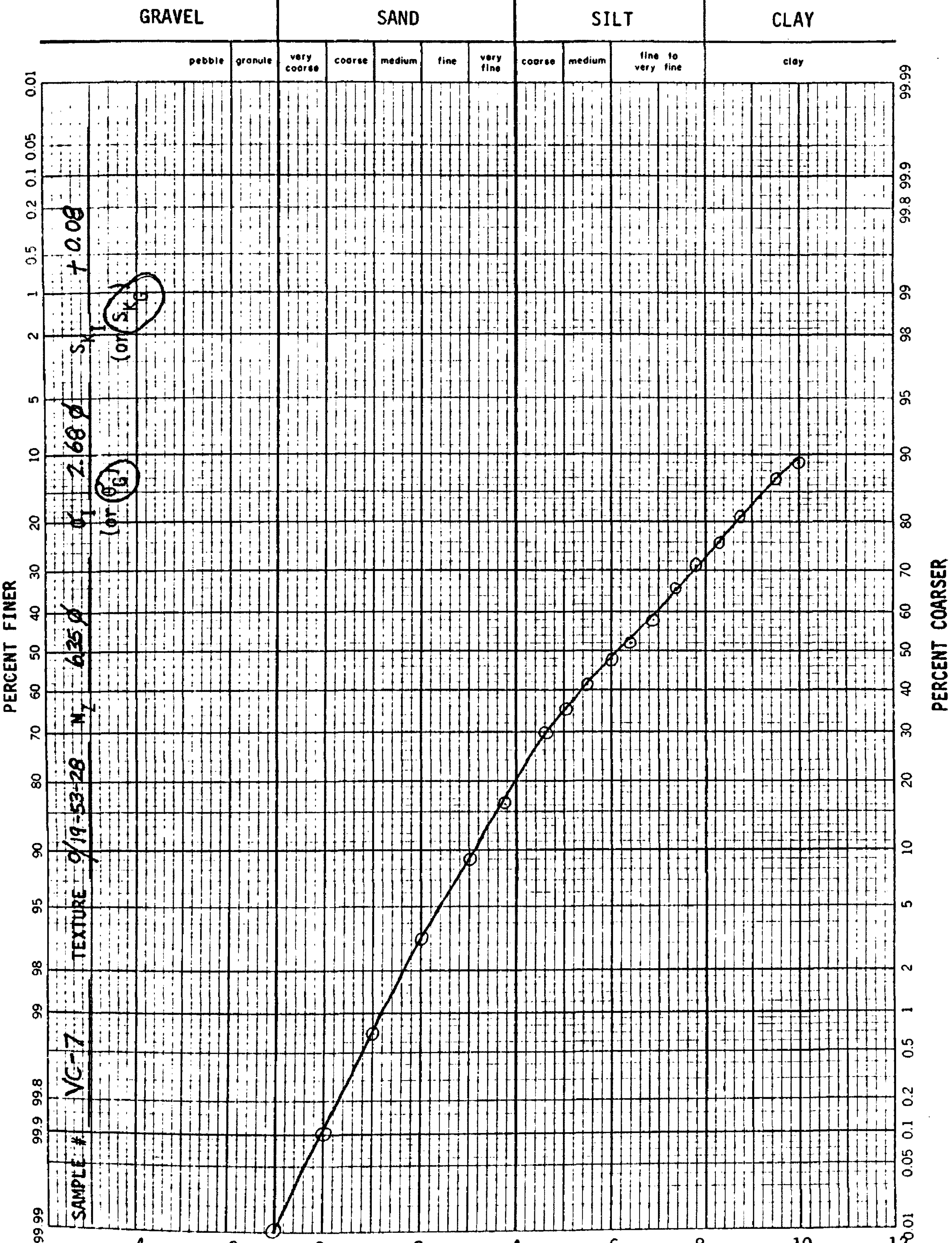
TEXTURE 0/14-58-28

M_Z 6.73φ

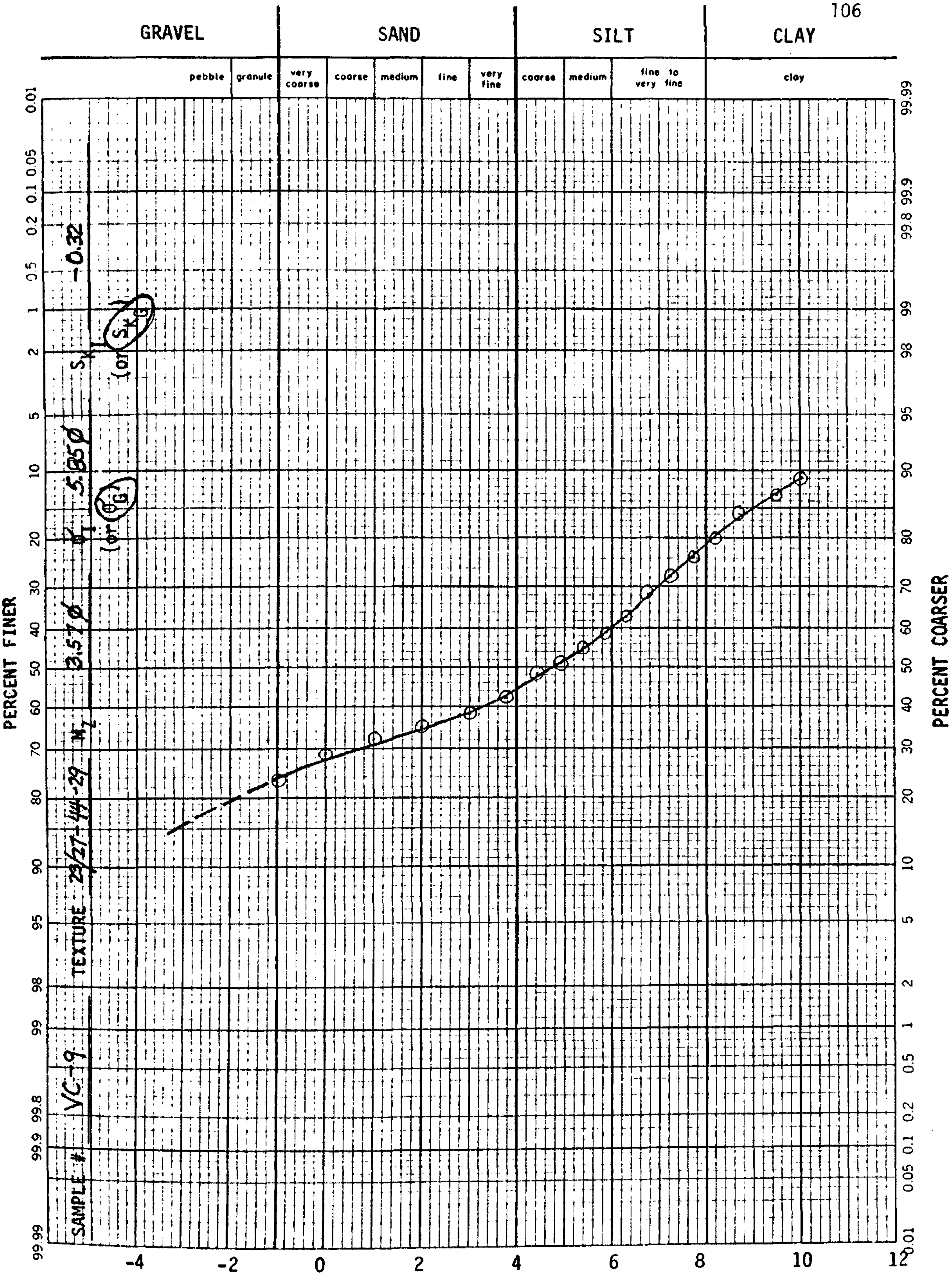
σ_I 2.20φ (or σ_G)

Sk_I -0.18 (or Sk_G)


GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12
SAMPLE # VC-2A
TEXTURE 16/14-45-41
M_z 5.47ø
σ_I 5.95ø (or σ_G)
Sk_I (or Sk_G) -0.26



GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
SAMPLE # VC-7
TEXTURE 9/19-53-28
M_z 6.25 ø
σ_I (or σ_G) 2.68 ø
Sk_I (or Sk_G) +0.08
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12



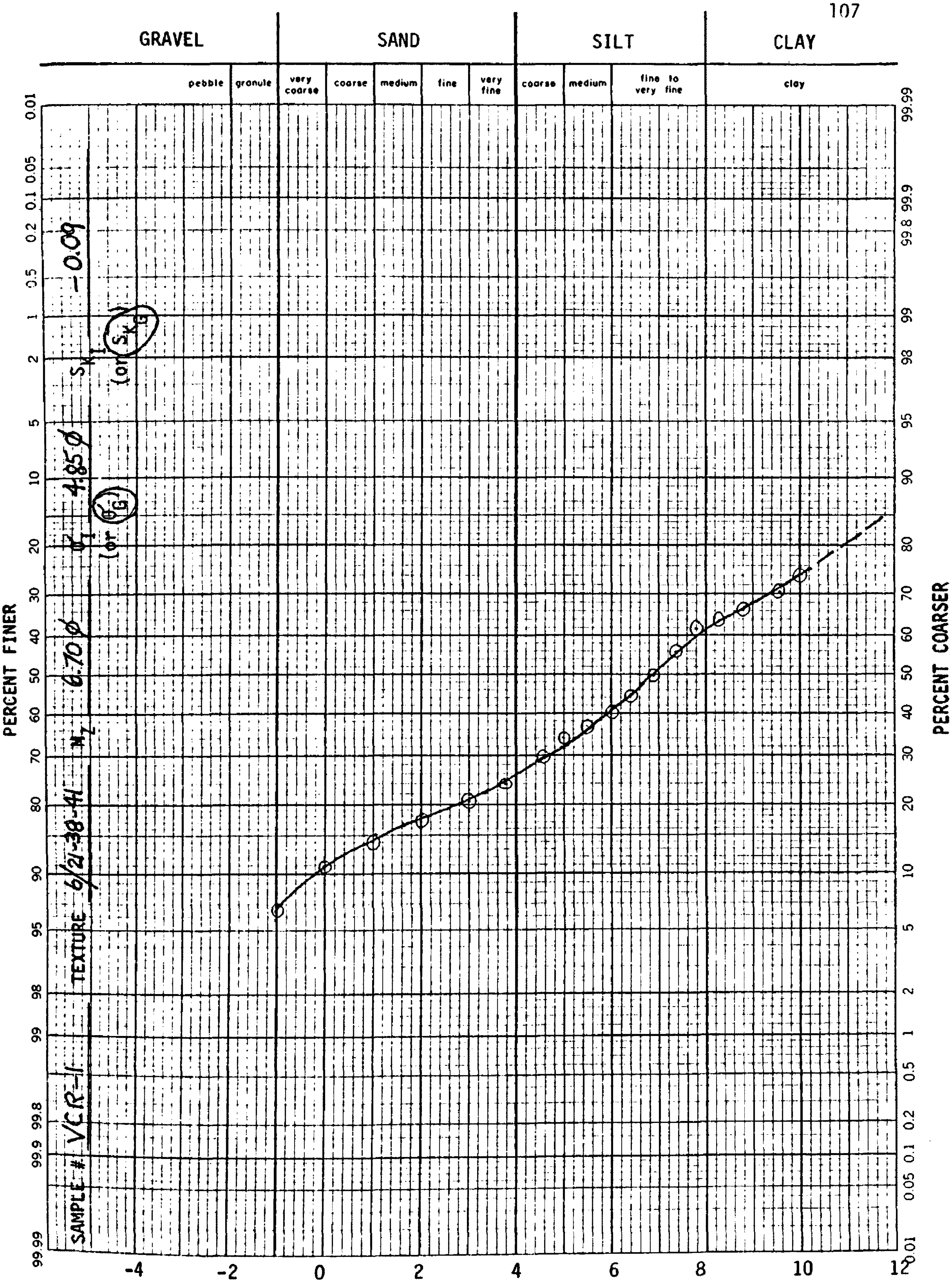
SAMPLE # VC-9

TEXTURE 23/27-44-29

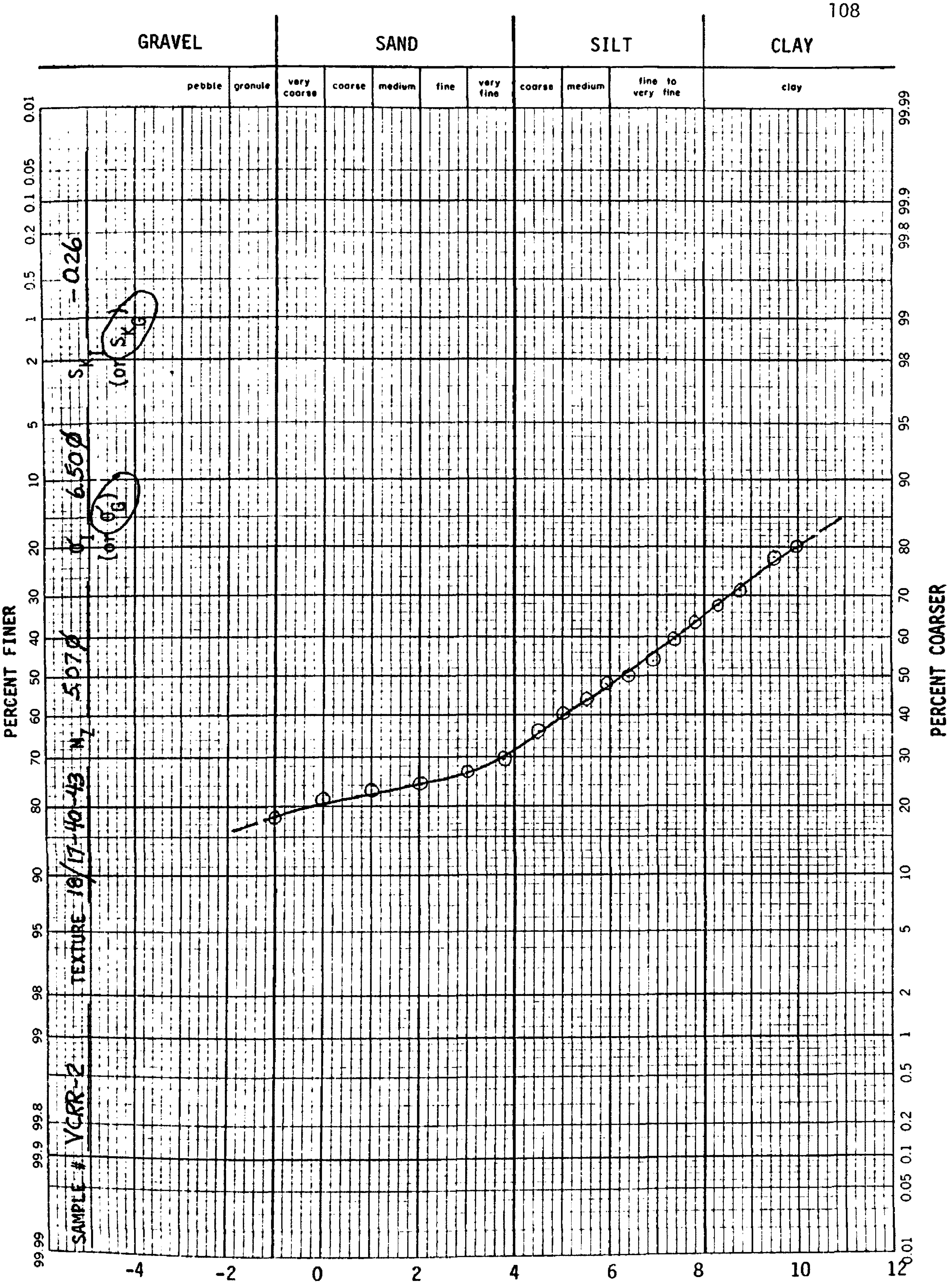
M_z 3.57φ

σ_I 5.85φ (or σ_G)

