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RECENT SEDIMENTS OF BOLINAS BAY CALIFORNIA

PART C. INTERPRETATION AND SUMMARY OF RESULTS

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RECENT MARINE SEDIMENTS OF BOLINAS BAY, CALIFORNIA

Part C -- Interpretation and Summary of Results

by

P. Wilde, C. Isselhardt, L. Osuch, and T. Yancey

Berkeley, California
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ABSTRACT

Grain size and heavy mineral analyses of 6 cliff, 12 beach, and 44 marine sediment and rock samples from Bolinas Bay were done as a part of a study of sediment transport on the continental shelf off Central California. This work indicates:

(1) The heavy mineral assemblage is predominantly green hornblende with secondary amounts of hypersthene and augite. Glaucophane and jadeite occur in locally high concentrations near shore.

(2) The pattern of distribution of the heavy minerals shows (a) a tongue of high concentrations of minerals with a granitic source extending northwest from the San Francisco Bar, (b) flanked on the north and northeast by increasing landward concentrations of Franciscan metamorphic minerals.

(3) The major source of heavy minerals is the San Francisco Bar. Secondary contributions come from Bolinas Lagoon and the adjacent cliffs.

(4) The circulation in the bay is primarily counterclock-wise; produced by a combination of wave refraction around Duxbury Reef and the tidal Coast Eddy Current. The tidal influence, however, of Bolinas Lagoon is restricted to about one mile from the lagoon mouth. Circulation patterns in the bay greatly influence the sediment distribution.

(5) The annual sediment flux in Bolinas Bay is about 300,000 cubic yards. The bottom sediments in the bay are apparently in quasi-equilibrium.

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I. INTRODUCTION

This work is part of a long term study of sediment transport on the continental shelf off central California sponsored by the U. S. Corps of Engineers and the Department of Civil Engineering, University of California, Berkeley. In addition, this work is part of a general study of the factors that influence the natural environment of Bolinas Lagoon now being conducted as a cooperative effort involving the University of California, Berkeley; the U. S. Corps of Engineers; the U. S. Geological Survey; the Department of Agriculture, Soil Conservation Service; and consultants for the Bolinas Harbor District.

Marine samples were collected from Bolinas Bay on 26-27 March 1968. The analyses of the marine sediments of Bolinas Bay were done at the University of California, Berkeley, utilizing the facilities of the Department of Civil Engineering and Department of Geology and the Institute of Marine Resources. The techniques and methods of sample preparation are described in Isselhardt and others (1968, 1969).

The results of the marine study are presented in three volumes:

Part A -- Introduction and Grain Size Analysis (Isselhardt and others, 1968)

Part B -- Mineralogical Data (Isselhardt and others, 1969)

Part C -- Interpretation and Summary of Results (this volume)

The chief goals of this study of Bolinas Bay are 1) characterization of the sediments, 2) identification of the sedimentary environments, and 3) determination of the sediment transport regimes.

II. REGIONAL SETTING

A. Location

Bolinas Bay is a parabolic shaped embayment of the Pacific Ocean at the southern tip of the Point Reyes Peninsula, ten miles north of the entrance to San Francisco Bay (Fig. 1). Bolinas Bay is bounded (1) on the north by the Bolinas Cliffs; (2) on the northeast by Sea Drift Spit, the barrier bar at the entrance to Bolinas Lagoon; (3) on the east by the Marin County Coast Ranges; (4) on the south by the Pacific Ocean; and (5) on the west by the shoals of Duxbury Reef. The long axis of the bay points towards Bolinas Lagoon and is oriented about N 40°W along the submarine trace of the San Andreas Fault.

B. Climate

The area enjoys a California maritime climate with a rainy winter season from November through April and a dry but foggy summer. Annual rainfall is about 30 to 40 inches. The prevailing winds are from the northwest with recorded winds from the southeast exceeding 75 miles per hour (Ritter, 1969, p. 7). Figure 2 shows the wave diffraction diagram for waves with 10 second period from the prevailing northwest wind direction.

C. Physiography and Drainage

The land area in the drainage adjacent to Bolinas Bay can be divided, east to west, respectively, into three topographic regions: (1) Bolinas Ridge which extends northeastward from Mount Tamalpais to Tomales Bay; (2) the San Andreas rift zone of rolling hills, sag ponds, and Bolinas Lagoon; and (3) the Bolinas Plateau with Duxbury Reef, a wave cut bench at the base of the western edge of the plateau (U.S.G.S.

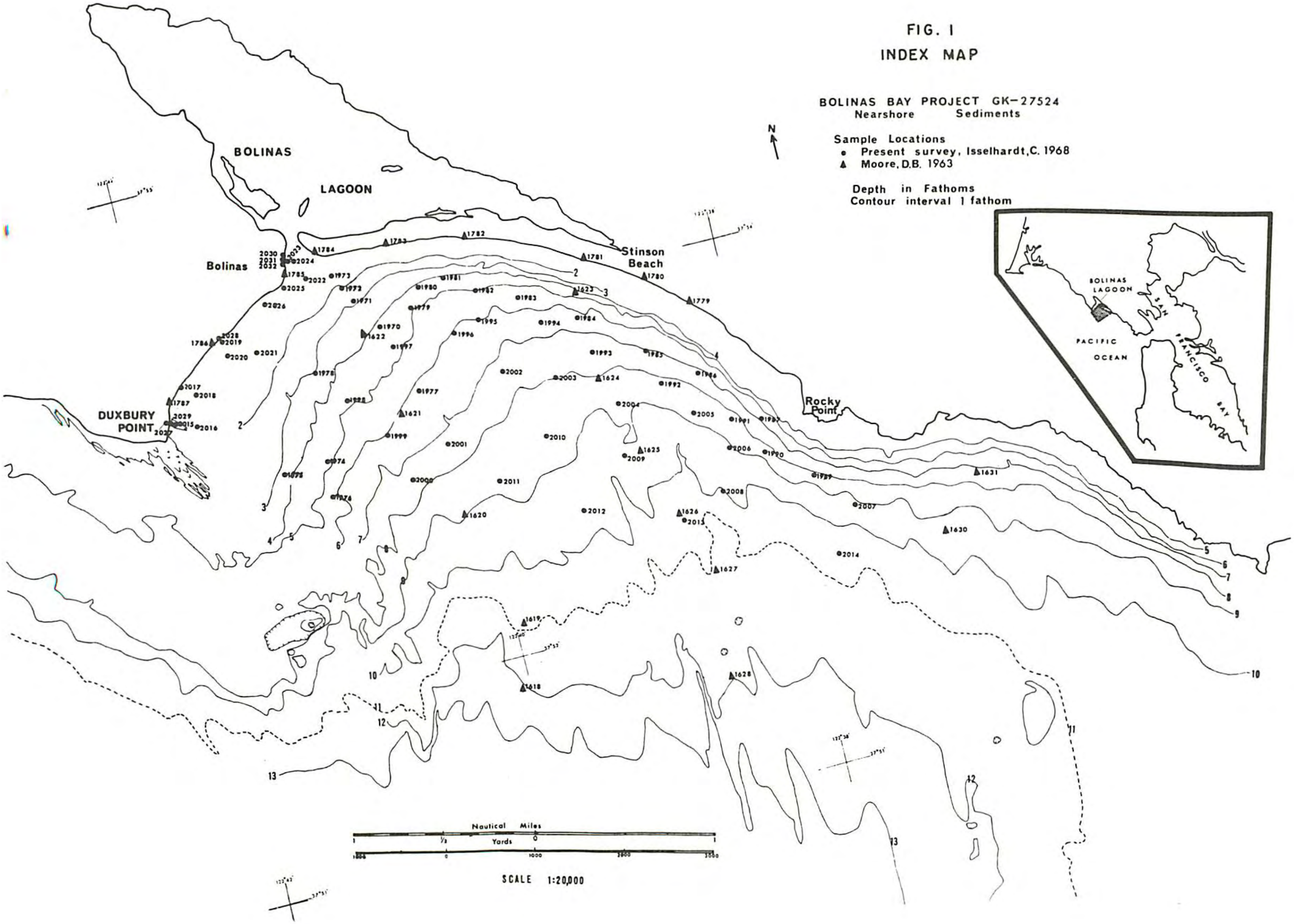


FIG. I
INDEX MAP

BOLINAS BAY PROJECT GK-27524
Nearshore Sediments

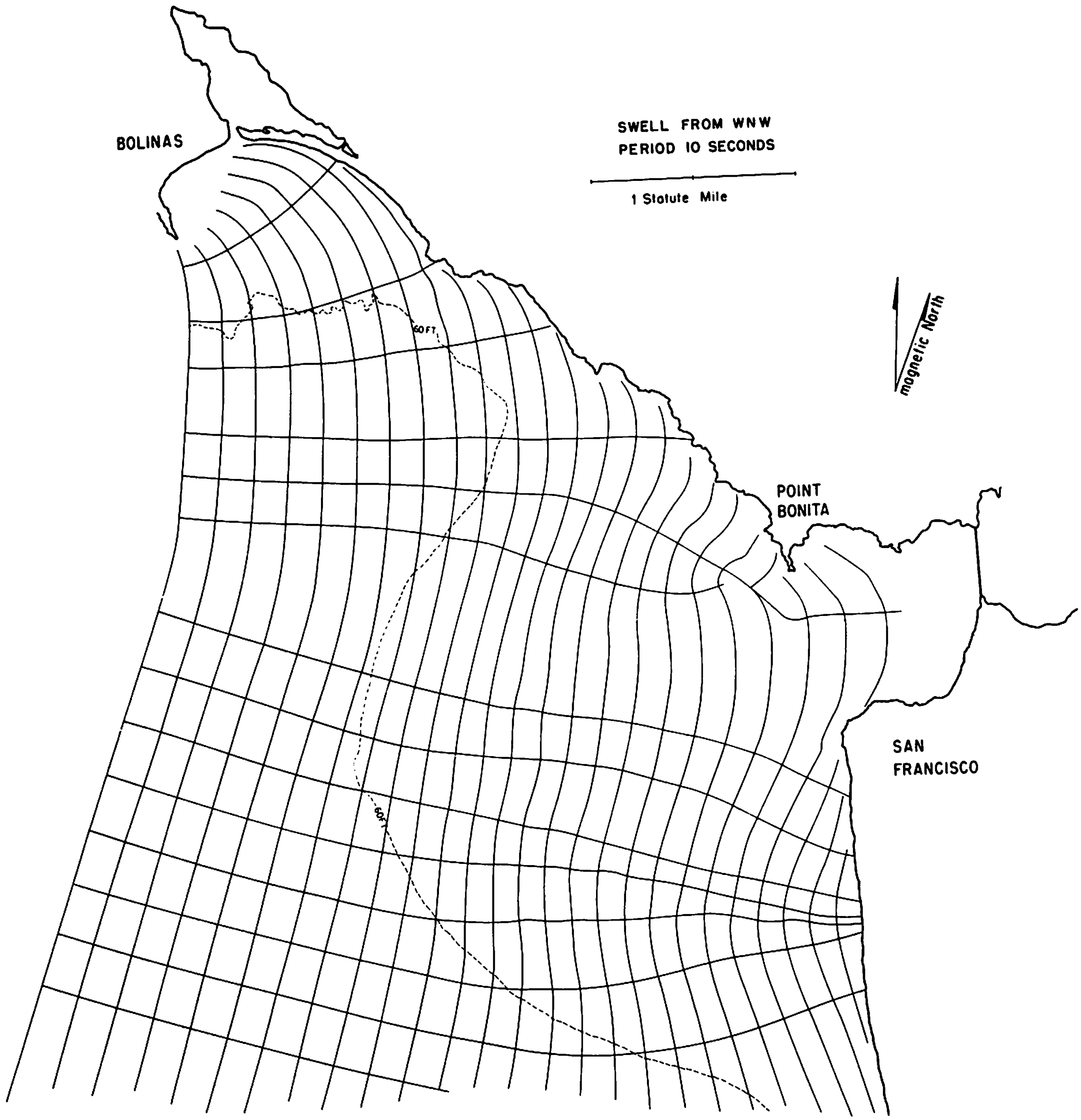


FIG. 2 WAVE REFRACTION DIAGRAM (WNW, 10 SEC) FOR MARIN-SAN FRANCISCO AREA

$7\frac{1}{2}$ minute quadrangle Bolinas sheet). The main feature of the Bolinas region is the conspicuous rift valley of the San Andreas Fault, which is prominently expressed by Bolinas Lagoon. In Bolinas Bay it can be traced, less conspicuously, in the submarine contours. This rift separates structural blocks of greatly different geological composition, as well as acting as a focus for drainage within the region (Fig. 3).

On the east side of the rift is the high Bolinas Ridge which has a steep western slope dropping directly down to Bolinas Lagoon and Bolinas Bay. Bolinas Ridge is a long NNW - SSE trending ridge with a crest line very close to the San Andreas rift. Because of this feature, the drainage divide separating watersheds of Bolinas Bay and Lagoon from those of San Francisco Bay lies very close to Bolinas Bay and Lagoon.

West of the rift there is a more varied topography than on the east side. To the northwest is a NNW - SSE trend of low and moderately high hills cut by deep stream valleys. Directly bordering the west side of Bolinas Lagoon is Bolinas Plateau, which is a marine terrace lying at an elevation of 180 feet. This terrace is bordered on the west, south, and east by steep cliffs. The terrace has been deeply incised by several small and large streams that drain to the east and to the southwest. South of Bolinas Plateau lies Duxbury Reef, which is the modern wave cut erosion surface extending off Duxbury Point. Ocean waves are cutting into and eroding the rocks of Duxbury Point and are gradually eroding away Bolinas Plateau. Duxbury Reef extends nearly two miles to the south of the Bolinas Cliffs, of which about three-quarters of a mile is exposed intertidally, and forms the west

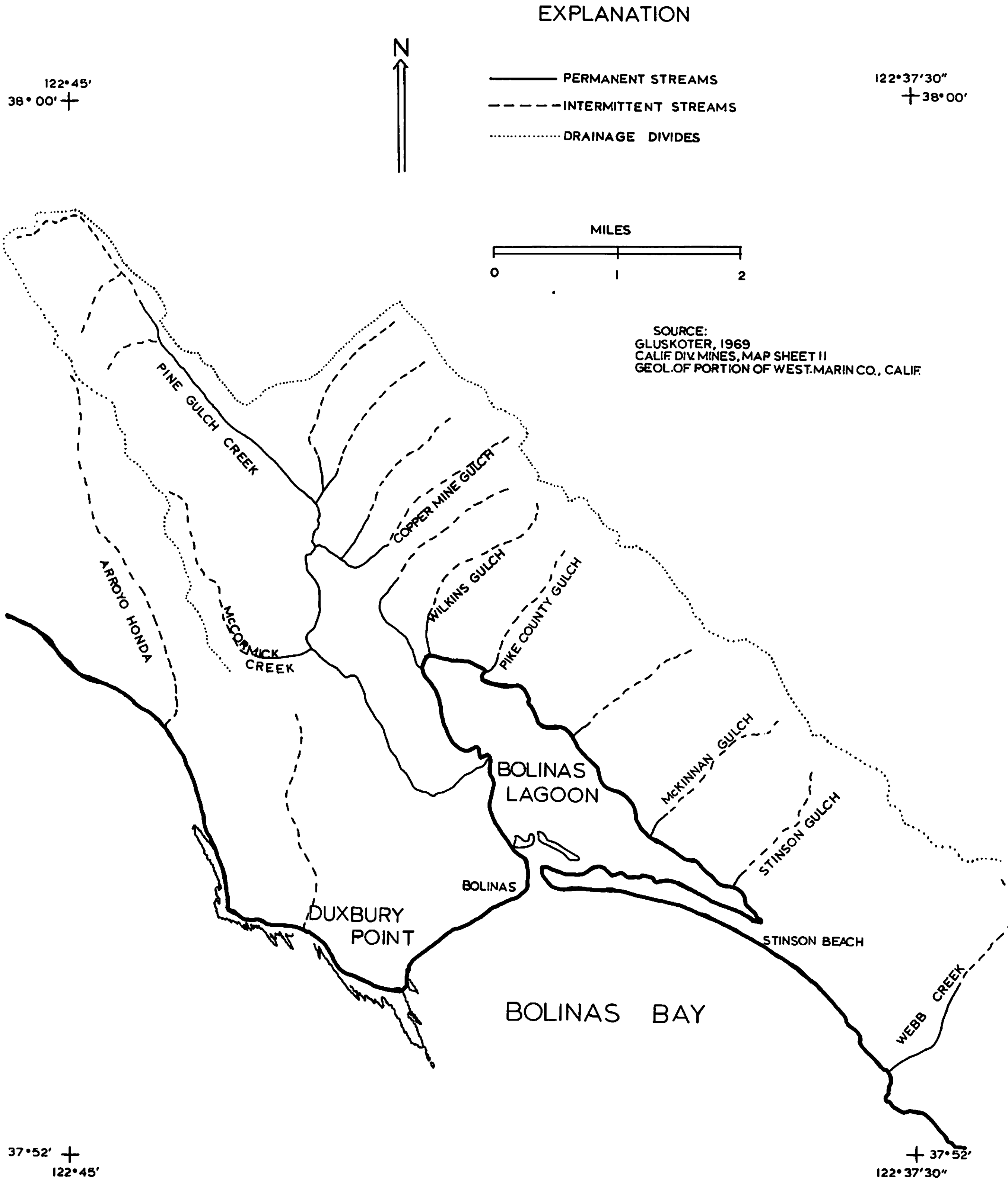


FIG. 3 BOLINAS BAY DRAINAGE BASIN

boundary of Bolinas Bay.