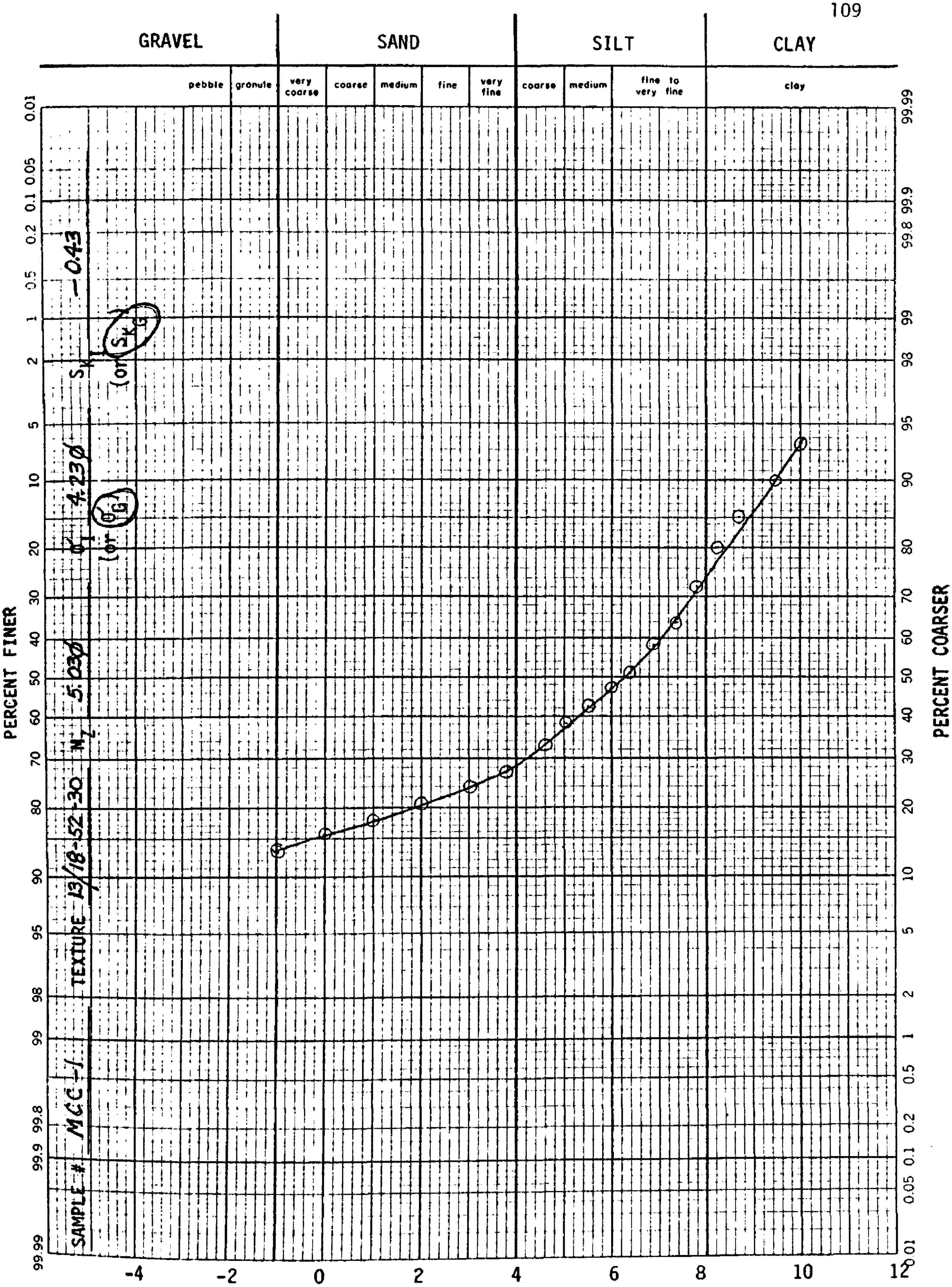
S_{kI} -0.32 (or S_{kG})

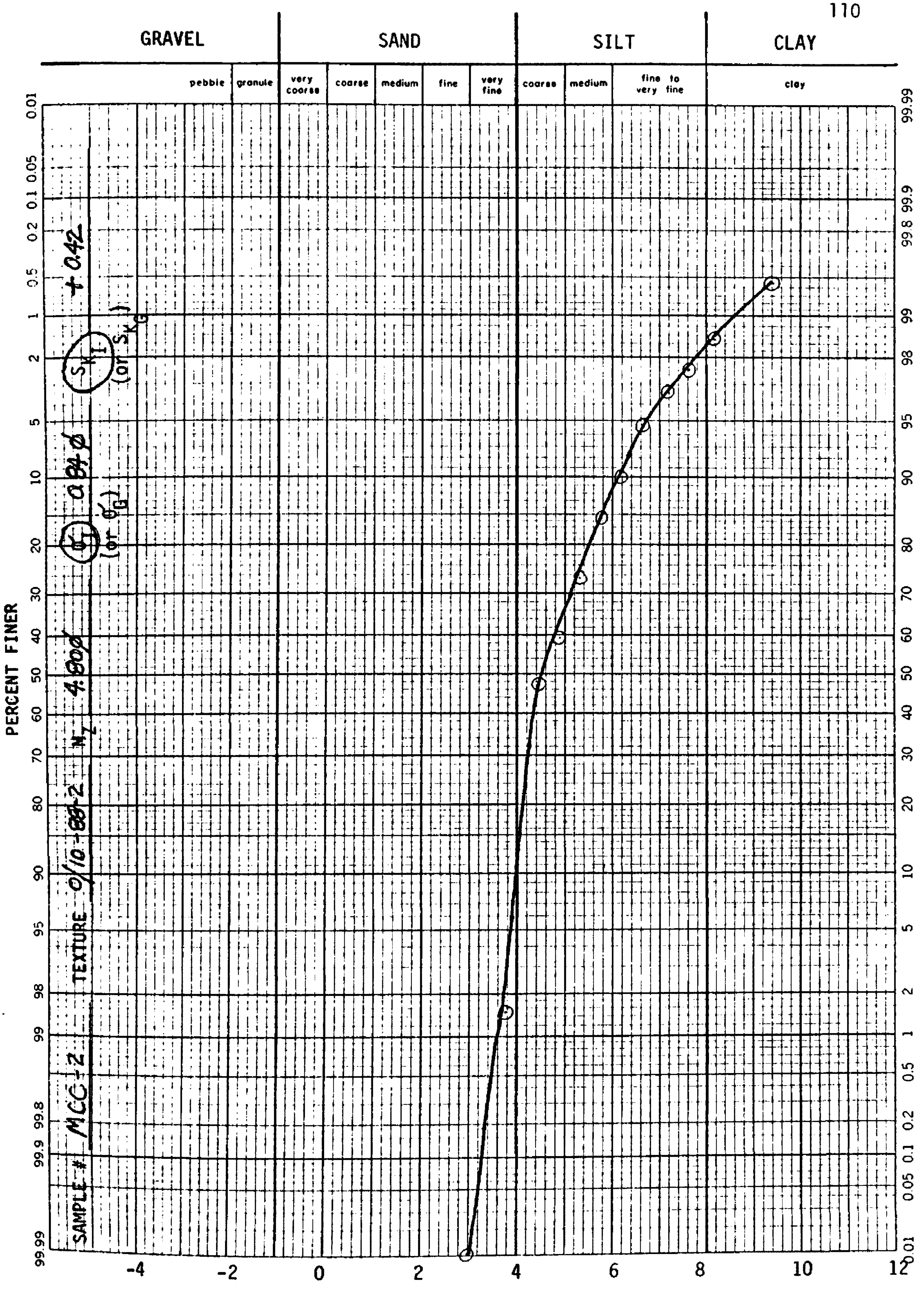


SAMPLE # VCR-1 TEXTURE 6/21-38-41 M_z 6.70 ϕ σ_I (or σ_G) 4.85 ϕ Sk_I (or Sk_G) −0.09

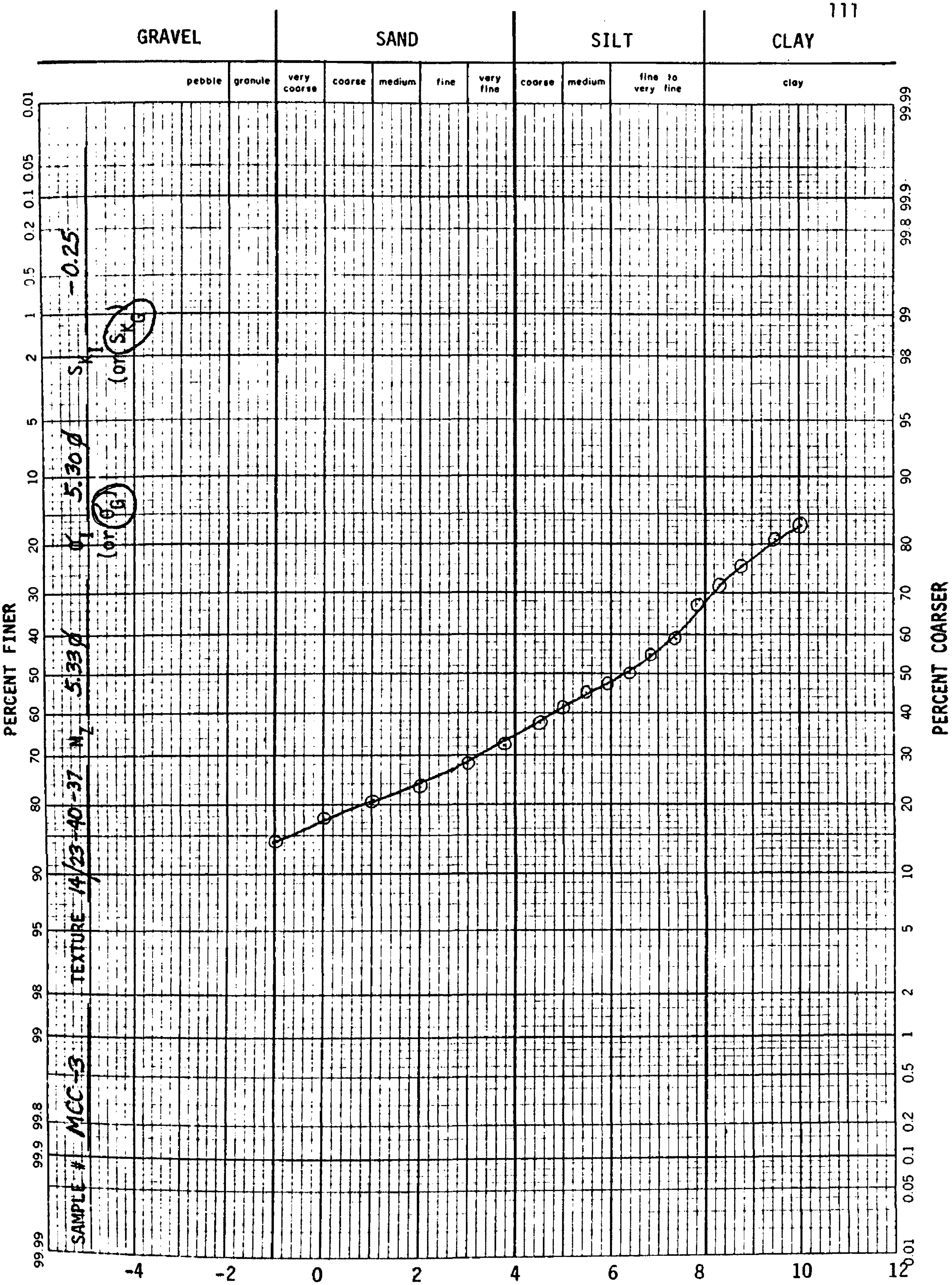


SAMPLE # VCRR-2 TEXTURE 18/17-40-43 M_Z 5.07Ø σ_I 6.50Ø (or σ_G) Sk_I -0.26 (or Sk_G)

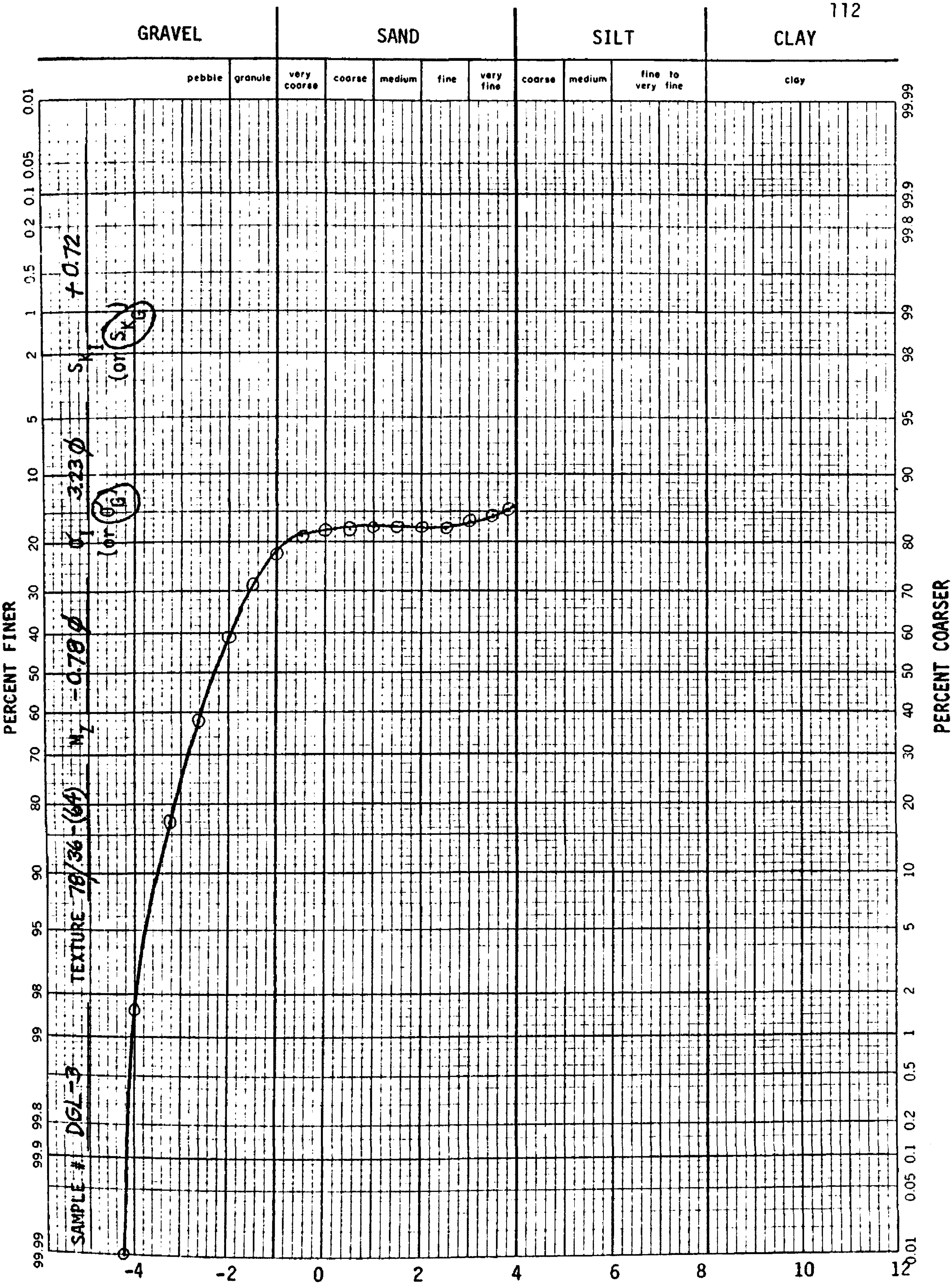

GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12
SAMPLE # MCC-1
TEXTURE 13/18-52-30
M_Z 5.03Ø
Ø_I 4.23Ø (or σ_G)
S_K_I -0.43 (or S_K_G)



SAMPLE # MCC-2 TEXTURE 9/10-~~88~~-2 M_z 4.80φ σ_I (or σ_G) 0.94φ Sk_I (or Sk_G) + 0.42



SAMPLE # MCC-3 TEXTURE 14/23-40-37 M_z 5.33ϕ σ_I (or σ_G) 5.30ϕ Sk_I (or Sk_G) -0.25