The drainage patterns in the Bolinas Bay drainage basin are markedly different on opposite sides of the rift valley. On the east side along Bolinas Ridge, the drainage consists of many small, short, high gradient streams running parallel to each other and are roughly equally spaced along the ridge. There are no major stream valleys on this side of the drainage basin. The largest stream is Webb Creek, at the south end of the study area. On the west side of the rift valley nearly all of the drainage is concentrated in Pine Gulch Creek, which empties into Bolinas Lagoon. Apart from Pine Gulch Creek, only one small stream drains the west side of the rift and this one runs SSE a short distance along the rift valley and empties into the head of Bolinas Lagoon. All the streams in the area except Webb Creek drain into Bolinas Lagoon which empties into Bolinas Bay.

D. Bathymetry

Depth contours in Bolinas Bay generally are sub-parallel to the shore line (Fig. 1). The bottom slopes are steepest on the eastern side near Rocky Point where the 10 fathom line is one-half mile offshore. The contours diverge to the west where adjacent to Duxbury Reef the 10 fathom line is one and three-quarters miles offshore.

Two submarine channels heading southeast downslope can be traced seaward of 7 fathoms. These channels are aligned with the northwest-southeast trend of the San Andreas Fault. The channels empty into a depression lying between Bolinas Bay and the north rim of the San Francisco Bar (Potato Patch Shoal).

Changes in bathymetry with tidal fluctuations apparently are limited to a small region with an off shore bar just seaward of the entrance to Bolinas Lagoon (Ritter, 1969). Seasonal depth changes are being studied now by comparison of various precision depth surveys of the bay. Preliminary results (Johnson, 1969) indicate that seasonal depth changes also are limited to shallow nearshore regions near the entrance to the lagoon.

E. Tides

The Bolinas area has a mixed tide (Fig. 4) like San Francisco Bay, with a maximum range of 8 feet from higher high water to lower low water (Ritter, 1969, p. 13).

F. Currents

1) Open Ocean Currents

The major offshore current off the central California coast is the southwesterly flowing California Current which is the eastern return gyre of the clockwise circulation pattern of the North Pacific (Reid and others, 1958; U. S. Hydro, 1947). During the winter months a coastal northward flowing current called the Davidson Current (Reid and Schwartz-lose, 1962) interposes itself between the coast and the California Current. The Davidson Current flows during the periods of maximum water runoff and erosion (Hendricks, 1964) on the adjacent land areas. Thus the Davidson current probably carries a significant load of suspended sediment in a northward direction along the coast.

2) Longshore Currents

The direction of longshore drift is a function of the angle of wave impingment on the coast. In Bolinas Bay, therefore, the prevailing direction of drift should develop in response to the prevailing west

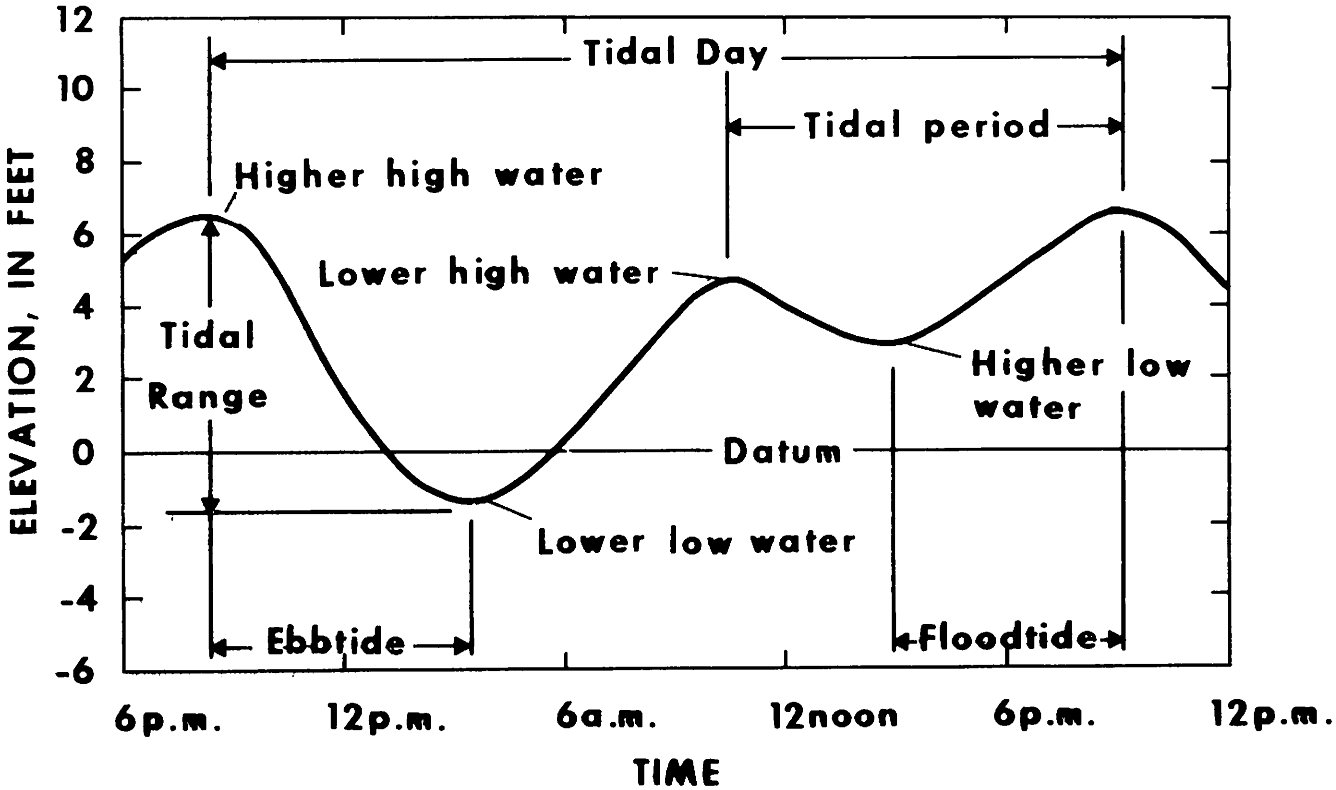


FIG. 4 A TYPICAL MIXED TIDE ON THE PACIFIC COAST NEAR BOLINAS LAGOON. DATUM IS MEAN LOWER LOW WATER. (FROM RITTER, p. 13, 1969)

northwest swell (Fig. 2). Refraction of the waves about Duxbury Reef would produce a northerly drift north of the Golden Gate. The drift probably is discontinuous from Point Bonita to at least Rocky Point because of (1) the tidal influence of San Francisco Bay, and (2) numerous headlands which tend to break up any long term drift.

Northerly drift within Bolinas Bay, at least on the eastern side, is suggested by the orientation of Sea Drift Spit across the mouth of Bolinas Lagoon. The spit is broached by tidal action from Bolinas Lagoon only on the western side, indicating major sand movement northwestward from Stinson Beach. Drift measurements by dye drops (rhodamine B) and floating rubber balls by the U. S. Geological Survey (Ritter, 1969, p. 30), and by milk bottle caps (Brown and Caldwell Consulting Eng., 1961) indicate counterclockwise drift in the eastern portion of Bolinas Bay.

Littoral drift of beach sand by tracing the movement of fluorescent sand is still being analyzed by the U. S. Geological Survey (Ritter, 1969, p. 32).

3) Tidal Currents

The most apparent water movements in Bolinas Bay are tidal, due to the configuration of the coastline and the tidal prisms of Bolinas Lagoon (see Ritter, 1969, p. 13-28) and San Francisco Bay (U.S.C.& G.S. Tidal Chart, San Francisco Bay, 1947). Scuba divers (R. Zelwer, 1968, personal communication) found strong non-surging currents (not of wave origin) extending to the bottom near station 1627 (outer central part of Bolinas Bay) in about 70 feet of water, indicating principally tidal flow. The U. S. Coast Pilot (No. 7, 1968, p. 152) notes the coast eddy current immediately outside the San Francisco Bar, where it is directed northwest.

G. Previous Work

Sediments of Bolinas Bay were initially studied by Trask (1958, 1959, 1961) as part of grain size studies of beaches north of San Francisco Bay. Trask's work was concerned with the grain size character of beach sediments and their relation to the morphological characters of various beaches and their seasonal changes. Trask included three beach profiles from Stinson Beach in his study, and maintained observations on them over a two year period.

Following the early work of Trask, a series of investigations were made on the grain size distribution and mineralogical composition of beach and submarine sediments of the coast north of San Francisco. Studies on beach and submarine sediments of Marin Co. have been made by Schatz (1963), Minard (1964), Moore (1965) and Cherry (1964, 1966) as part of the Coastal Sediments project of the U. S. Army Corps of Engineers. Moore (1965) investigated the modern marine sediments near the Golden Gate and the San Francisco Bar, and included Bolinas Bay in the limits of his area of study. He obtained six submarine samples in Bolinas Bay and nine beach samples from both Stinson Beach and the beach at the foot of Bolinas Cliffs. This work produced the first data on light mineral and heavy mineral composition of sediments in Bolinas Bay, and revealed regional trends in the composition of submarine sediments in this area. Bolinas Bay lies mostly within one of the heavy mineral provinces outlined by Moore.