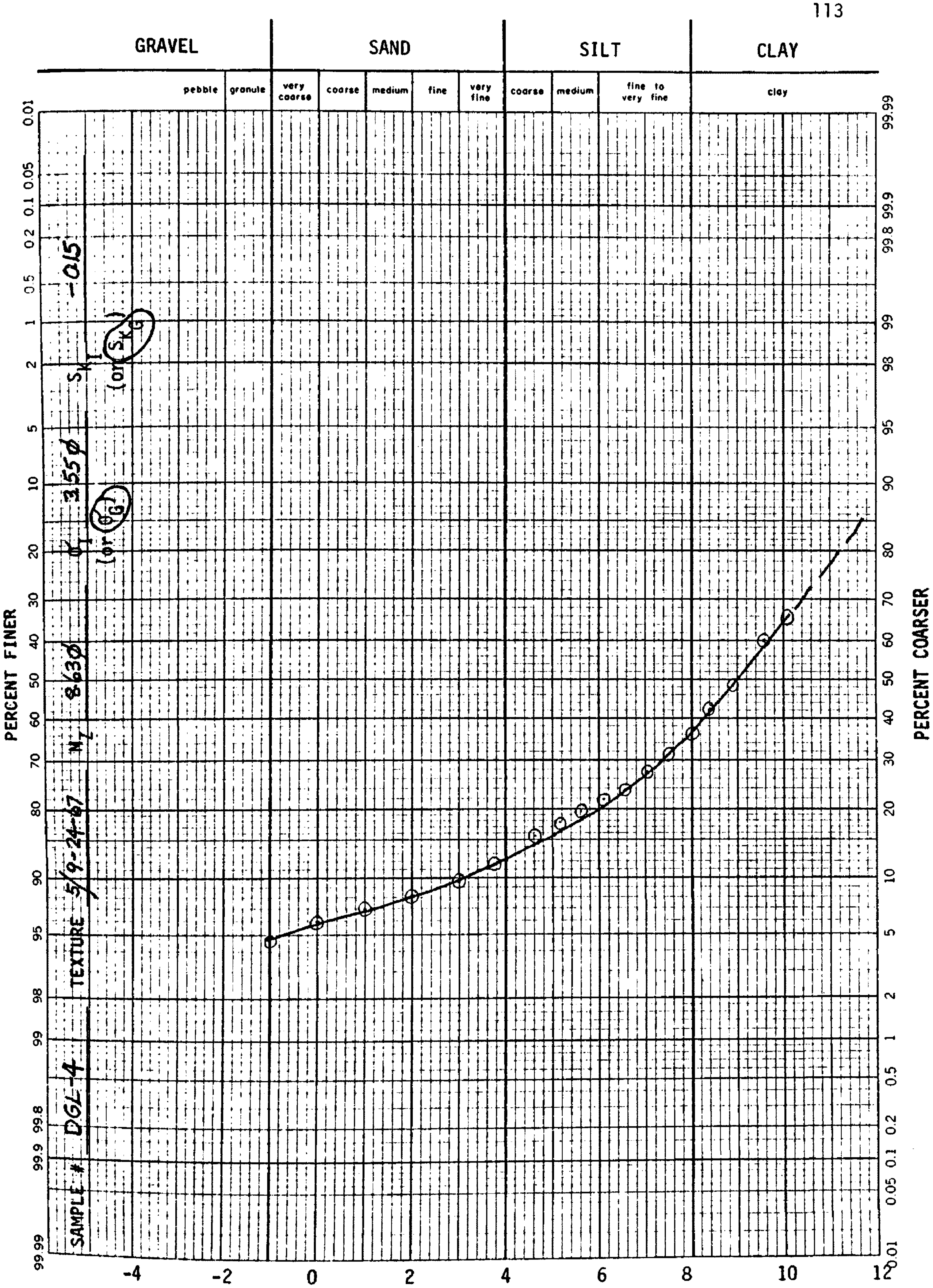
SAMPLE # DGL-3

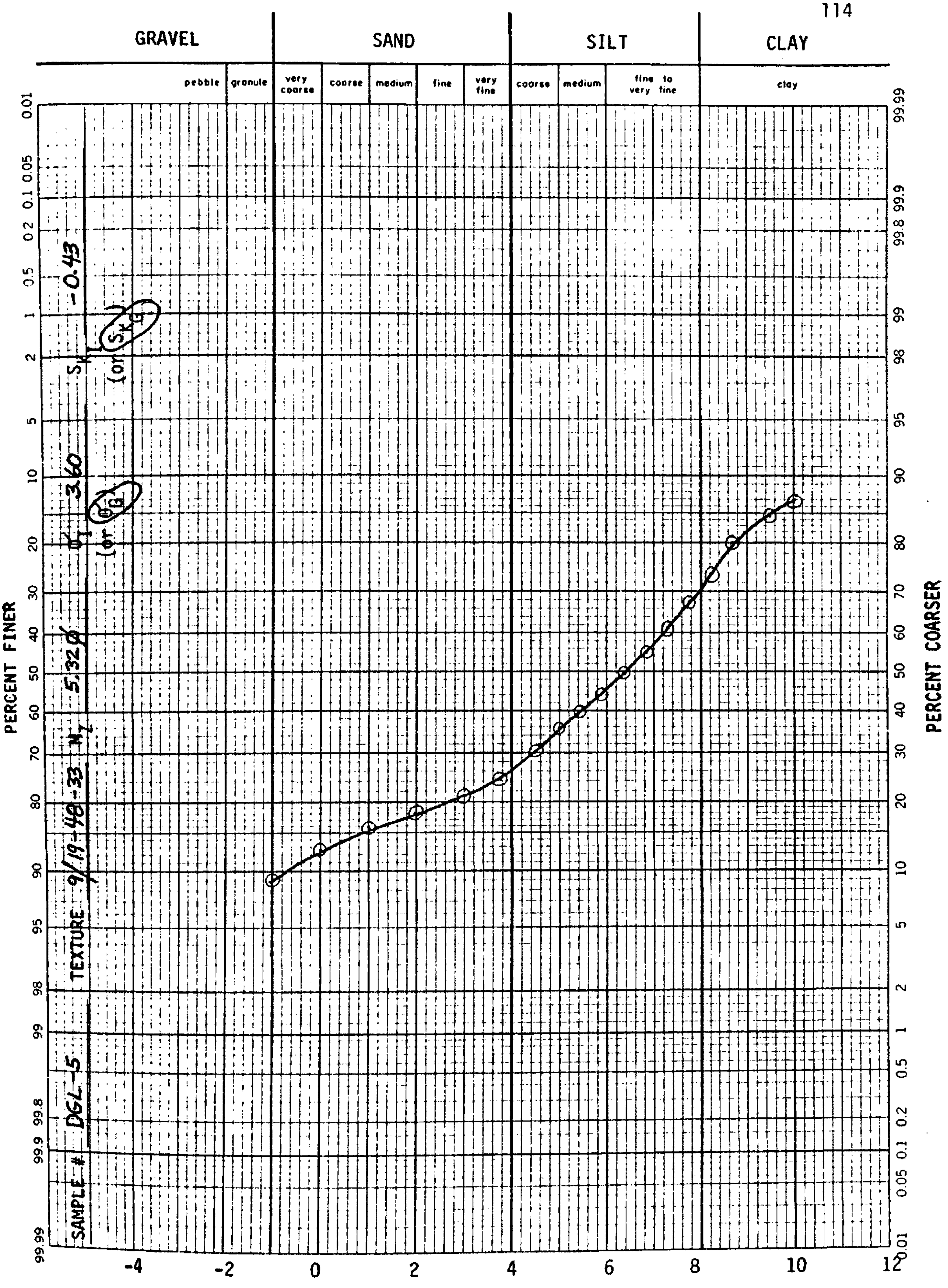
TEXTURE 78/36-(64)

M_z -0.78 φ

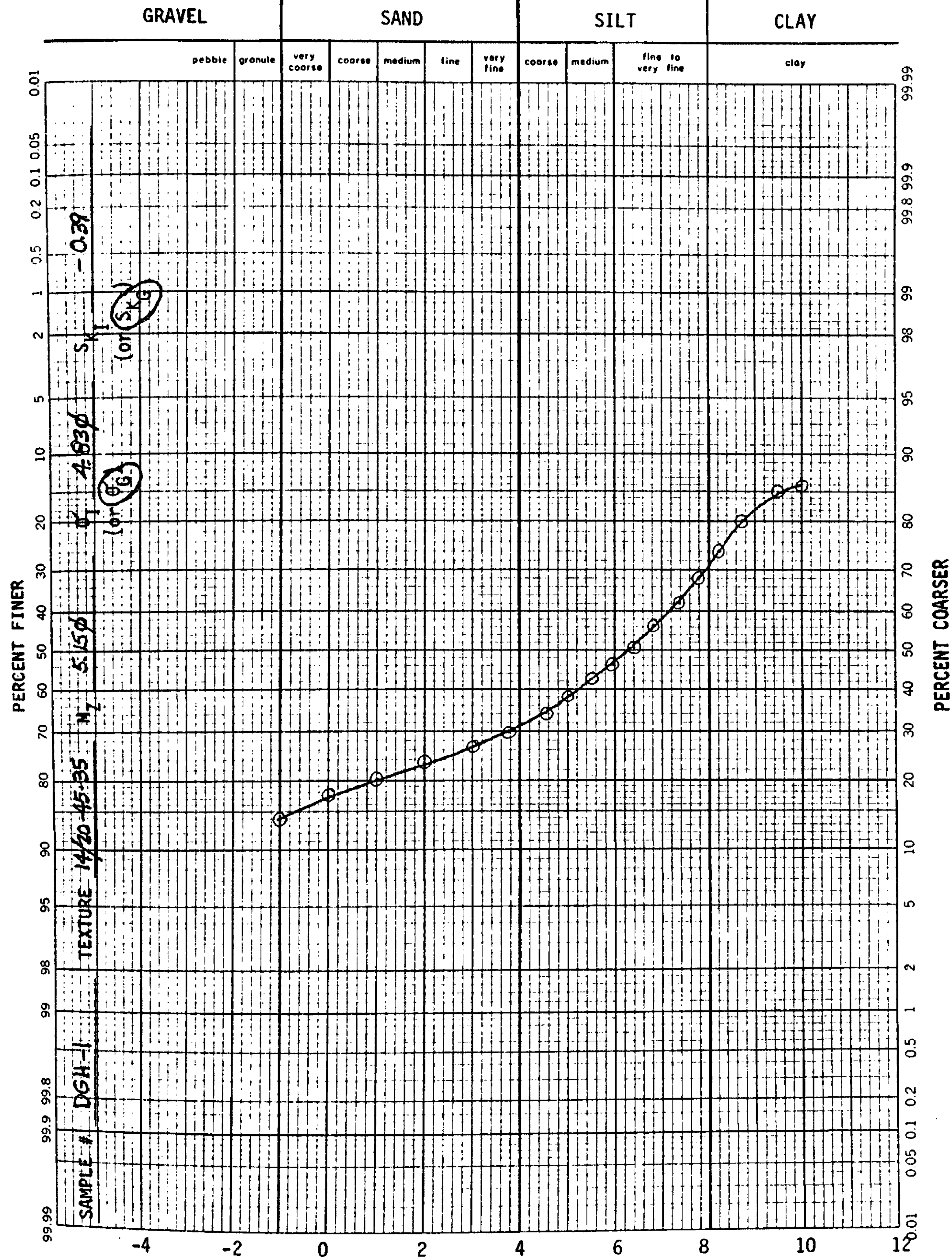
σ_I (or σ_G) 3.23 φ

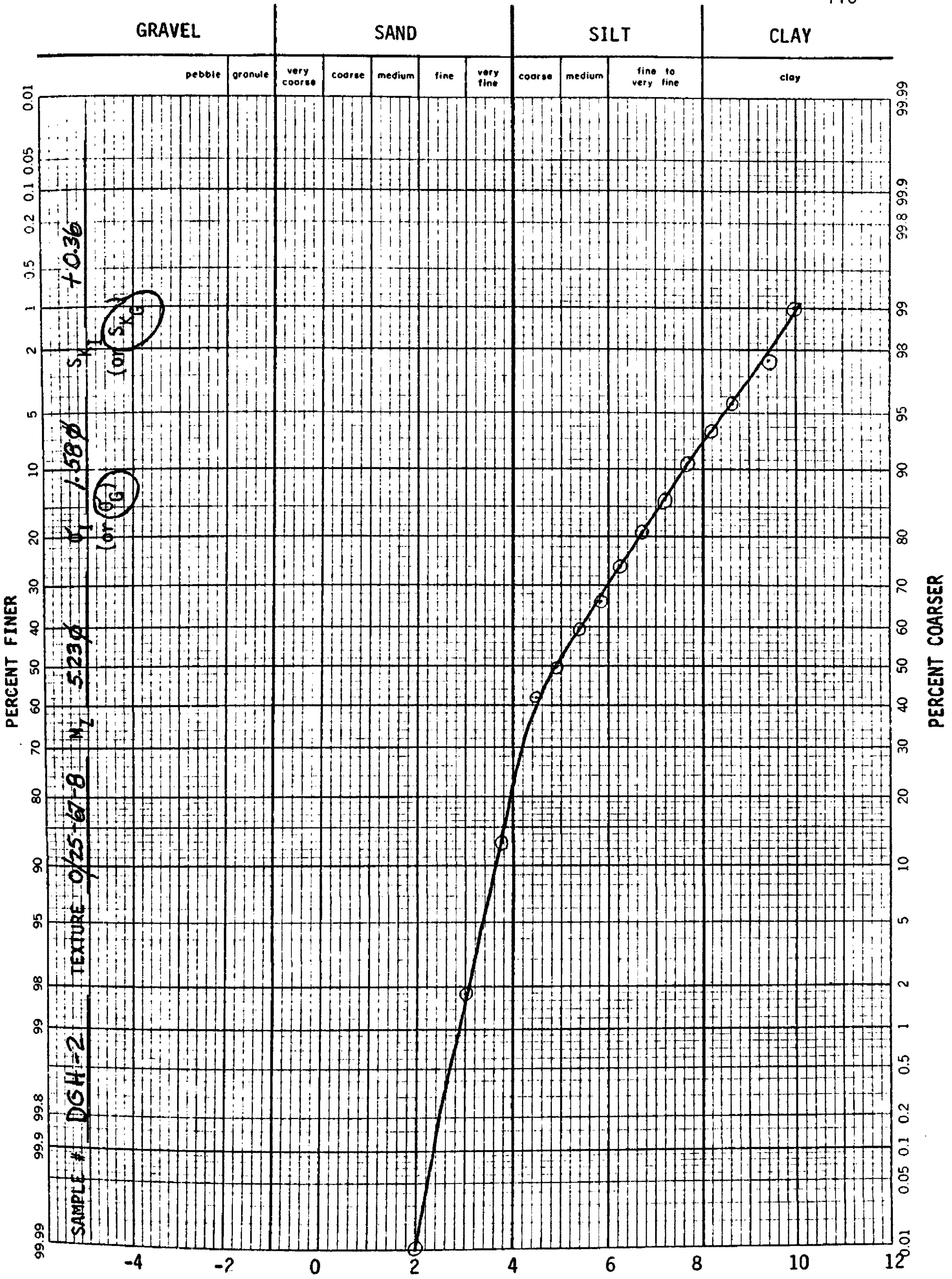
Sk_I (or Sk_G) +0.72


GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12
SAMPLE # DGL-4
TEXTURE 5/9-24-67
M_Z 8.63ø
σ_I 3.55ø (or σ_G)
Sk_I -0.15 (or Sk_G)



SAMPLE # DGL-5 TEXTURE 9/19-48-33 M_z 5.32Ø σ_I 3.60 (or σ_G) Sk_I -0.43 (or Sk_G)


GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12
SAMPLE # DGH-1
TEXTURE 14/20-45-35
M_z 5.15φ
σ_I 4.83φ
(or σ_G)
Sk_I -0.39
(or Sk_G)