The next, and most recent, work on the sediments of Bolinas Bay has been that of Isselhardt and others (1968), Isselhardt and others (1969), Ritter (1969), and Helley (in Ritter, 1969). Isselhardt and others have studied the submarine and beach sediments of Bolinas Bay, and have presented reports on the grain size distributions (Isselhardt and others, 1968) and on the heavy mineral composition (Isselhardt and others, 1969). Helley (in Ritter, 1969) has investigated the sediments of Bolinas Lagoon, and of the open ocean beach sediments adjacent to the mouth of Bolinas Lagoon, including several samples from the length of Stinson Beach. He studied only the light mineral fraction of these sediments. Ritter (1969) studied the grain size distribution of sediments in this same area.

The subareal geology of the neighboring region has been studied by Anderson (1899), Gilbert (1908) in conjunction with the 1906 movement of the San Andreas Fault, Lawson (1914), Douglas and Rhoades (1915), Gluskoter (1962, 1969), and Galloway (1966).

H. Geology

The Bolinas Bay drainage area is at the southern edge of the Northern Coast Ranges and is divided by the San Andreas rift zone into two distinct geological provinces (Fig. 5). The eastern section noted topographically as Bolinas Ridge consists entirely of Franciscan Formation rocks except for recent alluvium in stream valleys. In the Bolinas Bay drainage area the Franciscan consists of undifferentiated sandstones, chert, serpentine, and diabases. Feldspathic sandstone is the most abundant rock type (Gluskoter, 1962).

The area to the west of the San Andreas fault is in the Salinian Quartz Diorite province; although no granitic type rocks crop

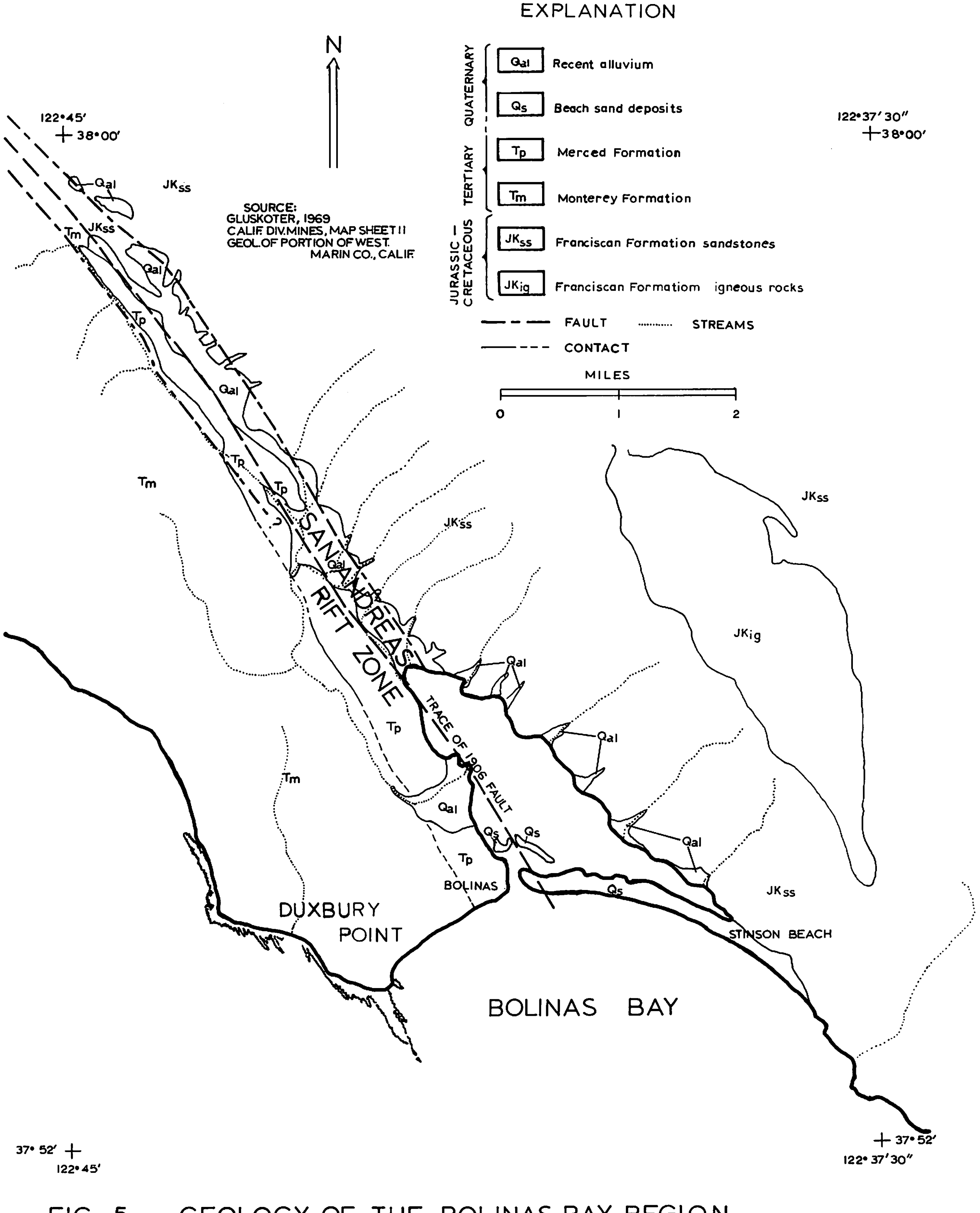


FIG. 5 GEOLOGY OF THE BOLINAS BAY REGION

out in the Bolinas Bay drainage, such rocks are found nearby at Point Reyes, Tomales Point, and Bodega, and presumably are the basement rocks in the Bolinas area. Two Cenozoic formations, the Monterey Fm., and the Merced Fm. form the surface exposures, except for patches of recent alluvium, over the entire Bolinas Peninsula. The Merced Formation, found as a thin band parallel to the fault, consists of fine grained, friable sandstones and siltstones with small amounts of fossiliferous sandstone and pebble conglomerates. The Monterey Formation is the most extensive unit found on the Bolinas Peninsula and forms the rapidly eroding cliffs extending from Duxbury Reef almost to the Bolinas Lagoon entrance. The Monterey rocks are predominately tan to gray mudstones, silty mudstones, and siltstones with occasional lenses of sandstones.

The San Andreas rift zone is a jumbled mass of rock composed of slivers from formations on both sides of the zone. The fault is active and displacements of one foot vertically and 8-14 feet horizontally were recorded in the Bolinas area from the 1906 earthquake (Lawson, 1908, p. 70, 84). In fact, the epicenter of the 1906 earthquake was located near Bolinas Bay on the Pt. Reyes Peninsula.

For more detailed information on the geology of the Bolinas area, see Weaver (1949), Gluskoter (1962, 1969), Galloway (1966), and Bailey (1964).

III. SEDIMENTARY DATA

A. Grain Size Properties

The statistical parameters median grain size, sorting, coefficient, skewness, and kurtosis are derived from data presented in Part A of this study (Isselhardt and others, 1968) and are plotted on maps of Bolinas Bay (Figs. 6, 7, 8, and 9).

The average of the median grain size for the bay sediments is about 0.100 mm, or fine sand, with extremes ranging from 0.400 (medium sand) to 0.070 (very fine sand). The median grain size (Fig. 6) generally decreases in a seaward direction. Several areas depart from this trend, where equal values of median grain size cut across the depth contours. They include an increase in grain size in a narrow band adjacent to Rocky Point; a decrease in grain size adjacent to Duxbury Reef; a narrow tongue of coarser sediment extending seaward from the entrance of Bolinas Lagoon; and, an unusual S-shaped pattern in the grain size contours in the middle of the bay.

The first two cases are associated with topographic irregularities of the sea floor; Rocky Point causing a seaward extension of coarse grain sizes, and Duxbury Reef being associated with finer sediment than found at similar depths in other parts of the bay. The case of Duxbury Reef is somewhat unexpected in view of the fact that underwater prominences normally produce greater water turbulence, and a resultant coarser sediment. The accumulation of finer sediment along the eastern reef front is a result of the average direction of open ocean waves, which come from the northwest. The eastern side of the reef is the protected side of the reef, and quieter conditions prevail permitting

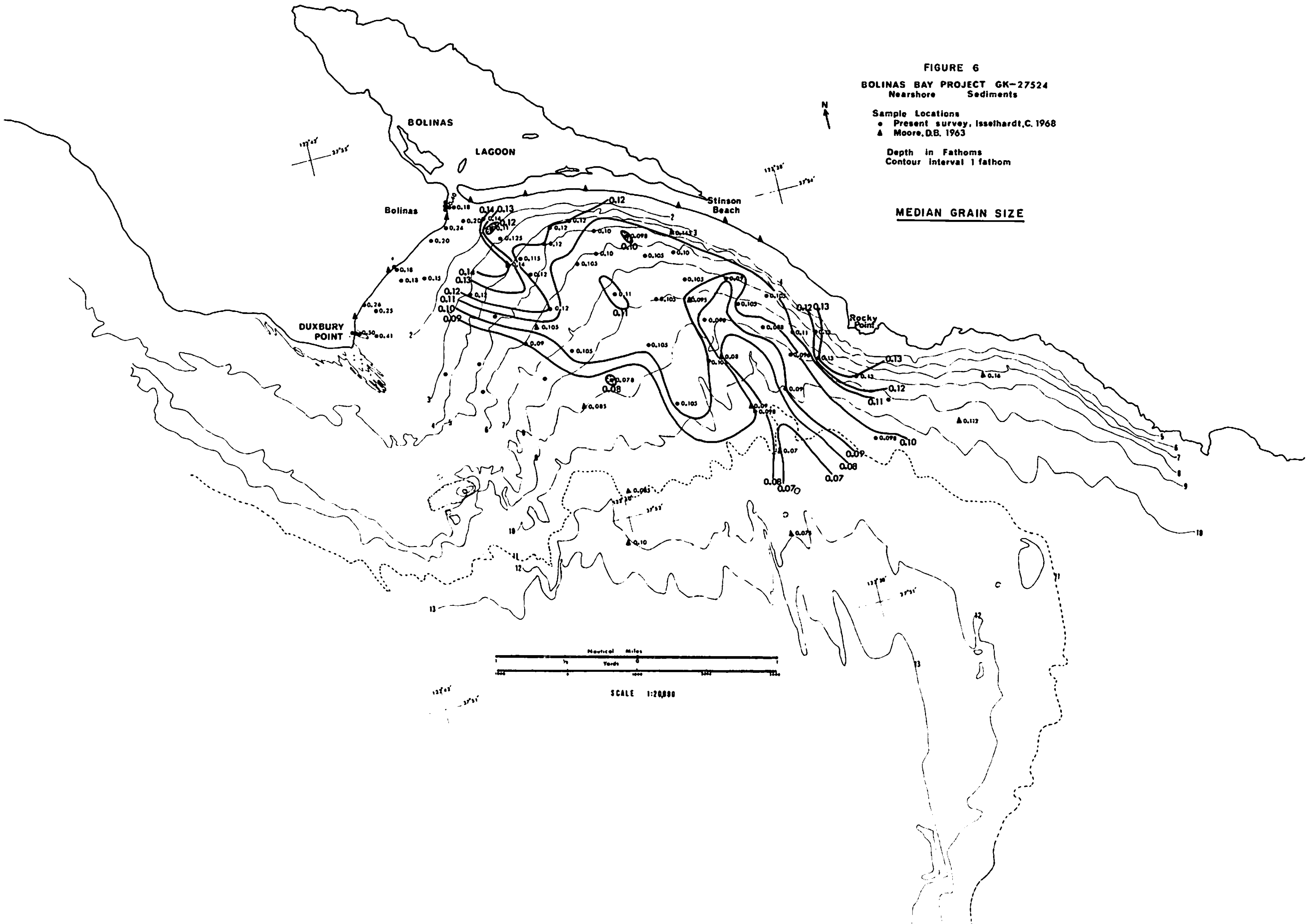


FIGURE 6
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
MEDIAN GRAIN SIZE
N
BOLINAS
LAGOON
Bolinas
Stinson
Beach
DUXBURY
POINT
Rocky
Point
Nautical Miles
Yards
SCALE 1:20,000

finer sediment to accumulate. Away from the reef, waves diffracting into the bay around Duxbury Reef produce a more nearly depth controlled pattern of grain size distribution.

The tongue of coarser sediment extending from the entrance to Bolinas Lagoon is continuously traceable to about 50 feet water depth. The tongue lies perpendicular to the depth contours, with the coarsest sediments lying closest to the entrance of the lagoon. The tongue is obviously formed by strong tidal currents flowing through the entrance of Bolinas Lagoon. This evidence corroborates the measurements of Ritter (1969) who demonstrated the occurrence of strong tidal currents, and demonstrates that the currents have an effect on bottom sediments at least a mile away from the entrance, or, that the currents have a scouring effect on the bottom to depths of at least 40 feet.

The greatest anomaly on the median grain size chart is the S-shaped pattern in the middle of the bay in deeper water. This feature consists of a narrow coarser sediment tongue extending seaward lying directly adjacent to a fine sediment tongue extending shoreward. These tongues lie nearly parallel to narrow topographic highs and lows running out to the seaward edge of the bay. The coarse sediment tongue is in alignment with the coarse sediment tongue lying off the entrance to Bolinas Lagoon, and is probably formed by the same current system. The several narrow ridges and lows conspicuous in this area are probably strike ridges of strata that are kept exposed because they are located below tidal currents flowing into and out of the bay.

The tongue of finer sediment extending in a shoreward direction and lying alongside the coarser sediment tongue lacks any obvious associated mechanisms that could explain its origin. It may be related to the development of small eddies along the edges of the tidal currents and wave currents which are present in this part of the bay. Eddying reduces the carrying capacity of sediment laden waters, and is a potential mechanism of fine sediment accumulation. This idea needs verification, but it fits well with the other processes present in the bay.

The sorting coefficient diagram (Fig. 7) indicates all the samples are well sorted, with the expected gradient of poorer sorting seaward. The gradient is greatly masked by sample to sample variation, but deep samples have values of 1.20 or greater while shallow samples have values usually less than 1.20. The best sorting in the bay is associated with the entrance to Bolinas Lagoon and with Rocky Point. The sorting roughly shows the same pattern as the median grain size, but much less clearly. In Bolinas Bay the sorting of the sediments is primarily a function of the grain size of the sediments, in both deep and shallow water.

The measures of skewness (Fig. 8) and kurtosis (Fig. 9) show no trends in the Bolinas Bay samples and have not been contoured. These measures show enough sample to sample variation to mask the influences of environment that are apparent in the median grain size and sorting coefficient.

Contours of weight per cent heavy minerals (Fig. 10) also gives strong indication of bottom currents flowing between the lagoon entrance and deeper water. The major trend is a linear concentration of heavy minerals aligned from the entrance to Bolinas Lagoon to the center of the bay. It extends between and connects the two tongues of