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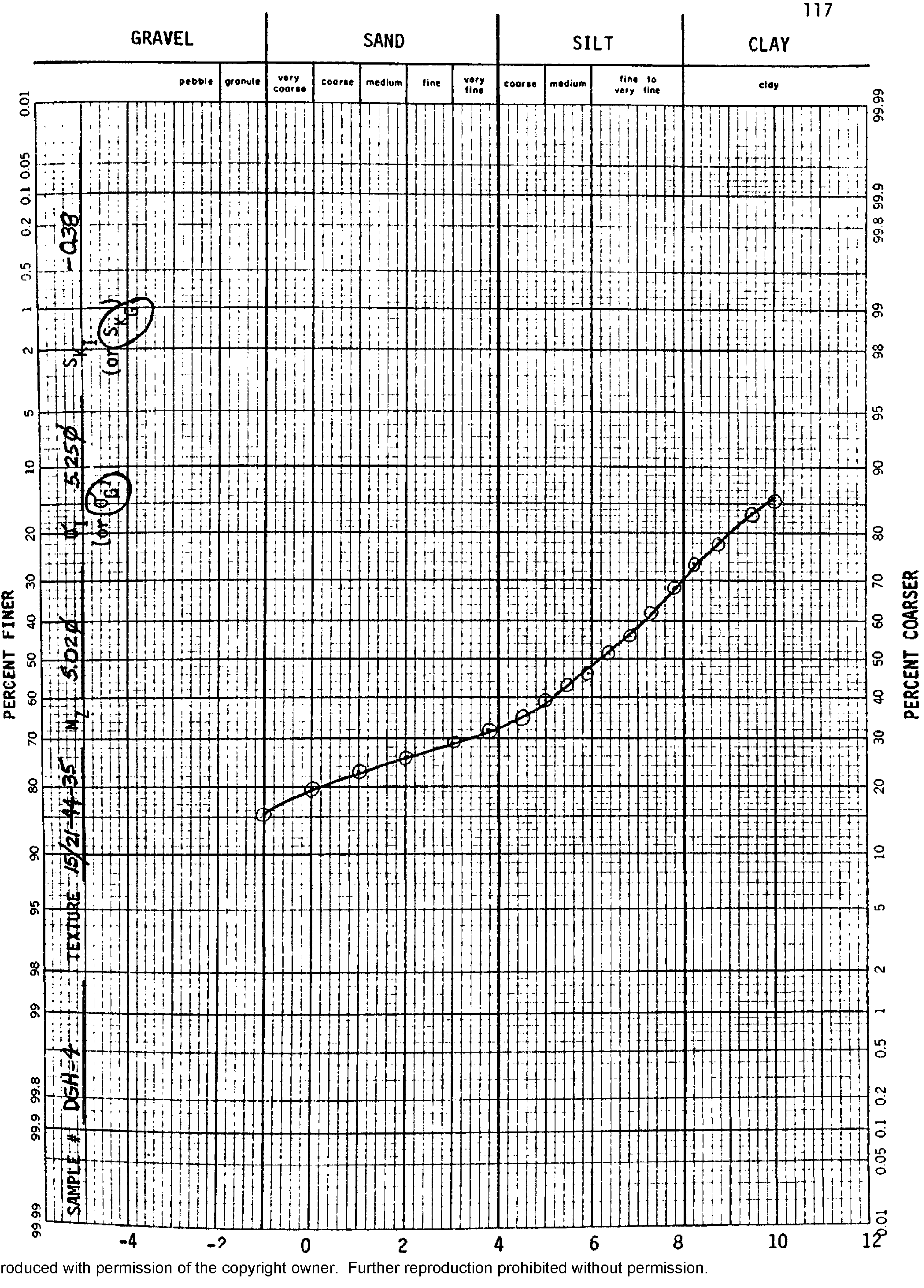
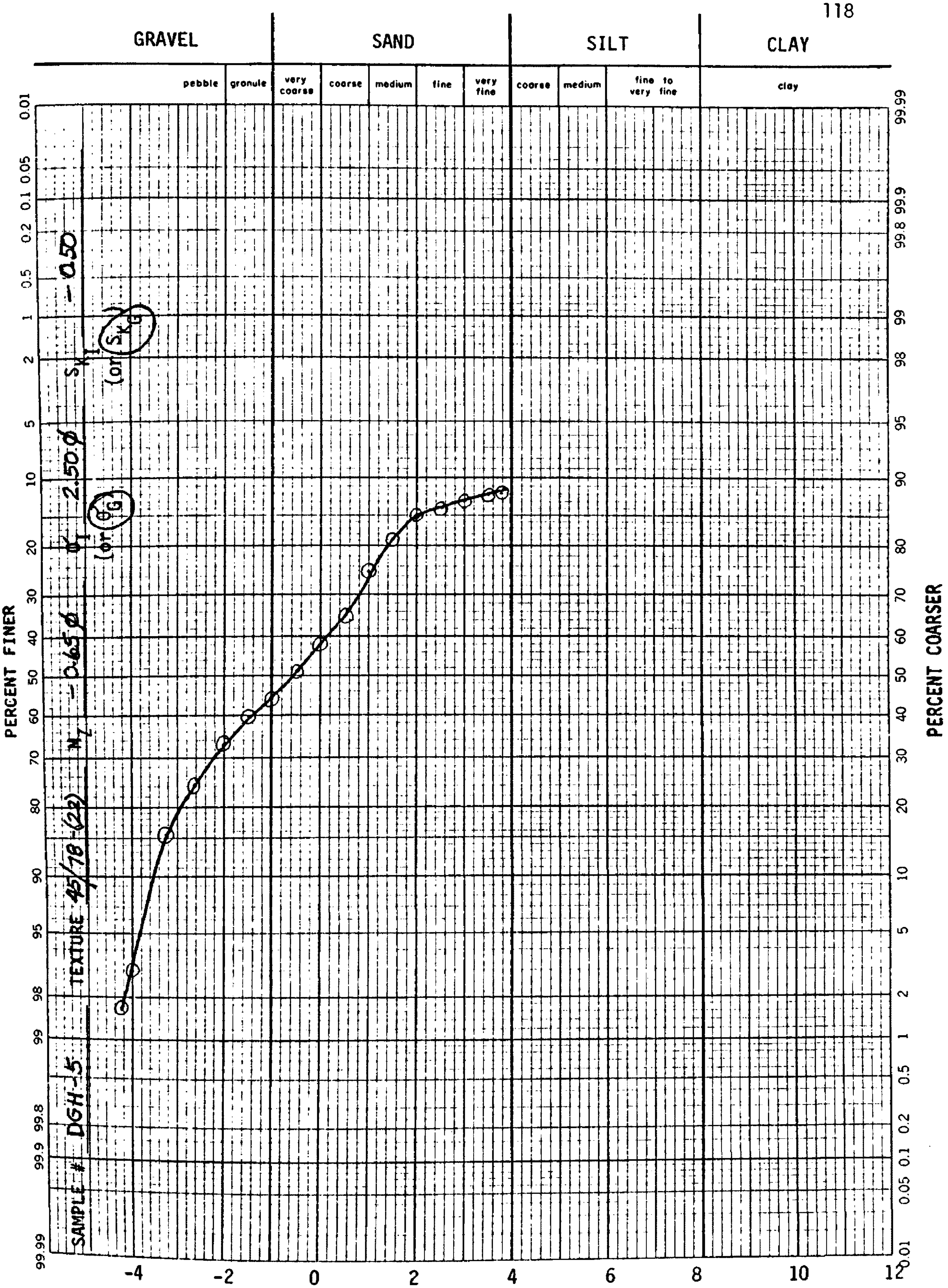
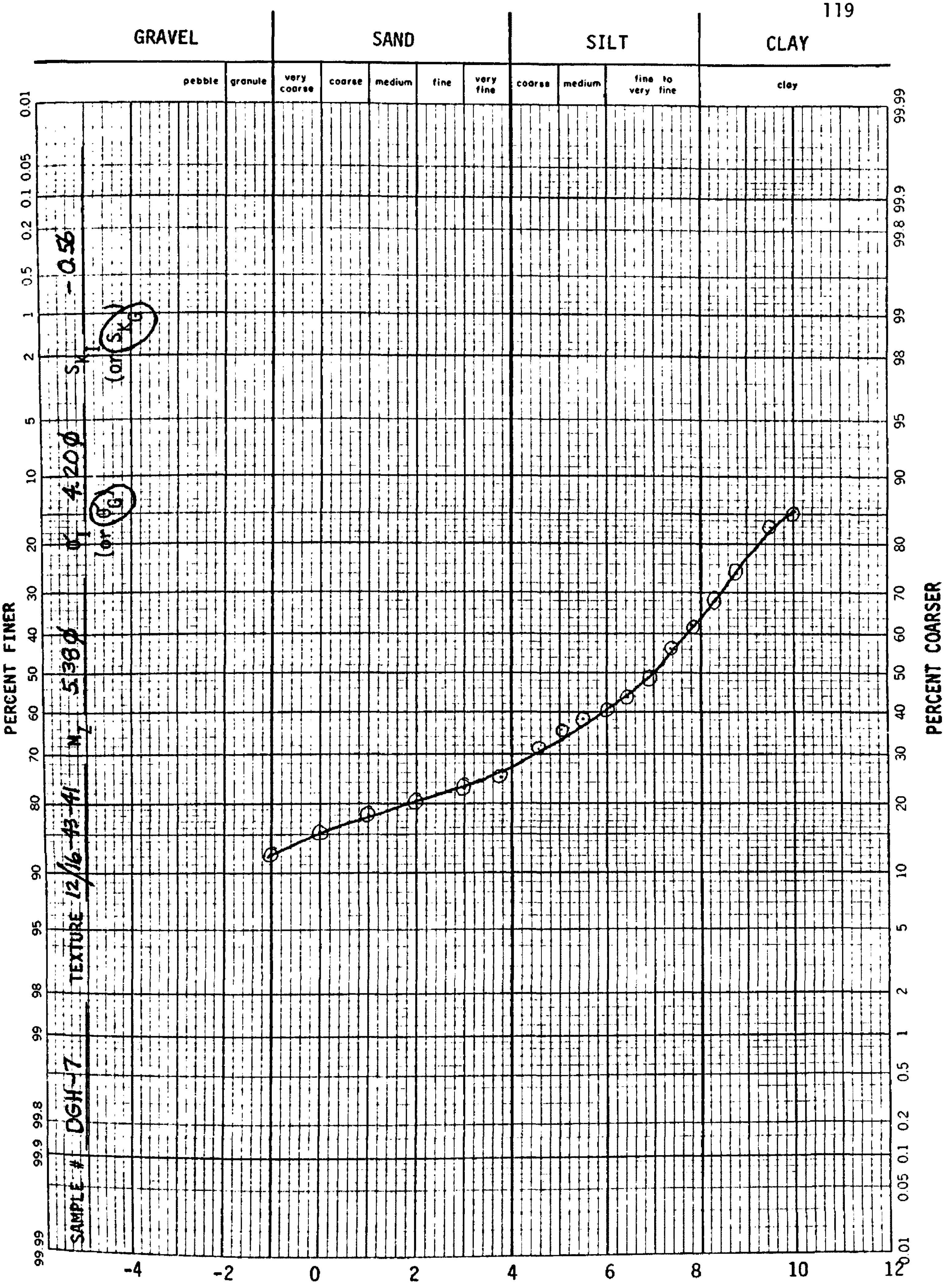
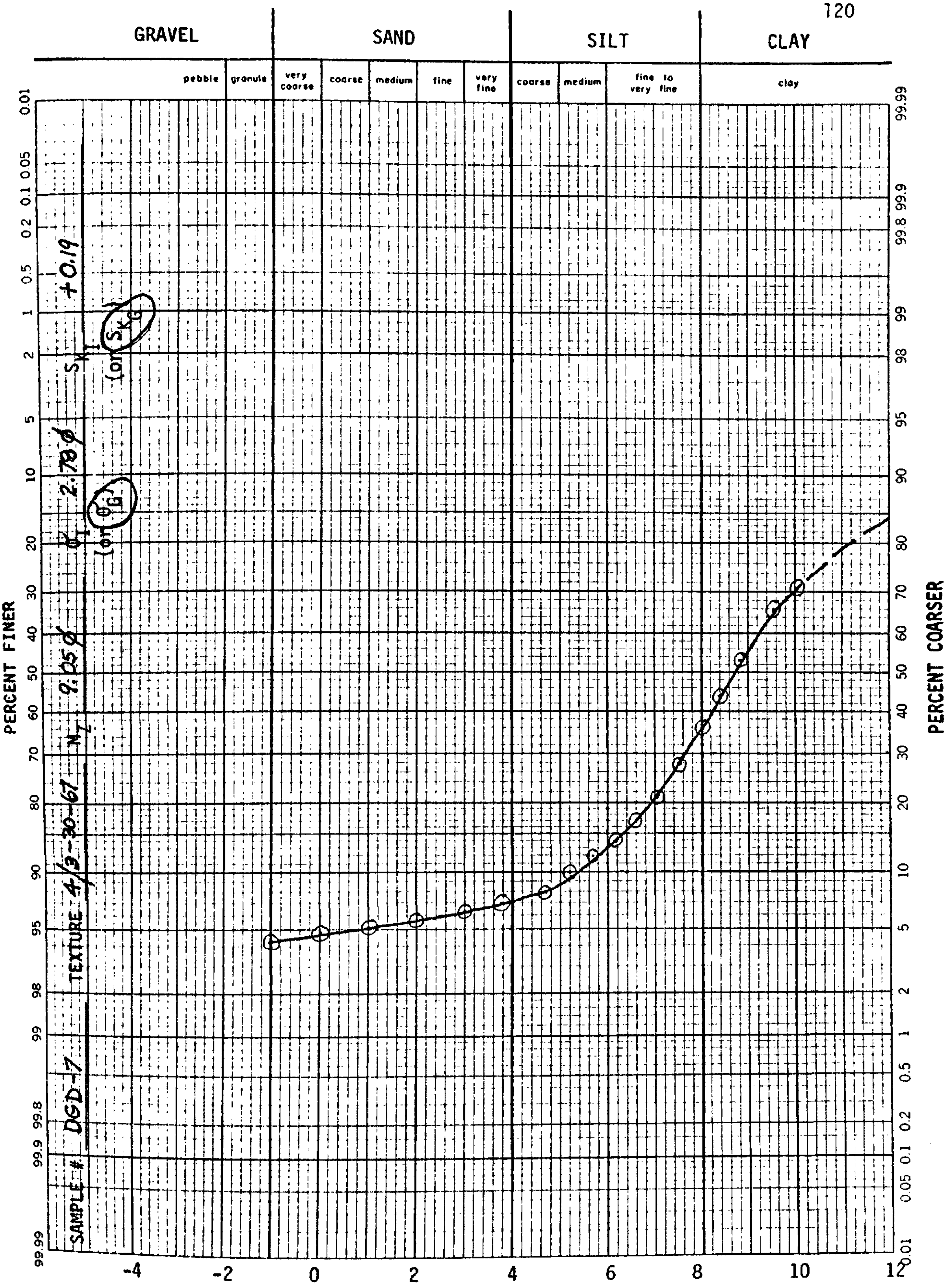


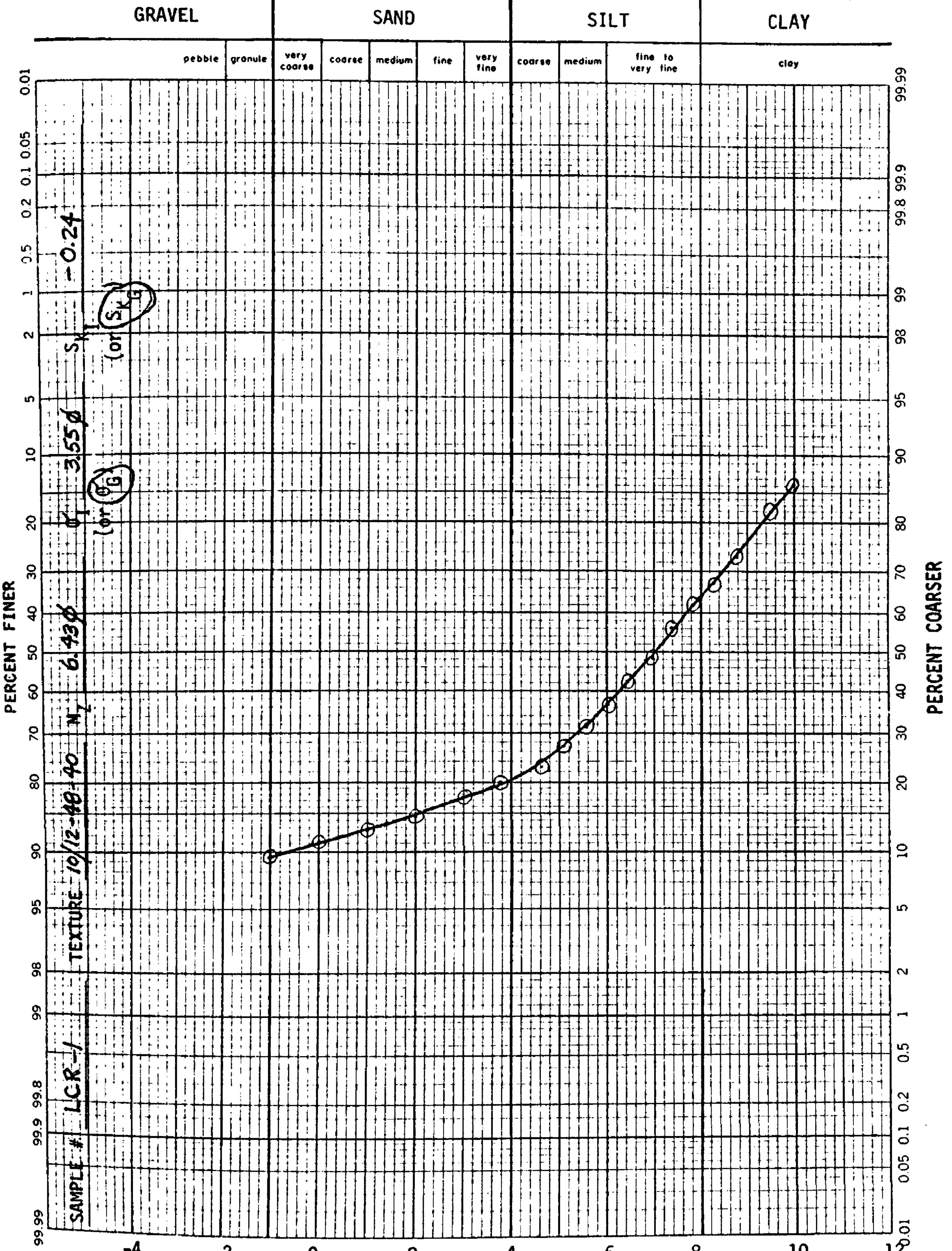
SAMPLE # DGH-4 TEXTURE 15/21-44-35 M_Z 5.02Ø σ_I (or σ_G) 5.25Ø S_{k_I} (or S_{k_G}) -0.38


GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12
SAMPLE # DGH-5
TEXTURE 45/18 (22)
M_z -0.65 φ
$σ_I$ 2.50 φ (or $σ_G$)
Sk_I -0.50 (or Sk_G)



SAMPLE # DGH-7 TEXTURE 12/16-43-41 M_z 5.38ϕ σ_I 4.20ϕ (or σ_G) Sk_I -0.56 (or Sk_G)


GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12
SAMPLE # DGD-7
TEXTURE 4/3-30-67
M_Z 9.05φ
σ_I 2.70φ
(or σ_G)
Sk_I +0.19
(or Sk_G)



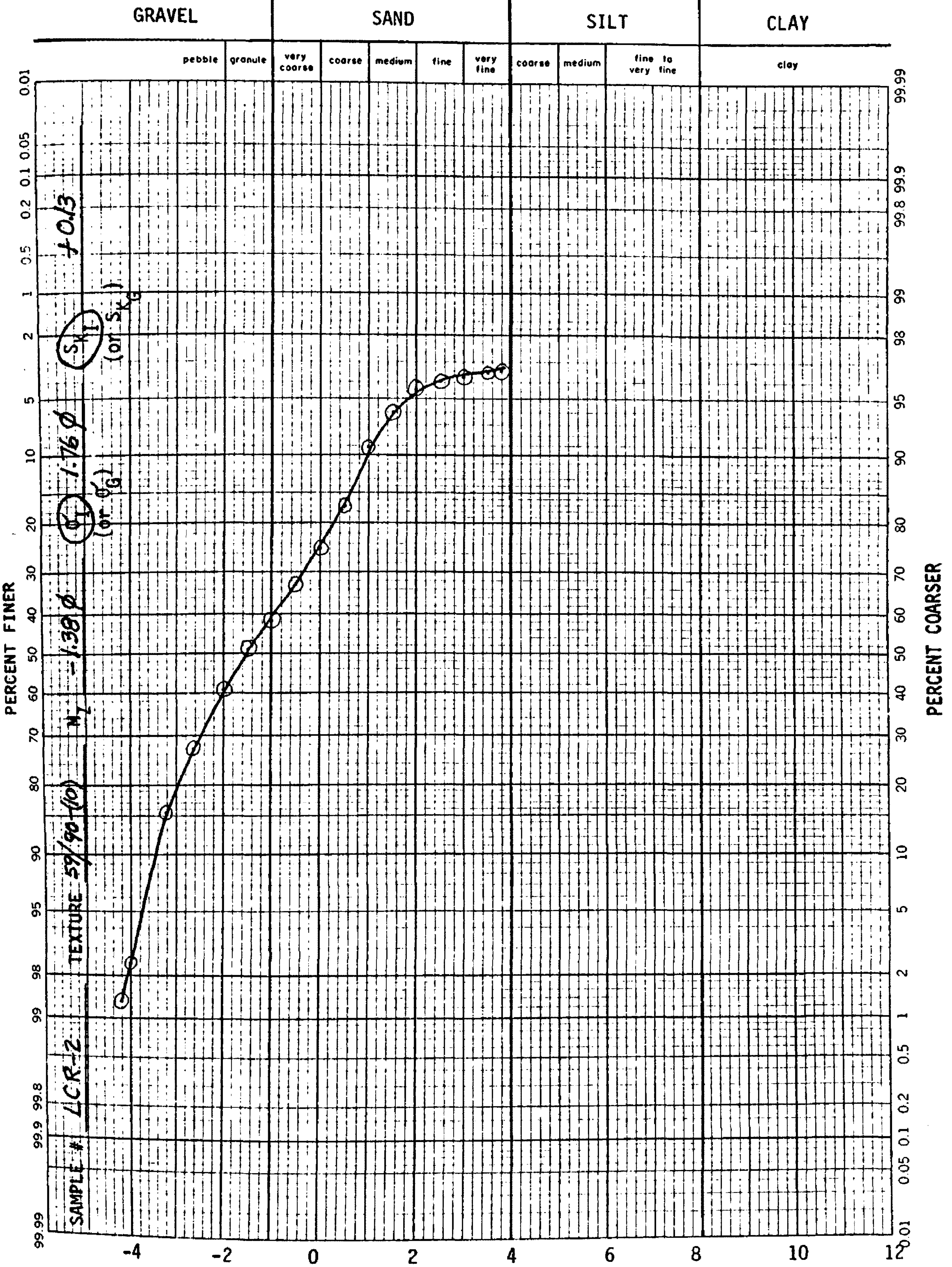
SAMPLE #: LCR-1

TEXTURE 10/12-48-40

M_z 6.43ø

σ_I (or σ_G) 3.55ø

Sk_I (or Sk_G) -0.24



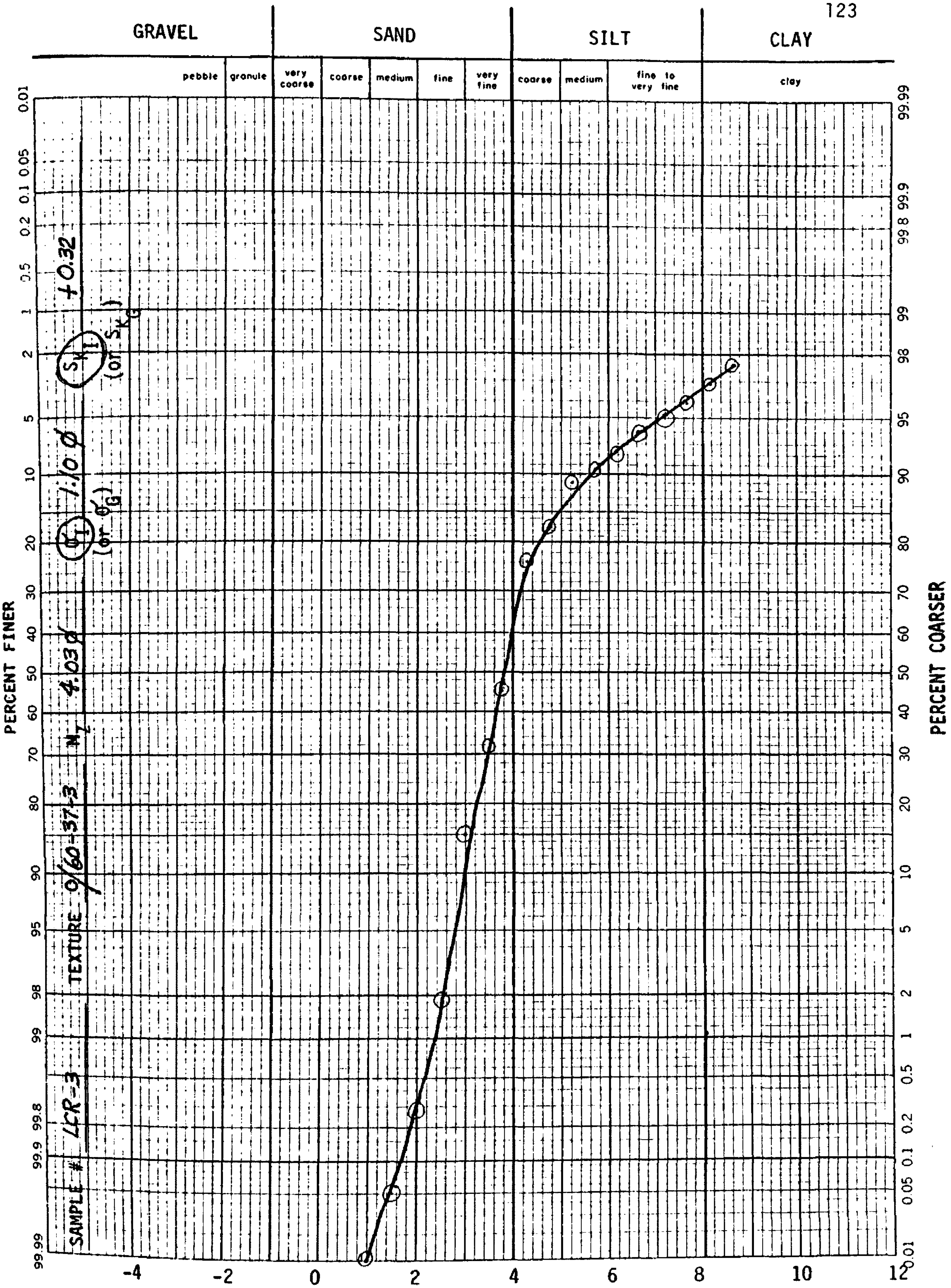
SAMPLE # LCR-2

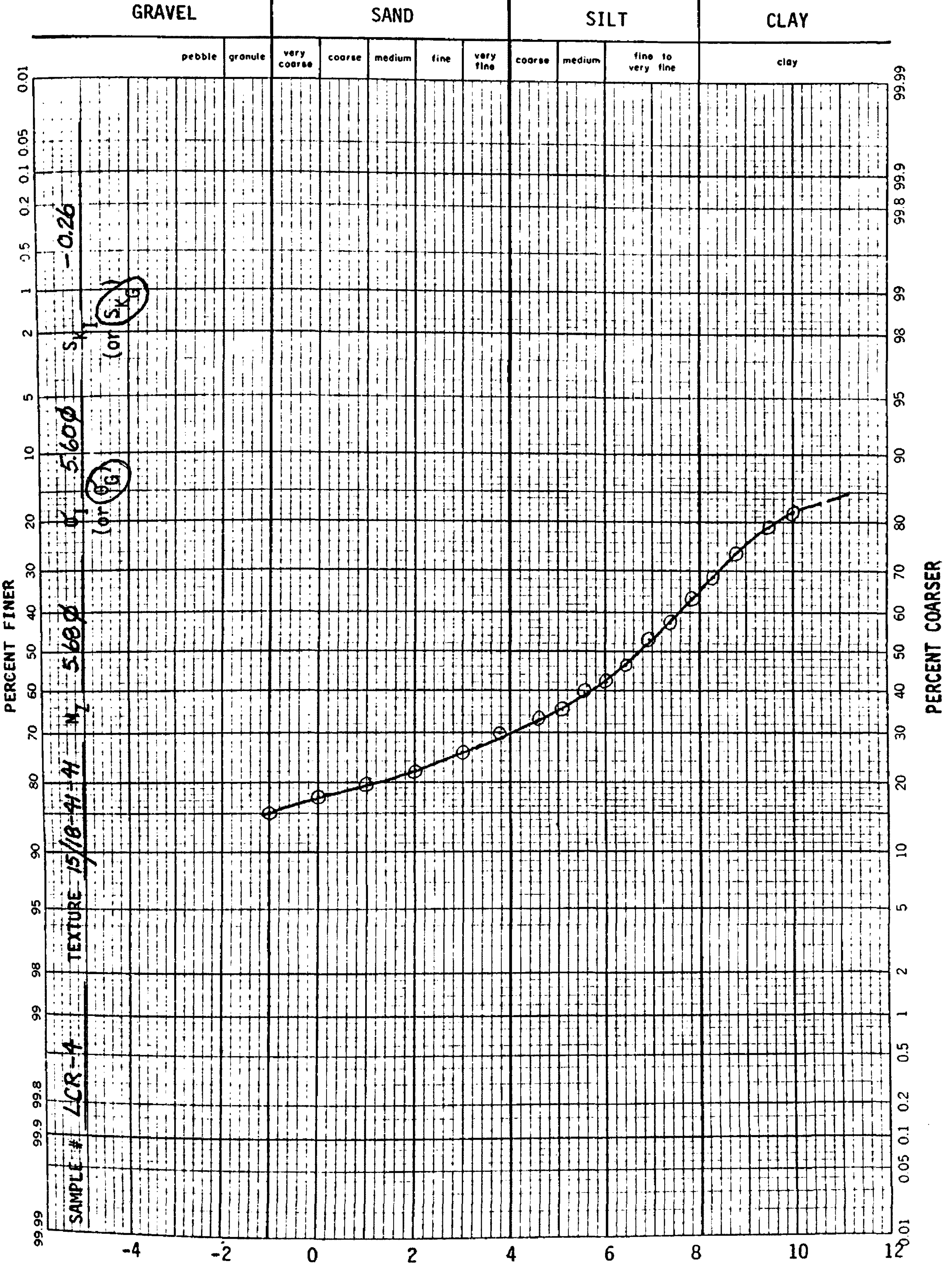
TEXTURE 59/90-(10)

M_Z -1.38 φ

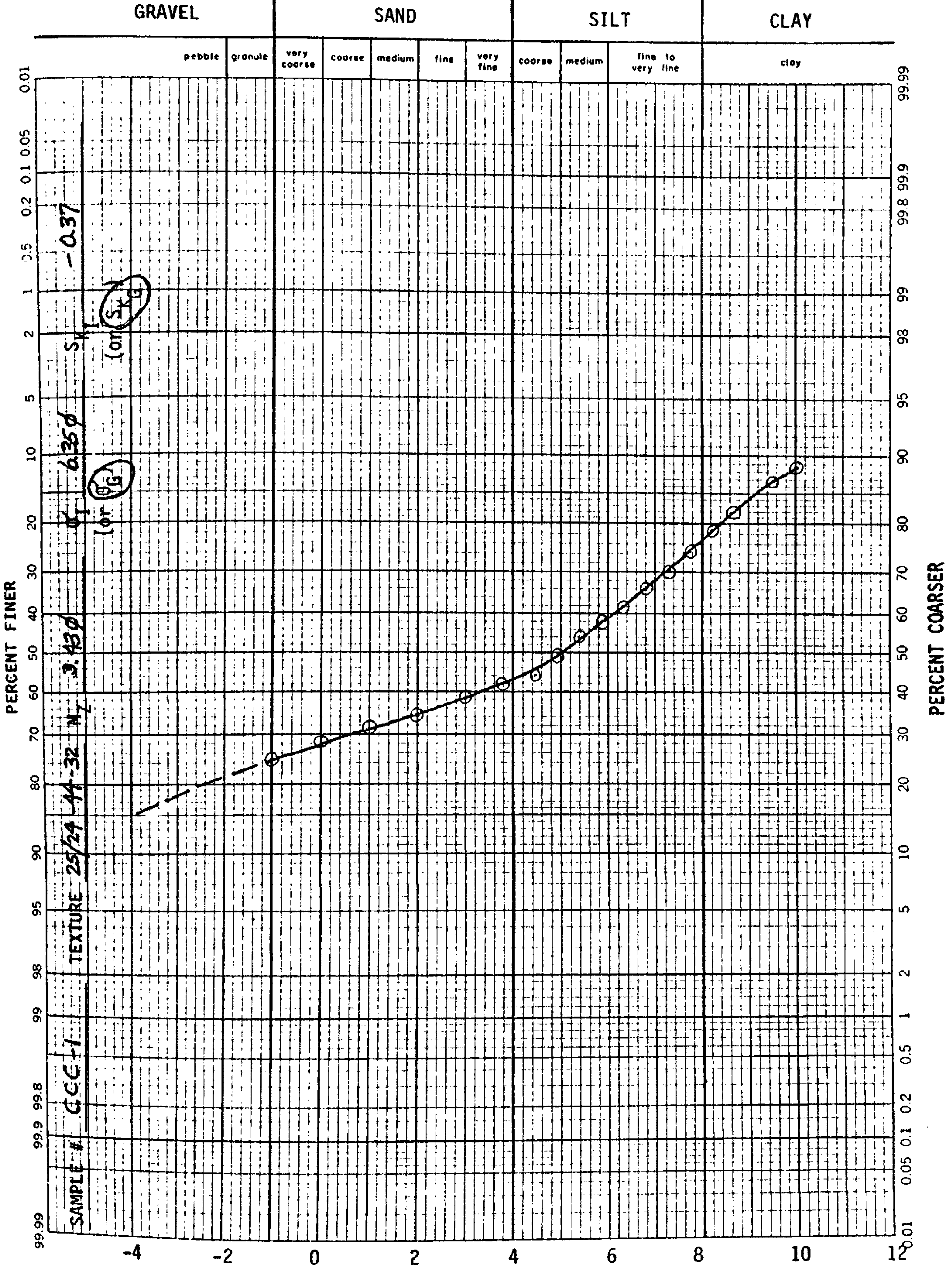
σ_I 1.76 φ (or σ_G)

Sk_I (or Sk_G) +0.13


GRAVEL
SAND
SILT
CLAY
pebble
granule
very coarse
coarse
medium
fine
very fine
coarse
medium
fine to very fine
clay
PERCENT FINER
PERCENT COARSER
SAMPLE # LCR-3
TEXTURE 0/60-37-3
M_Z 4.03 ϕ
σ_I (or σ_G') 1.10 ϕ
Sk_I (or Sk_G) +0.32
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
-4
-2
0
2
4
6
8
10
12



SAMPLE # LCR-4 TEXTURE 15/18-41-41 M_z 5.60φ σ_I (or σ_G) 5.60φ S_{k_I} (or S_{k_G}) −0.26