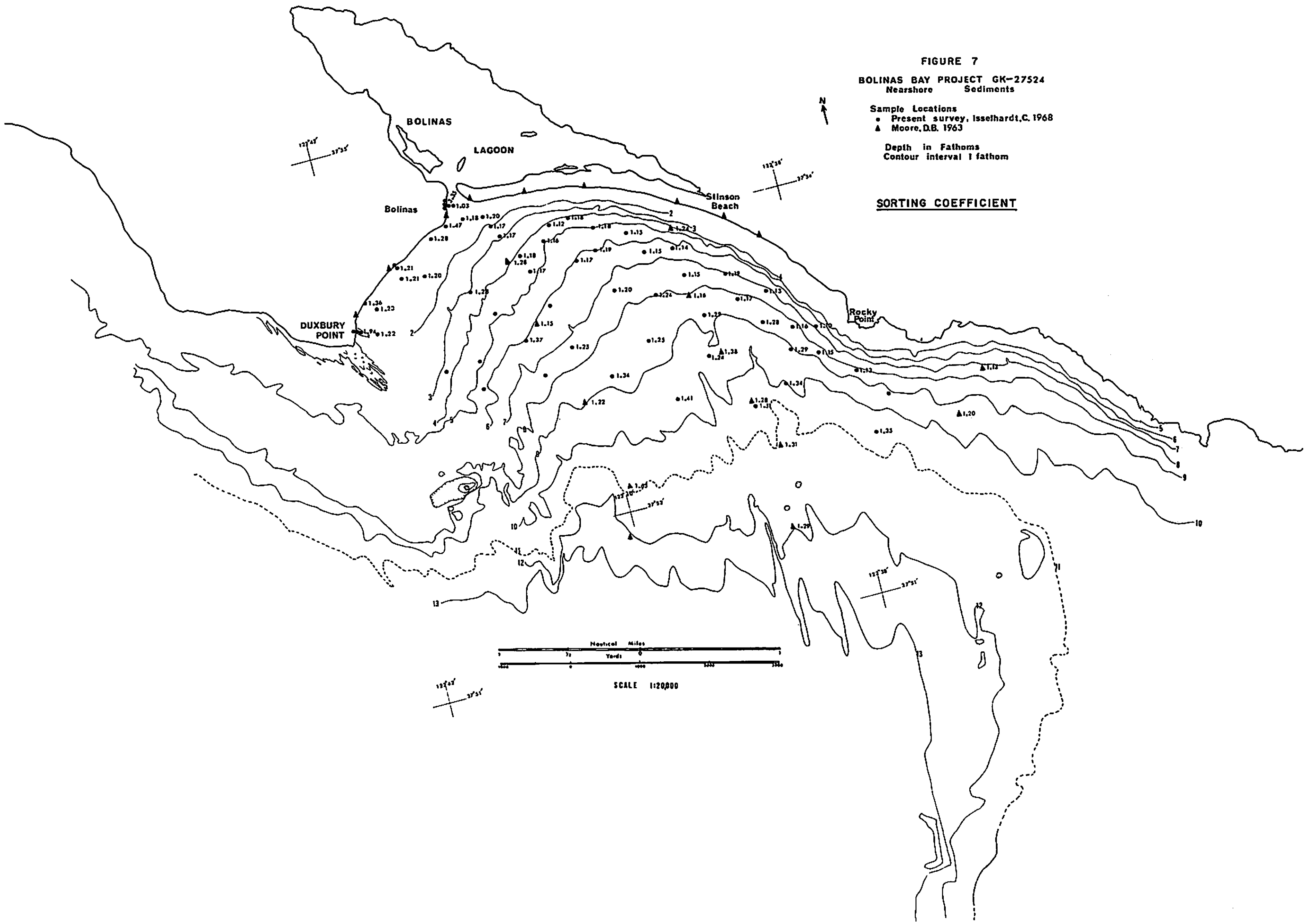


FIGURE 7

BOLINAS BAY PROJECT GK-27524
Nearshore Sediments

Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963

Depth in Fathoms
Contour interval 1 fathom

SORTING COEFFICIENT

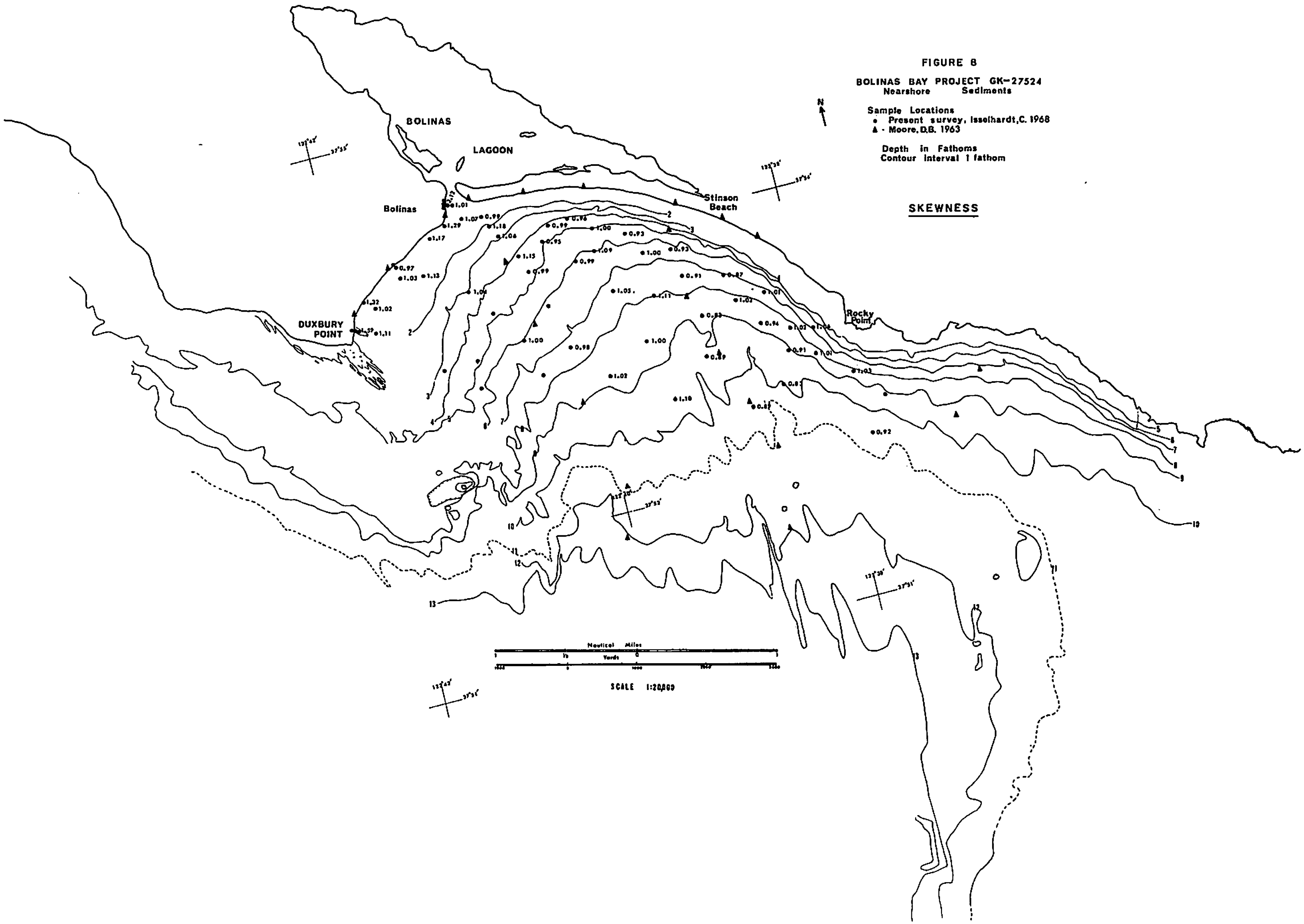


FIGURE 8
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ - Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
SKEWNESS
N
BOLINAS
LAGOON
Bolinas
DUXBURY
POINT
Stinson
Beach
Rocky
Point
Nautical Miles
Yards
SCALE 1:20,000