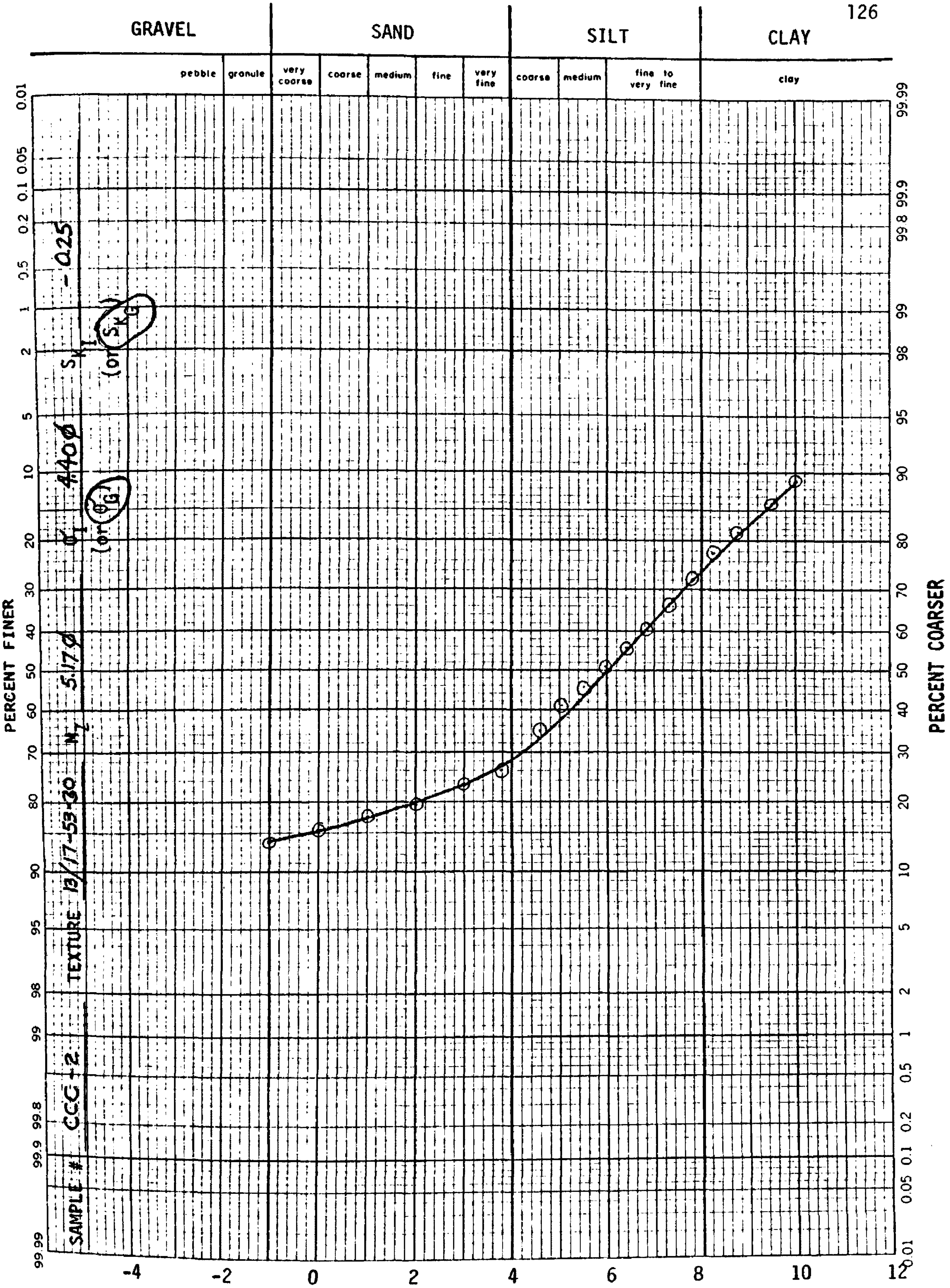
SAMPLE # CCC-1

TEXTURE 25/24-44-32

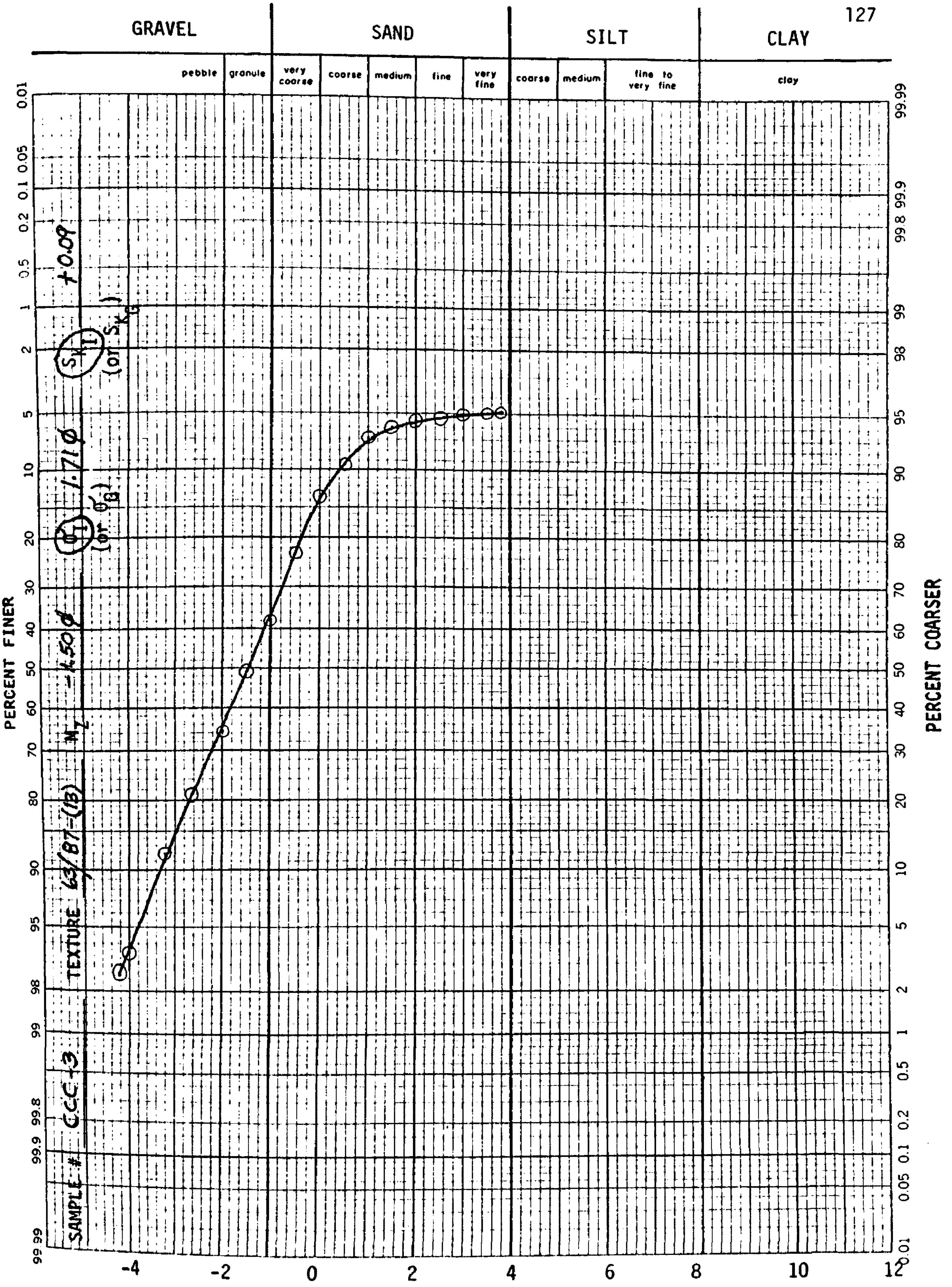
M_Z 3.43φ

σ_I 6.35φ (or σ_G)

Sk_I -0.37 (or Sk_G)



SAMPLE # CCC-2 TEXTURE 13/17-53-30 M_Z 5.17φ σ_I 4.40φ (or σ_G) Sk_I (or Sk_G) - 0.25



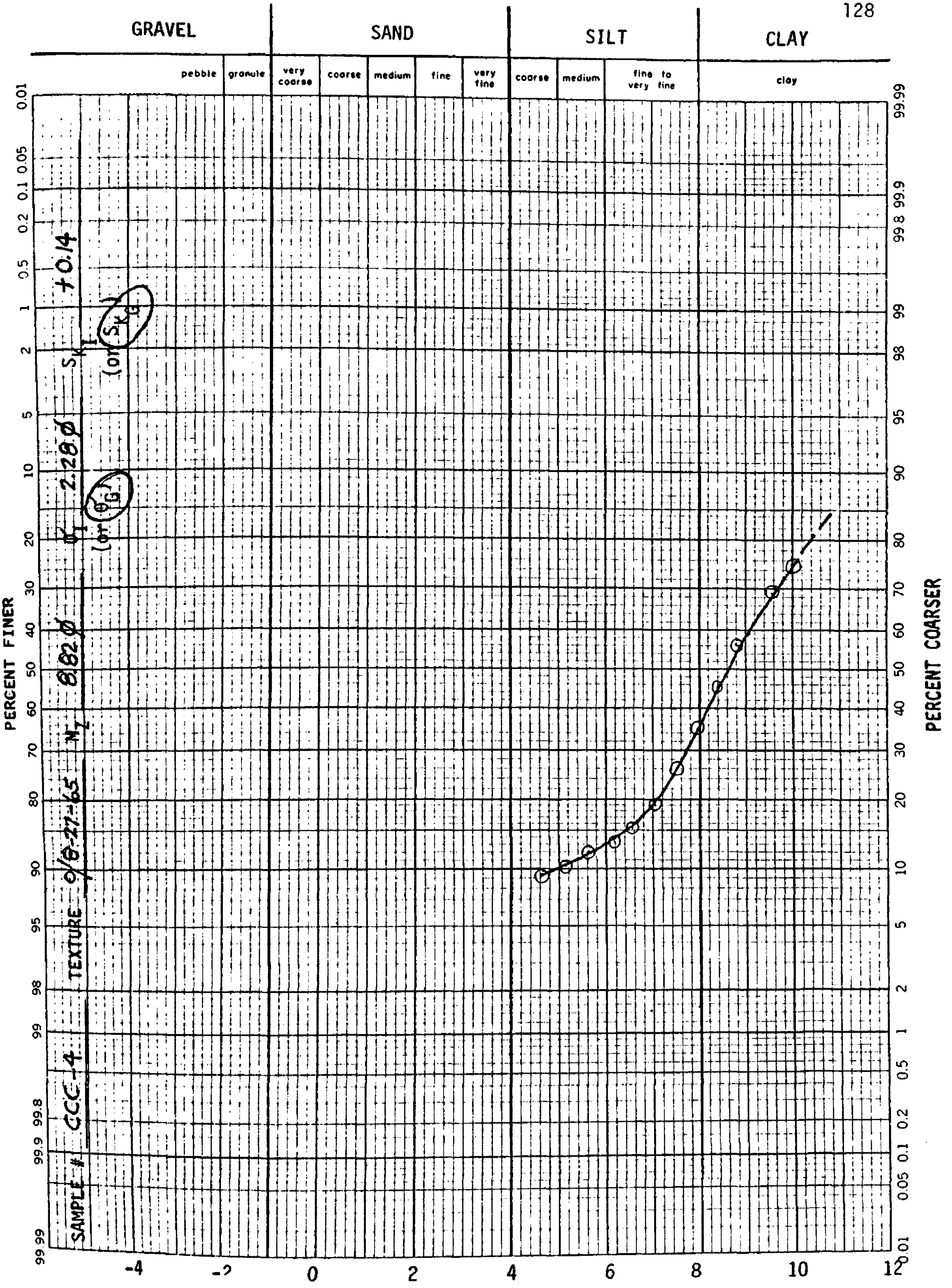
SAMPLE #: CCC-3

TEXTURE 63/87-(1B)

M_Z -1.50ϕ

σ_I (or σ_G) 1.71ϕ

Sk_I (or Sk_G) +0.09



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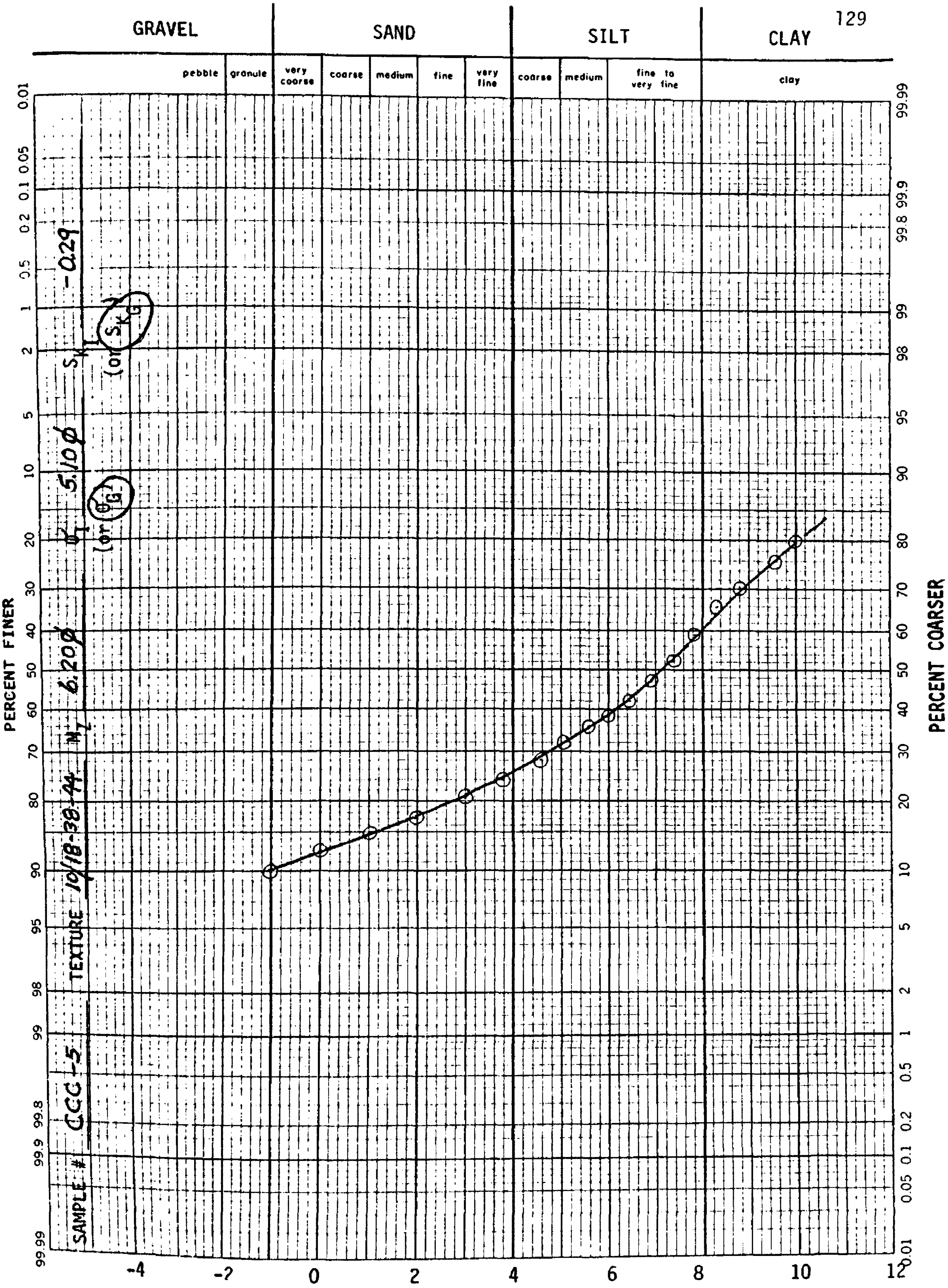


SAMPLE # CCG-5

TEXTURE 10/18-38-44

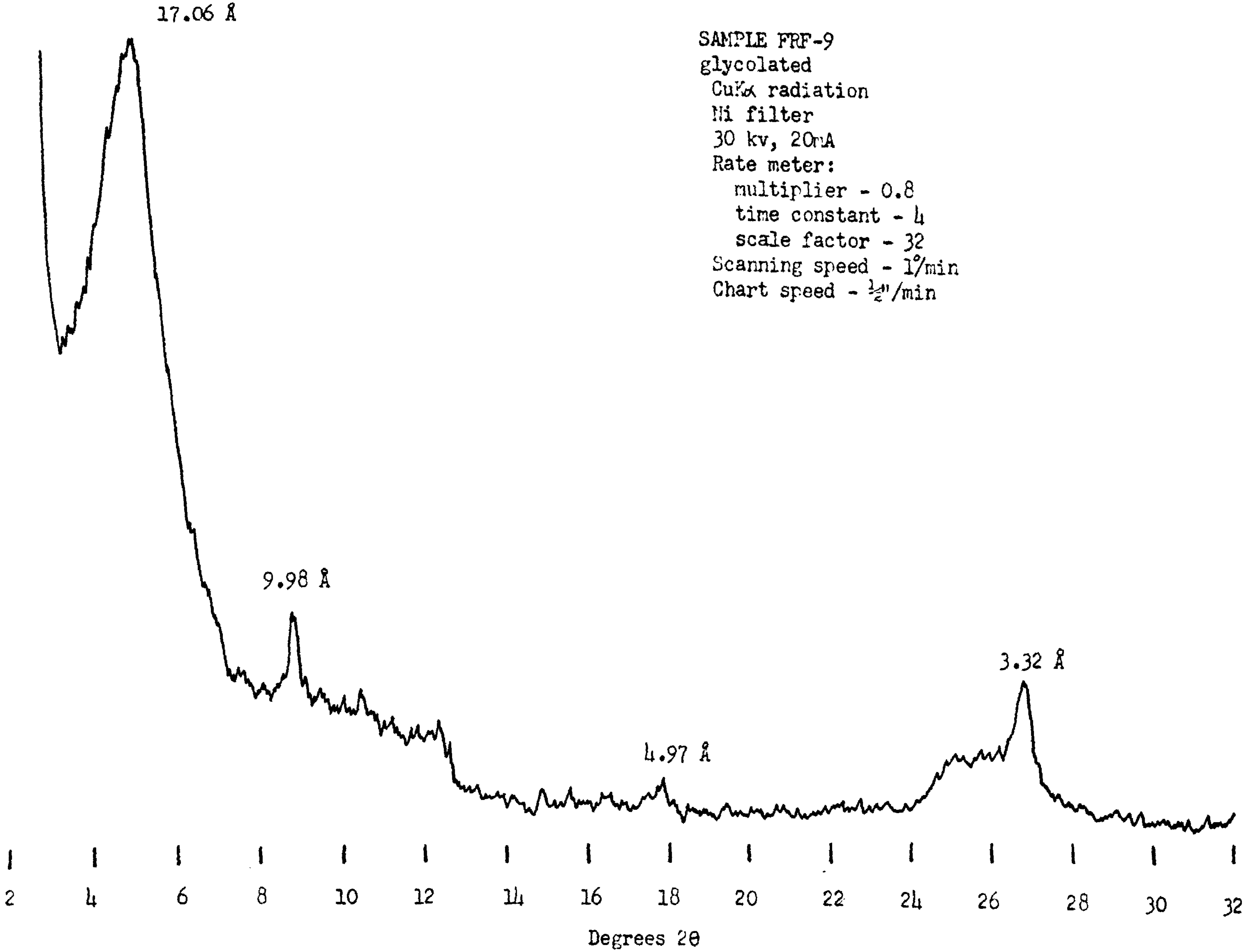
M_I 6.20φ

σ_I (or σ_G) 5.10φ

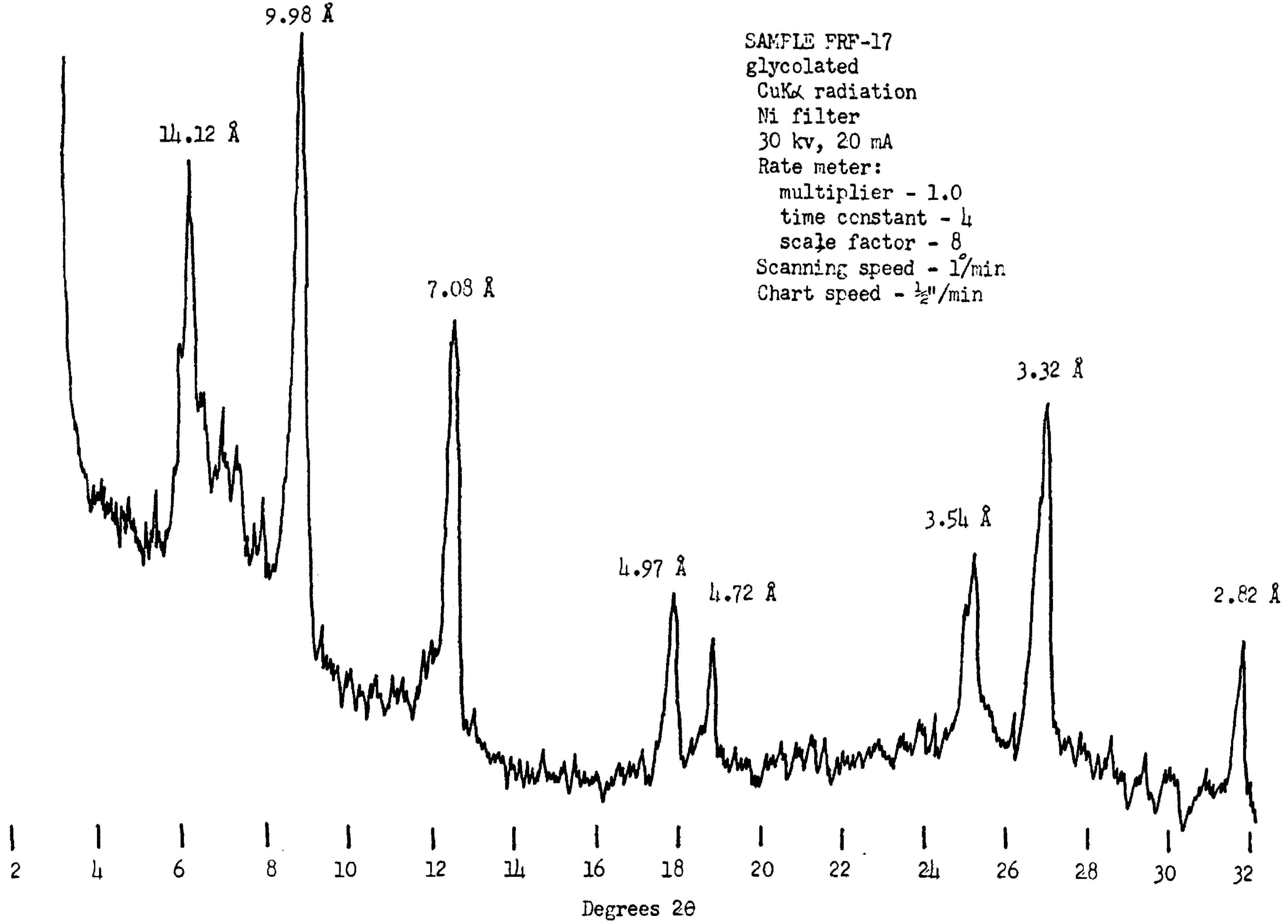
Sk_I (or Sk_G) -0.29

APPENDIX C

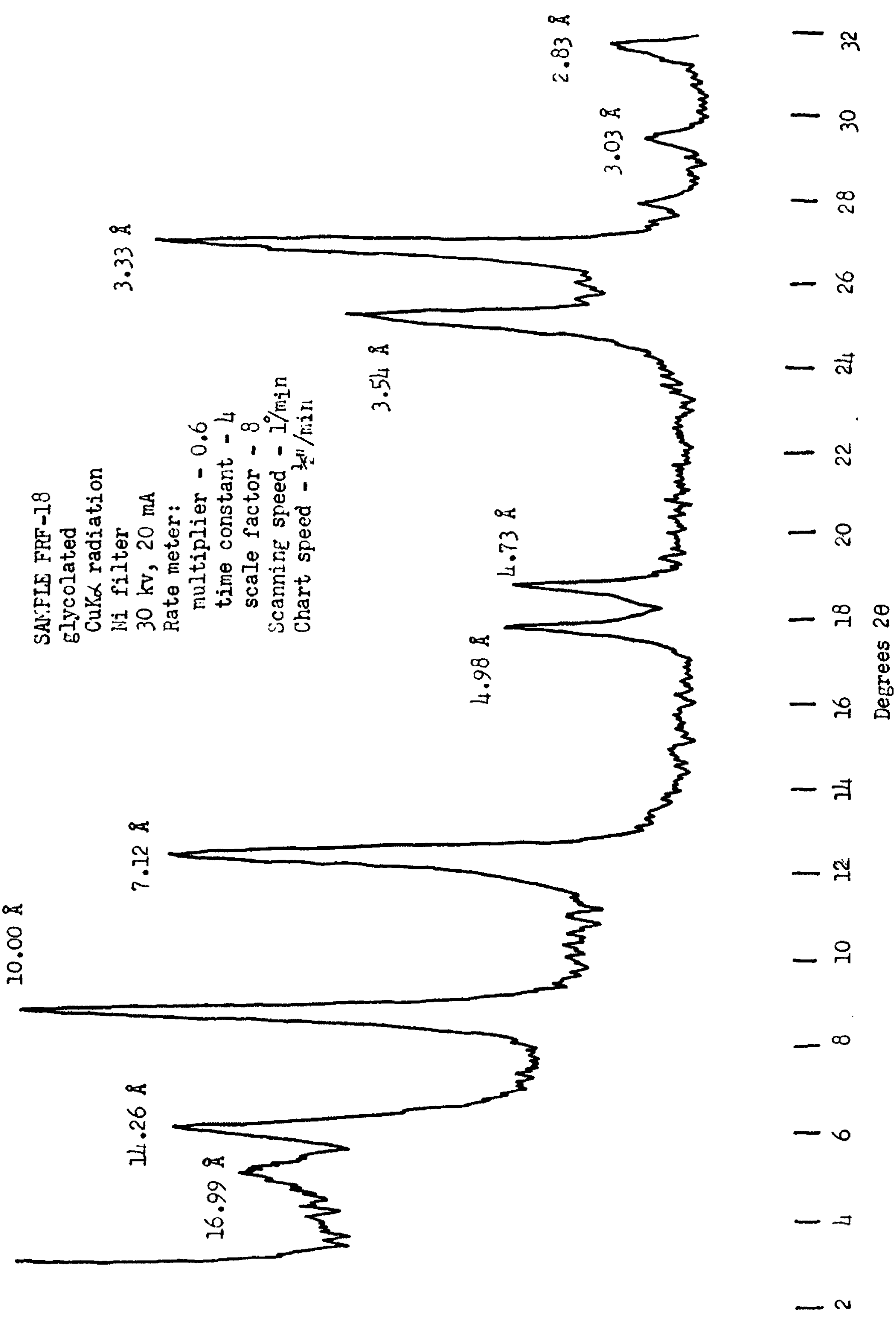
REPRESENTATIVE X-RAY DIFFRACTION PATTERNS



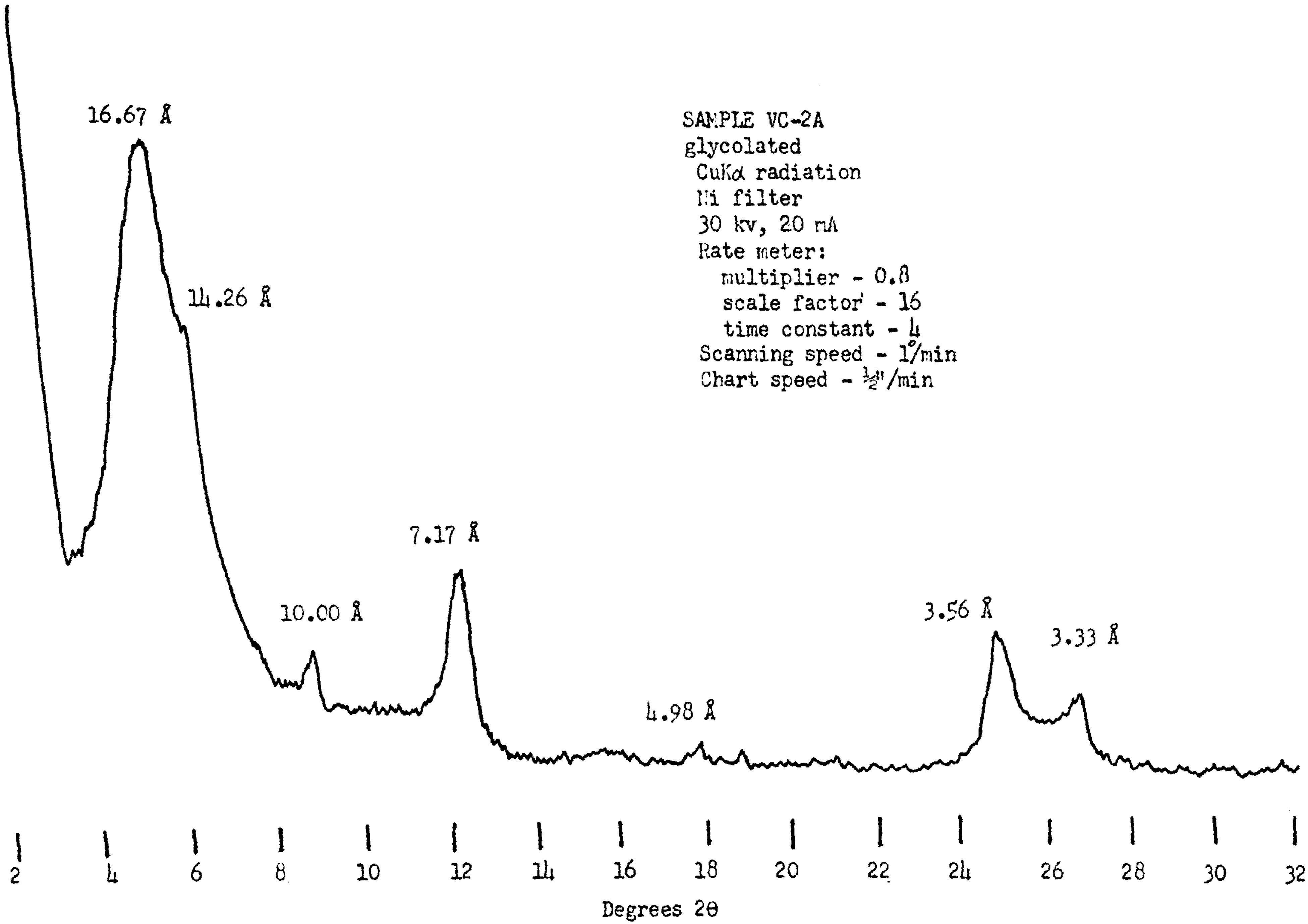
SAMPLE FRF-9
glycolated
CuKα radiation
Ni filter
30 kv, 20mA
Rate meter:
multiplier - 0.8
time constant - 4
scale factor - 32
Scanning speed - 1°/min
Chart speed - ½"/min



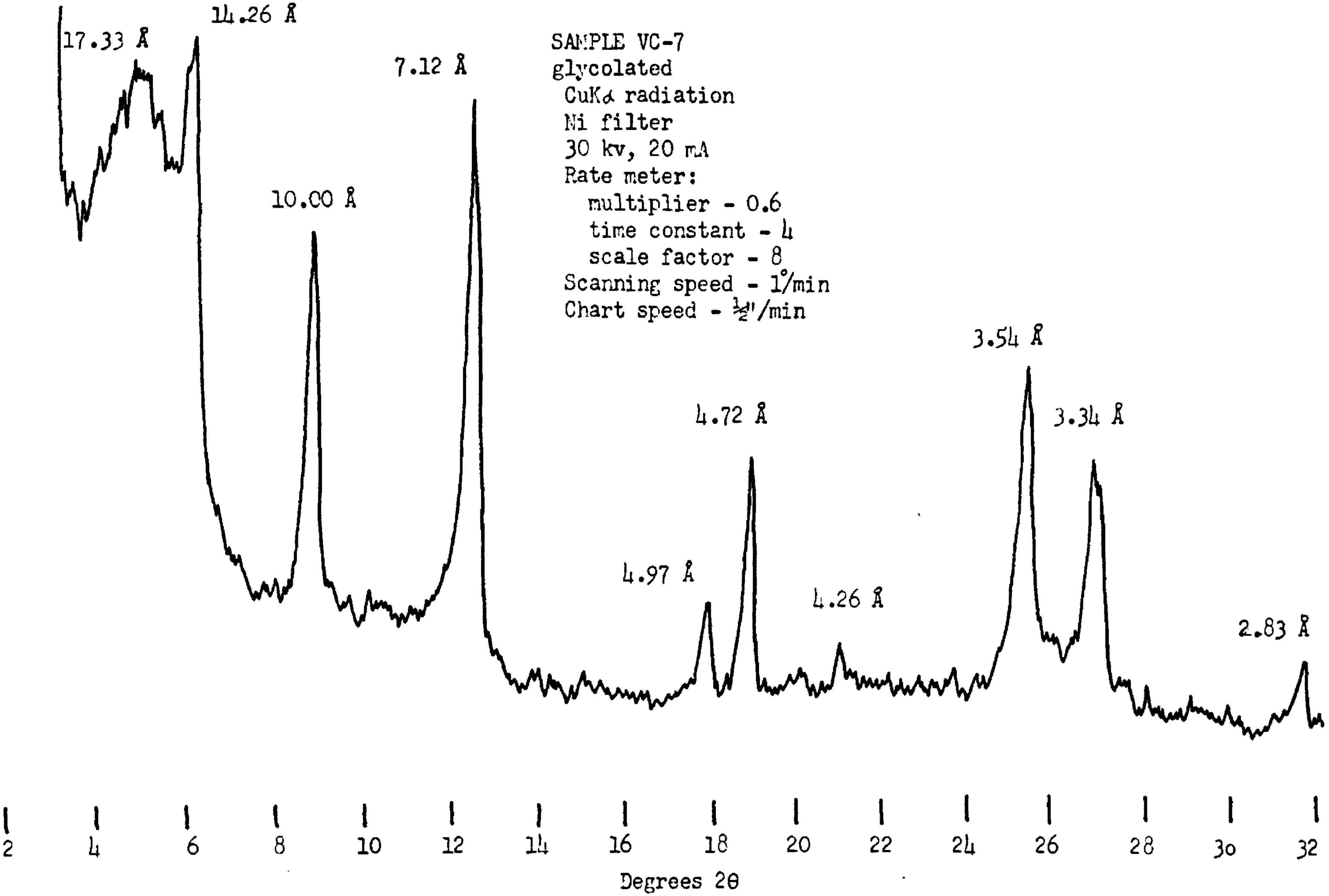
SAMPLE PRF-17
glycolated
CuKα radiation
Ni filter
30 kv, 20 mA
Rate meter:
multiplier - 1.0
time constant - 4
scale factor - 8
Scanning speed - 1°/min
Chart speed - ½"/min

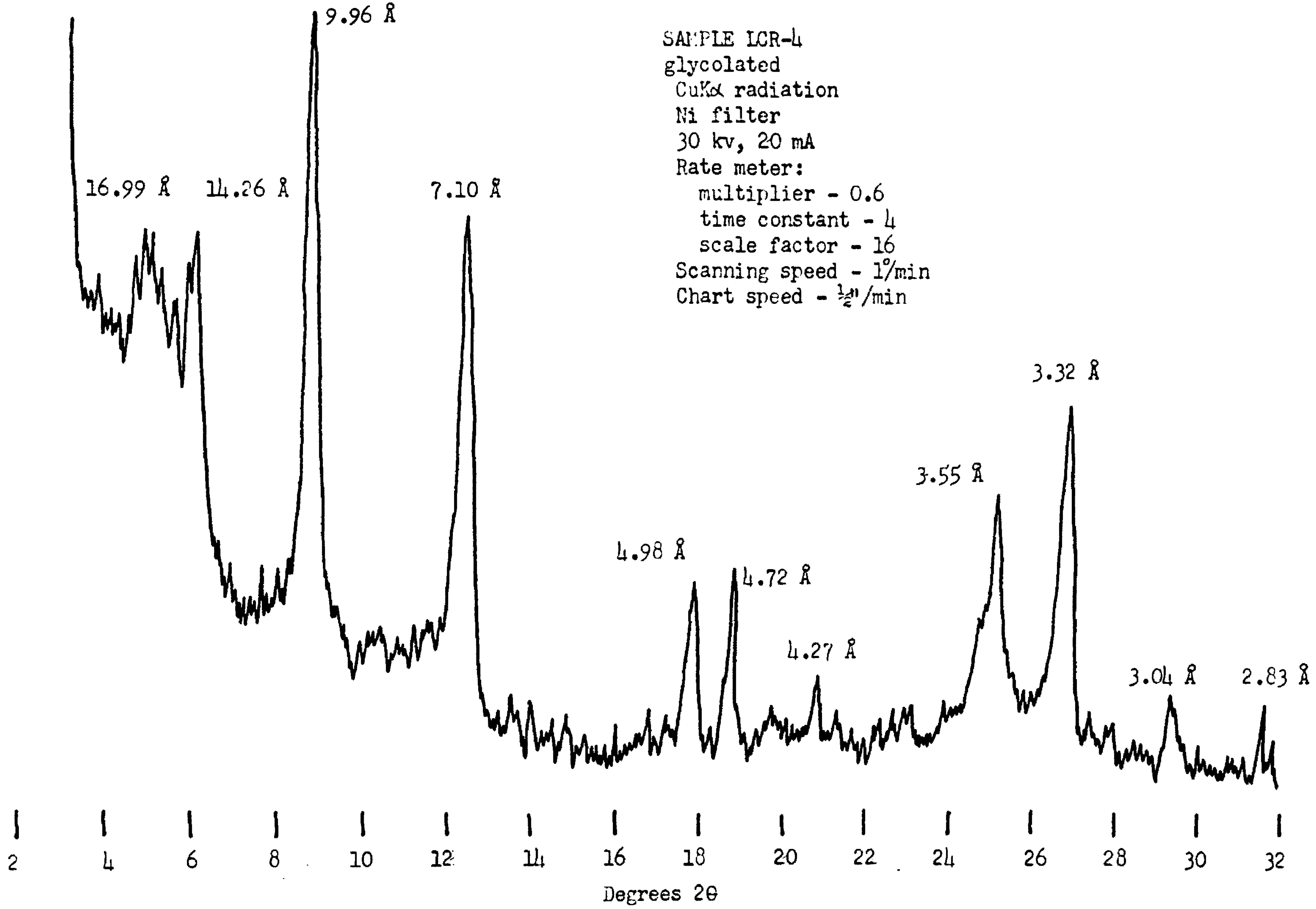


SAMPLE FRF-18
glycolated
CuKα radiation
Ni filter
30 kv, 20 mA
Rate meter:
multiplier - 0.6
time constant - 4
scale factor - 8
Scanning speed - 1°/min
Chart speed - ½"/min