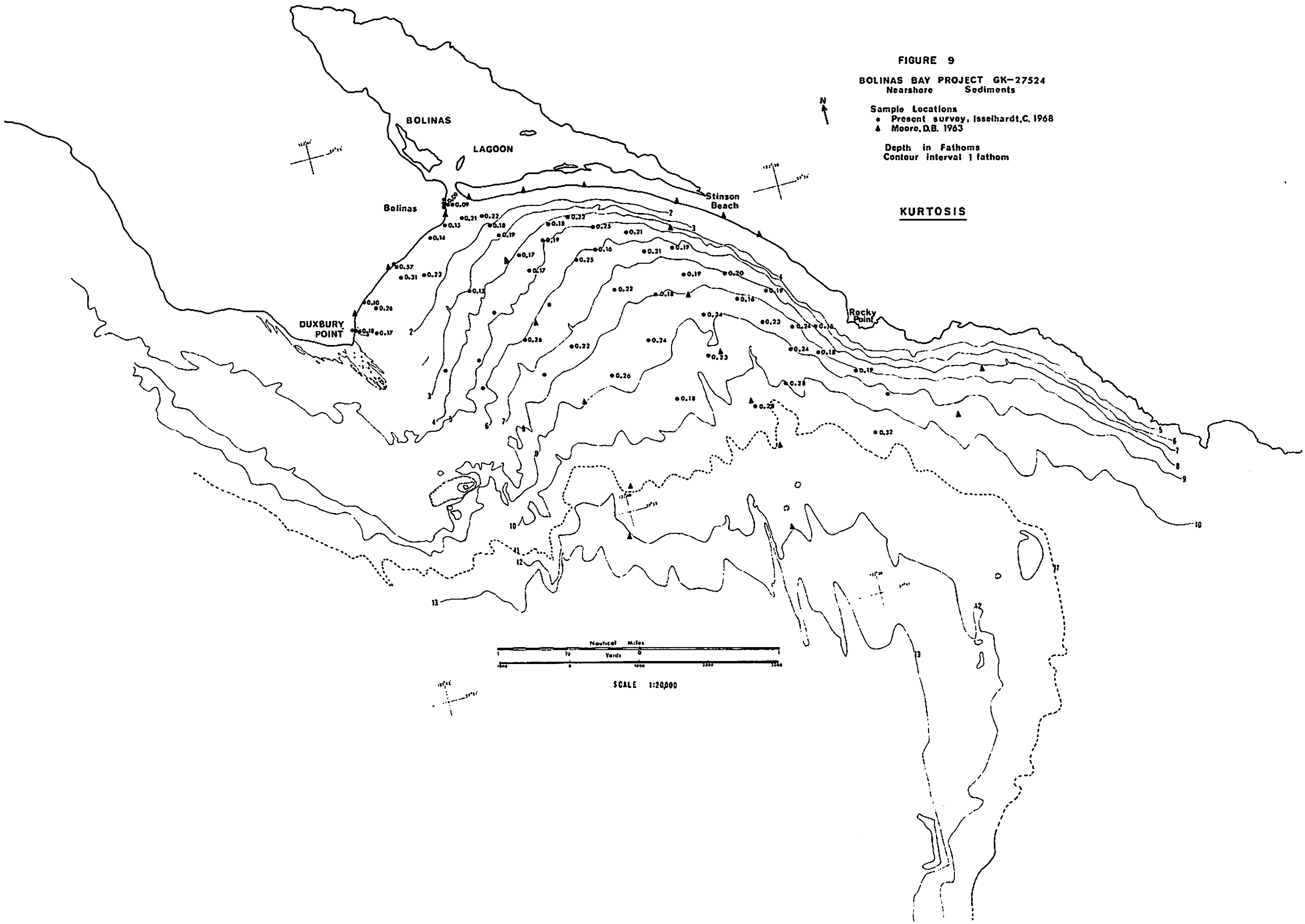


FIGURE 9

BOLINAS BAY PROJECT GK-27524
Nearshore Sediments

Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963

Depth in Fathoms
Contour interval 1 fathom

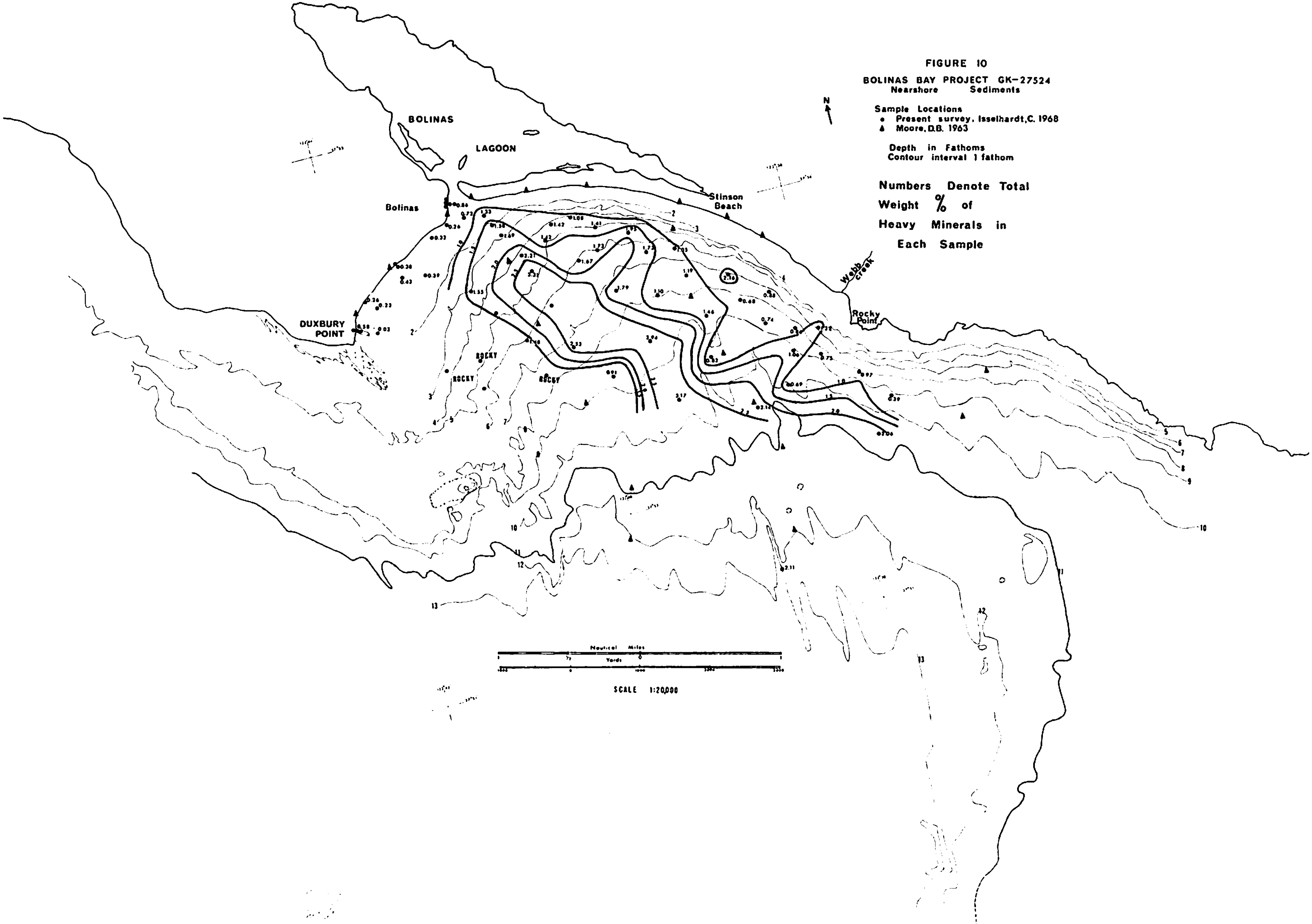


FIGURE 10
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments

coarse sediment noted on the median grain size chart, and apparently is caused by tidal currents.

B. Mineralogy

Heavy minerals of the Bolinas Bay sediments have been identified and point counted, with the data from this study presented in Part B of this study (Isselhardt and others, 1969). Each sample was separated into three size fractions, .061 - .088 mm, .088 - .124 mm, and .124 - 1.77 mm, and the heavy minerals from each size fraction were counted separately. In Bolinas Bay sediments, size fractions larger than .177 mm contain insignificant quantities of heavy mineral grains. The three size fractions were counted separately to test for selective sorting, and to circumscribe some of these effects in comparing the heavy mineral contents of the samples.

Selective sorting does not have a strong effect on the heavy mineral composition of any of the sediments. The heavy mineral composition is closely similar for all of the submarine samples, showing only minor influences from selective sorting. Beach samples show the greatest amounts of selective sorting, containing slightly higher amounts of zircon, picotite, magnetite-ilmenite, and epidote. Zircon, picotite and magnetite-ilmenite are high density minerals that occur in residual concentrates of repeated wave washing. A few submarine samples in or near the channel of the entrance to Bolinas Lagoon are selectively sorted in this manner by the strong tidal currents running through the channel.

While selective sorting differences are not important between submarine samples, mineral compositions are slightly different in the different size fractions of a single sample. This difference is consistently found in the minerals zircon and apatite, which have predominantly small grain size, and are most abundant in the finest size fraction. Both minerals are minor components of the sediment, except for zircon in a few of the beach samples, and do not affect our consideration of provenance.

Appendix I and II gives discussions of the clay mineralogy and carbonate distribution respectively.

C. Mineralogic Provinces

1) Mineral Percentage Distribution

The map distributions of most minerals plotted in the diagrams presented in Part B (Isselhardt and others, 1969) are given in Figs. 11-31. The data is plotted on maps of Bolinas Bay, and contoured where deemed to be significant. Map distributions have been prepared for three grain size ranges of each mineral, .061 - .088 mm, .088 - .124 mm, and .124 - .177 mm.

Trends in mineral distribution are readily apparent on most of the maps. Furthermore, the trends shown by one mineral are closely similar to trends in other minerals. The major trend is a tongue-like projection from the center of the bay toward the entrance to Bolinas Lagoon. This is best shown on Figs. 14 and 15 for green hornblende distribution and on Fig. 26 for hypersthene distribution. Maps of the other grain sizes of these two minerals show roughly similar patterns but are not very clear cut. Figure 13 for clinozoisite-epidote distribution also shows this tongue extending from the center of the bay.

The second prominent trend includes two areas of high concentration

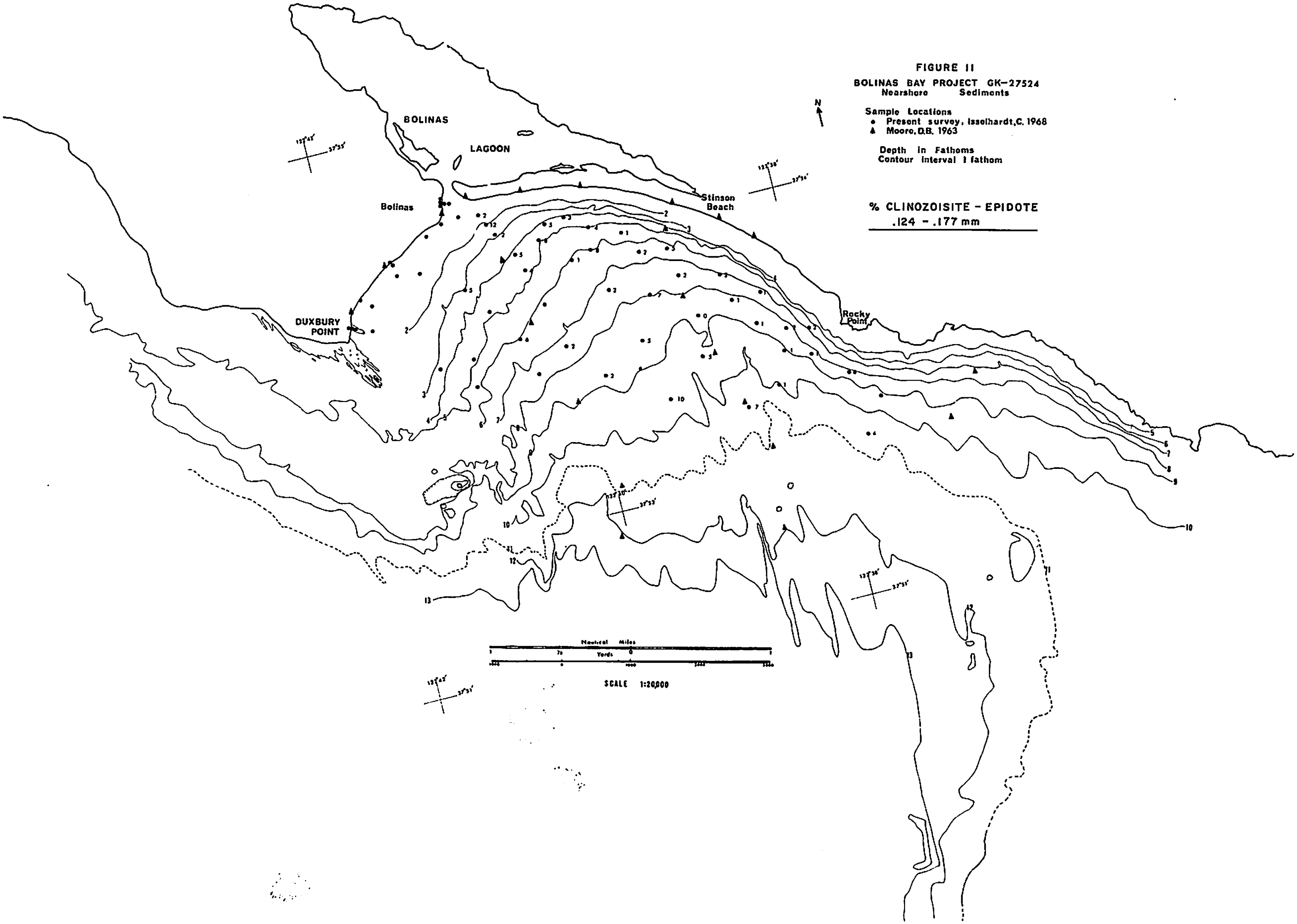


FIGURE 11
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% CLINOZOISITE - EPIDOTE
.124 - .177 mm
N
BOLINAS
LAGOON
Bolinas
Stinson Beach
DUXBURY POINT
Rocky Point
SCALE 1:20,000