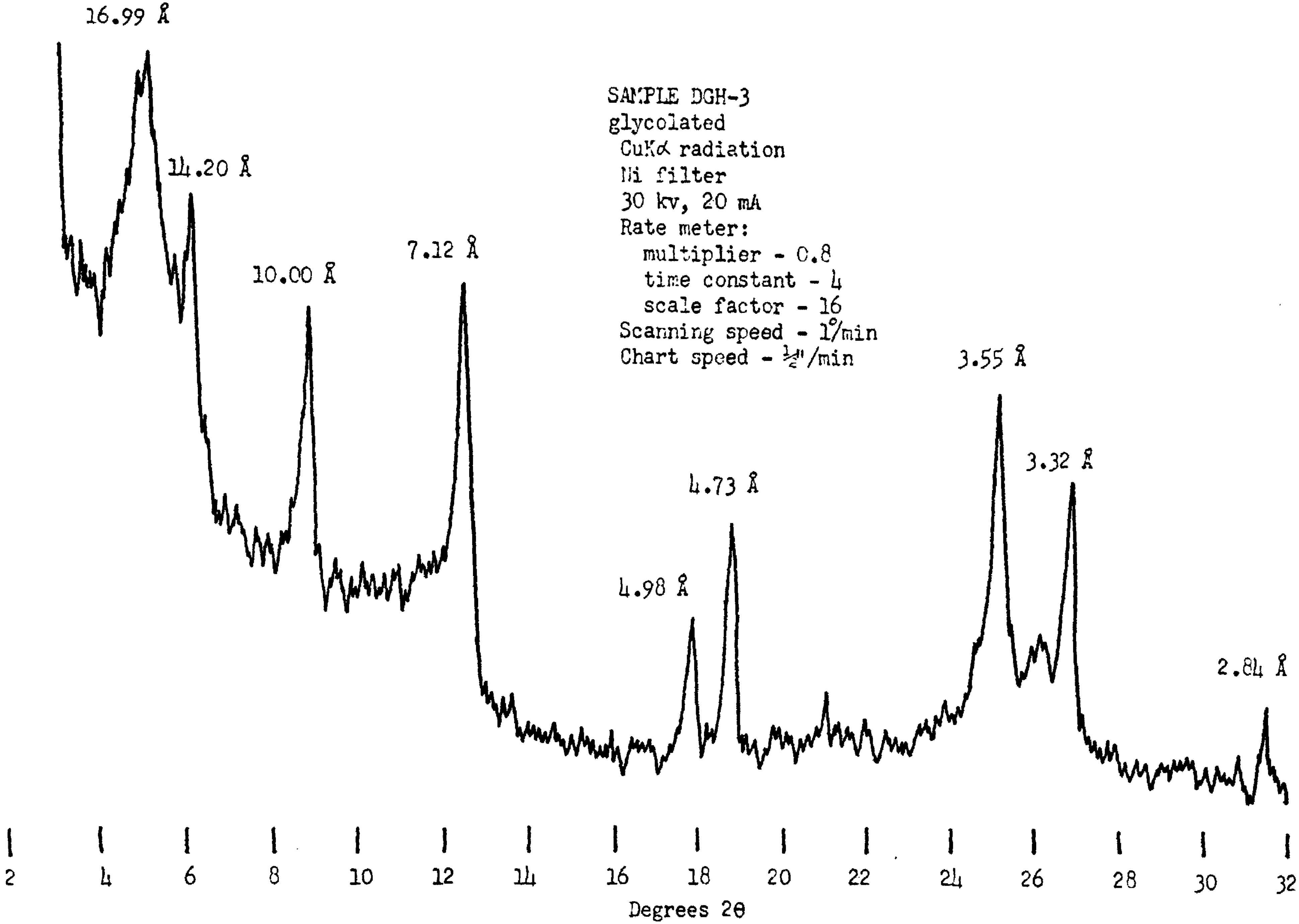


SAMPLE VC-2A
glycolated
CuKα radiation
Ni filter
30 kv, 20 mA
Rate meter:
multiplier - 0.8
scale factor - 16
time constant - 4
Scanning speed - 1°/min
Chart speed - ½"/min

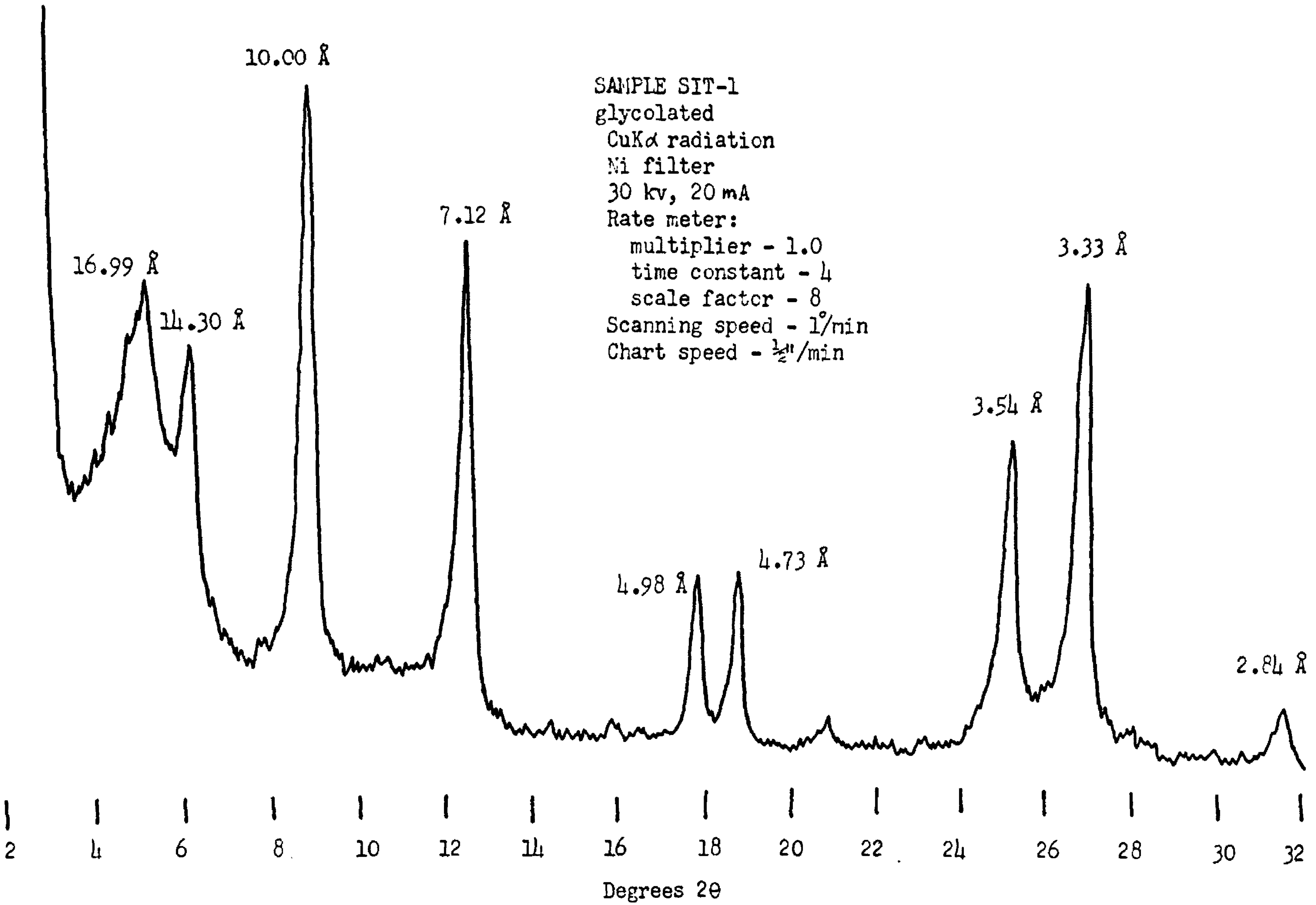

17.33 Å
14.26 Å
7.12 Å
SAMPLE VC-7
glycolated
CuKα radiation
Ni filter
30 kv, 20 mA
Rate meter:
multiplier - 0.6
time constant - 4
scale factor - 8
Scanning speed - 1°/min
Chart speed - ½"/min
10.00 Å
3.54 Å
4.72 Å
3.34 Å
4.97 Å
4.26 Å
2.83 Å
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Degrees 2θ

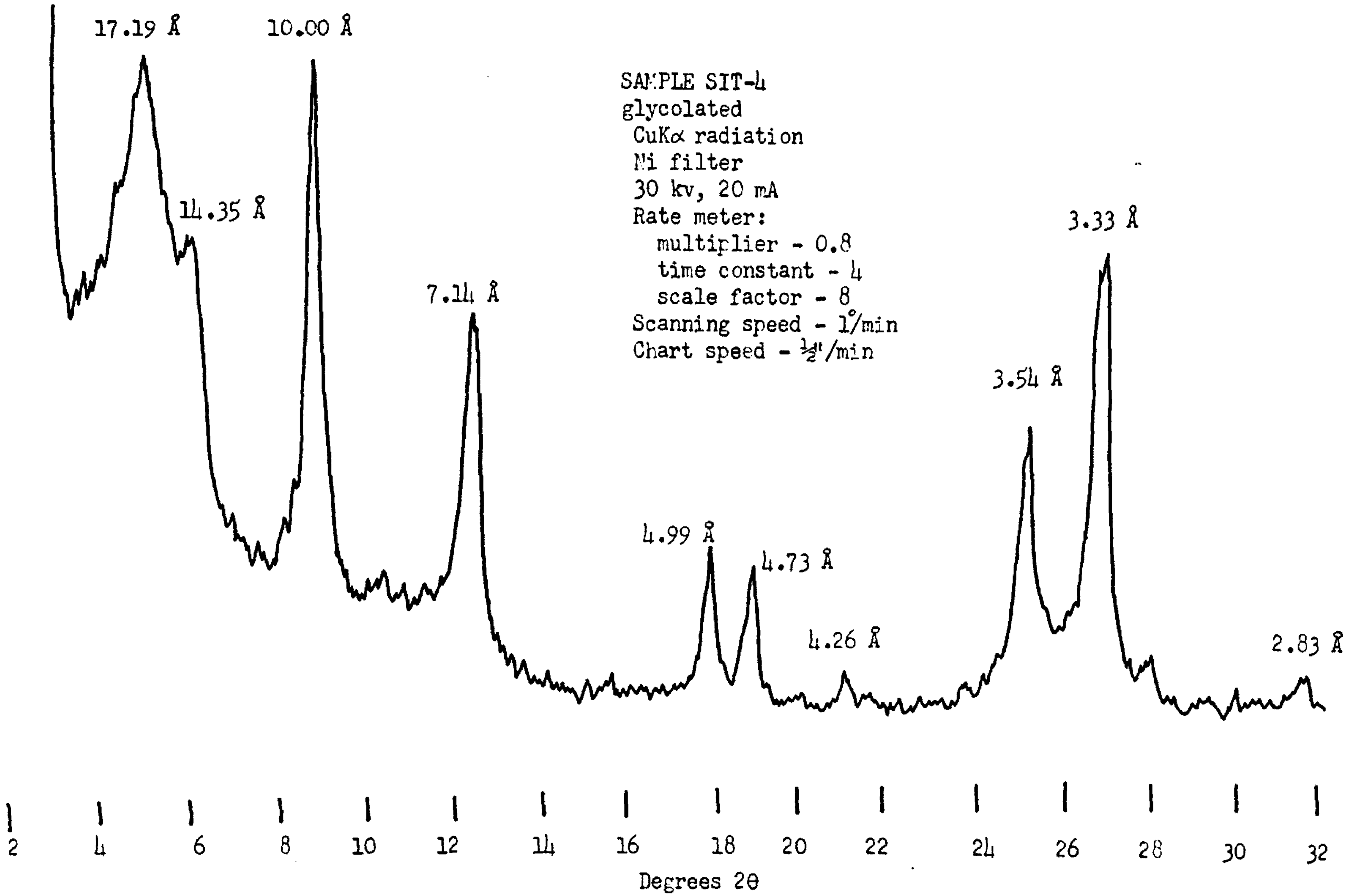


SAMPLE LCR-4
glycolated
CuKα radiation
Ni filter
30 kv, 20 mA
Rate meter:
multiplier - 0.6
time constant - 4
scale factor - 16
Scanning speed - 1°/min
Chart speed - ½"/min



SAMPLE DGH-3
glycolated
CuKα radiation
Ni filter
30 kv, 20 mA
Rate meter:
multiplier - 0.8
time constant - 4
scale factor - 16
Scanning speed - 1°/min
Chart speed - ½"/min


10.00 Å
SAMPLE SIT-1
glycolated
CuKα radiation
Ni filter
30 kv, 20 mA
Rate meter:
multiplier - 1.0
time constant - 4
scale factor - 8
Scanning speed - 1°/min
Chart speed - ½"/min
7.12 Å
16.99 Å
14.30 Å
3.33 Å
3.54 Å
4.73 Å
4.98 Å
2.84 Å
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Degrees 2θ



SAMPLE SIT-4
glycolated
CuKα radiation
Ni filter
30 kv, 20 mA
Rate meter:
multiplier - 0.8
time constant - 4
scale factor - 8
Scanning speed - 1°/min
Chart speed - ½"/min

APPENDIX D

SAND FRACTION LITHOLOGY DATA

SAMPLE CCC-1

Grains counted 293

limestone -- 11%

tan sandstone -- 23%

yellowish-white quartzite and argillite -- 9%

green quartzite and argillite -- 10%

gray quartzite and argillite -- 20%

purple and purplish-red quartzite -- 14%

purple and purplish-red argillite -- 13%

SAMPLE CCC-5

grains counted 306

limestone -- 10%

tan sandstone -- 16%

yellowish-white quartzite and argillite -- 21%

green quartzite and argillite -- 11%

gray quartzite and argillite -- 24%

purple and purplish-red quartzite -- 7%

purple and purplish-red argillite -- 11%

SAMPLE MCC-3

grains counted 291

limestone -- 9%

tan sandstone -- 17%

yellowish-white quartzite and argillite -- 21%

green quartzite and argillite -- 8%

gray quartzite and argillite -- 30%

purple and purplish-red quartzite -- 3%

purple and purplish-red argillite -- 12%

SAMPLE LCR-1

grains counted 303

limestone -- 9%

tan sandstone -- 23%

yellowish-white quartzite and argillite -- 15%

green quartzite and argillite -- 6%

gray quartzite and argillite -- 31%

purple and purplish-red quartzite -- 13%

purple and purplish-red argillite -- 8%

SAMPLE DGH-7

grains counted 298

limestone -- 7%

tan sandstone -- 25%

yellowish-white quartzite and argillite -- 15%

green quartzite and argillite -- 12%

gray quartzite and argillite -- 27%

purple and purplish-red quartzite -- 6%

purple and purplish-red argillite -- 5%

SAMPLE FRF-11

grains counted 295

limestone -- 14%

tan sandstone -- 22%

yellowish-white quartzite and argillite -- 12%

green quartzite and argillite -- 9%

gray quartzite and argillite -- 23%

purple and purplish-red quartzite -- 9%

purple and purplish-red argillite -- 11%

SAMPLE FRF-17

grains counted 307

limestone -- 15%

tan sandstone -- 23%

yellowish-white quartzite and argillite -- 9%

green quartzite and argillite -- 7%

gray quartzite and argillite -- 23%

purple and purplish-red quartzite -- 14%

purple and purplish-red argillite -- 9%

SAMPLE SIT-4

grains counted 304

limestone -- 11%

tan sandstone -- 16%

yellowish-white quartzite and argillite -- 10%

green quartzite and argillite -- 11%

gray quartzite and argillite -- 27%

purple and purplish-red quartzite -- 8%

purple and purplish-red argillite -- 18%

SAMPLE VC-2A

grains counted 300

limestone -- none

tan sandstone -- 25%

yellowish-white quartzite and argillite -- 8%

green quartzite and argillite -- 2%

gray quartzite and argillite -- 54%

purple and purplish-red quartzite -- 6%

purple and purplish-red argillite -- 5%

All grains are non-calcareous and oxidized, some quite strongly. The matrix of many of the quartzites is often oxidized, giving the quartzites a pitted appearance.

SAMPLE VC-9

grains counted 307

limestone -- none

tan sandstone -- 30%

yellowish-white quartzite and argillite -- 4%

green quartzite and argillite -- 5%

gray quartzite and argillite -- 54%

purple and purplish-red quartzite -- 2%

purple and purplish-red argillite -- 5%

All grains are non-calcareous and oxidized, some quite strongly. The matrix of many of the quartzites is often oxidized, giving the quartzites a pitted appearance.