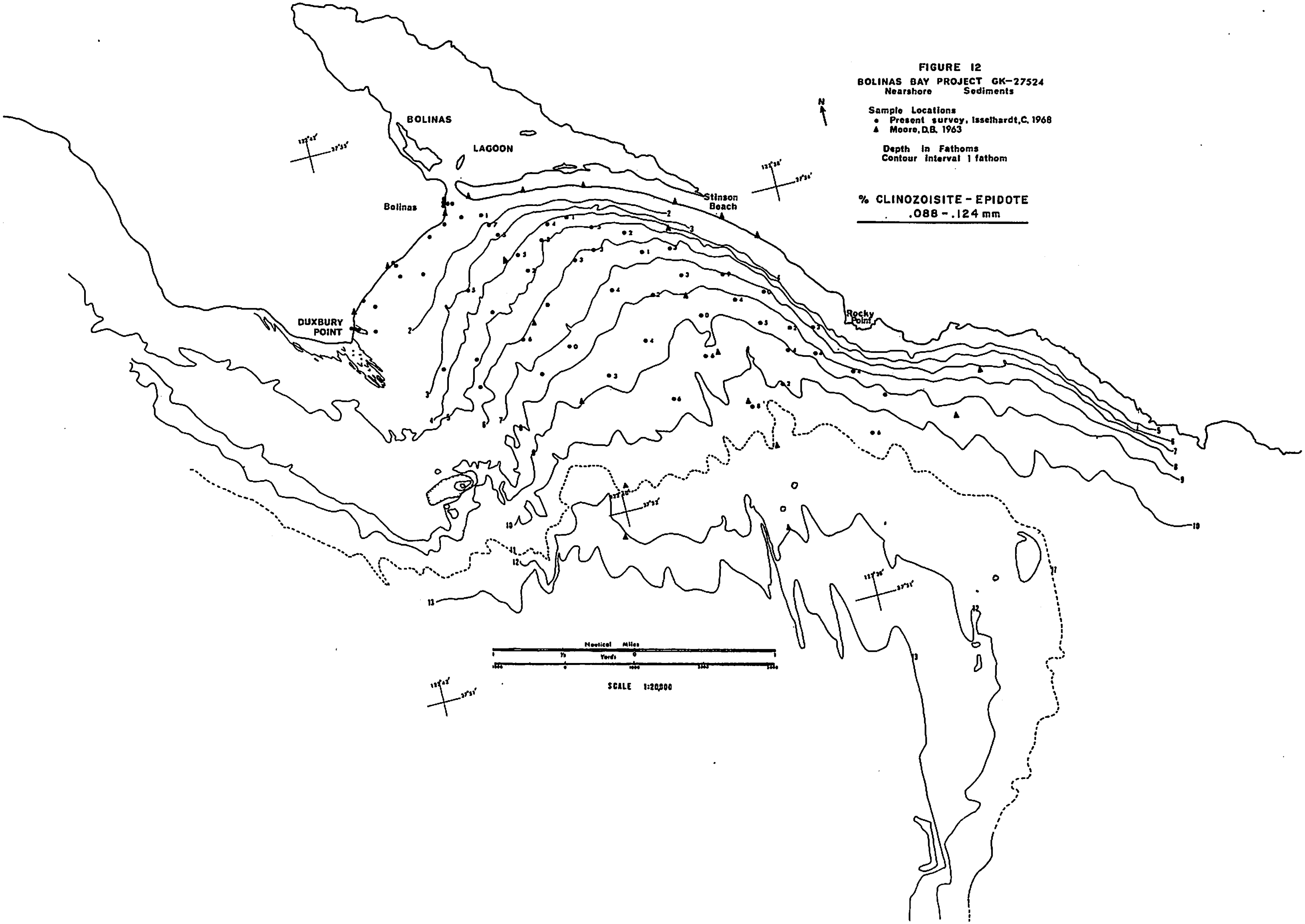


FIGURE 12
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments

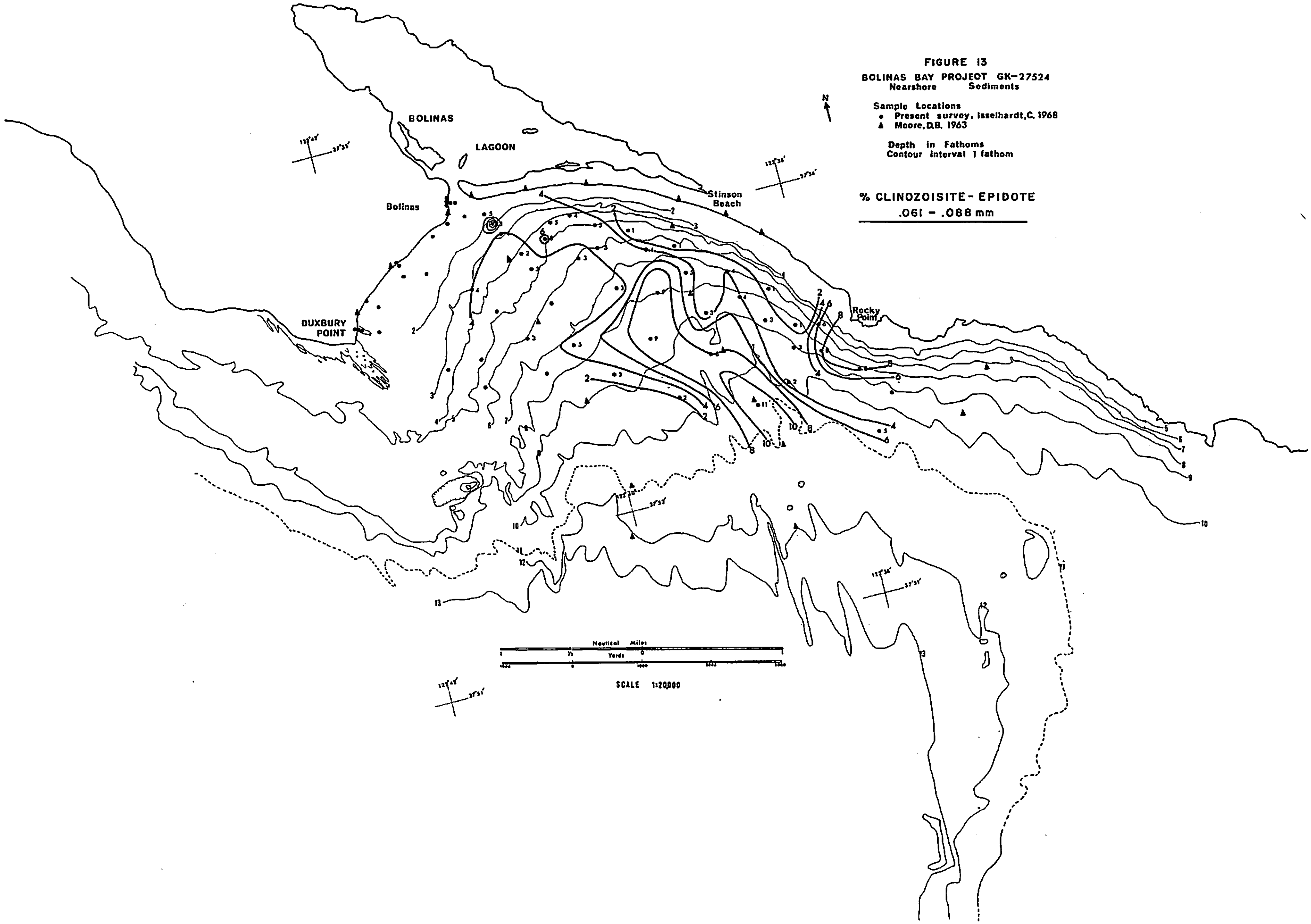


FIGURE 13
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% CLINOZOISITE - EPIDOTE
.061 - .088 mm
N
BOLINAS
LAGOON
Bolinas
DUXBURY
POINT
Stinson
Beach
Rocky
Point
Nautical Miles
Yards
SCALE 1:20,000

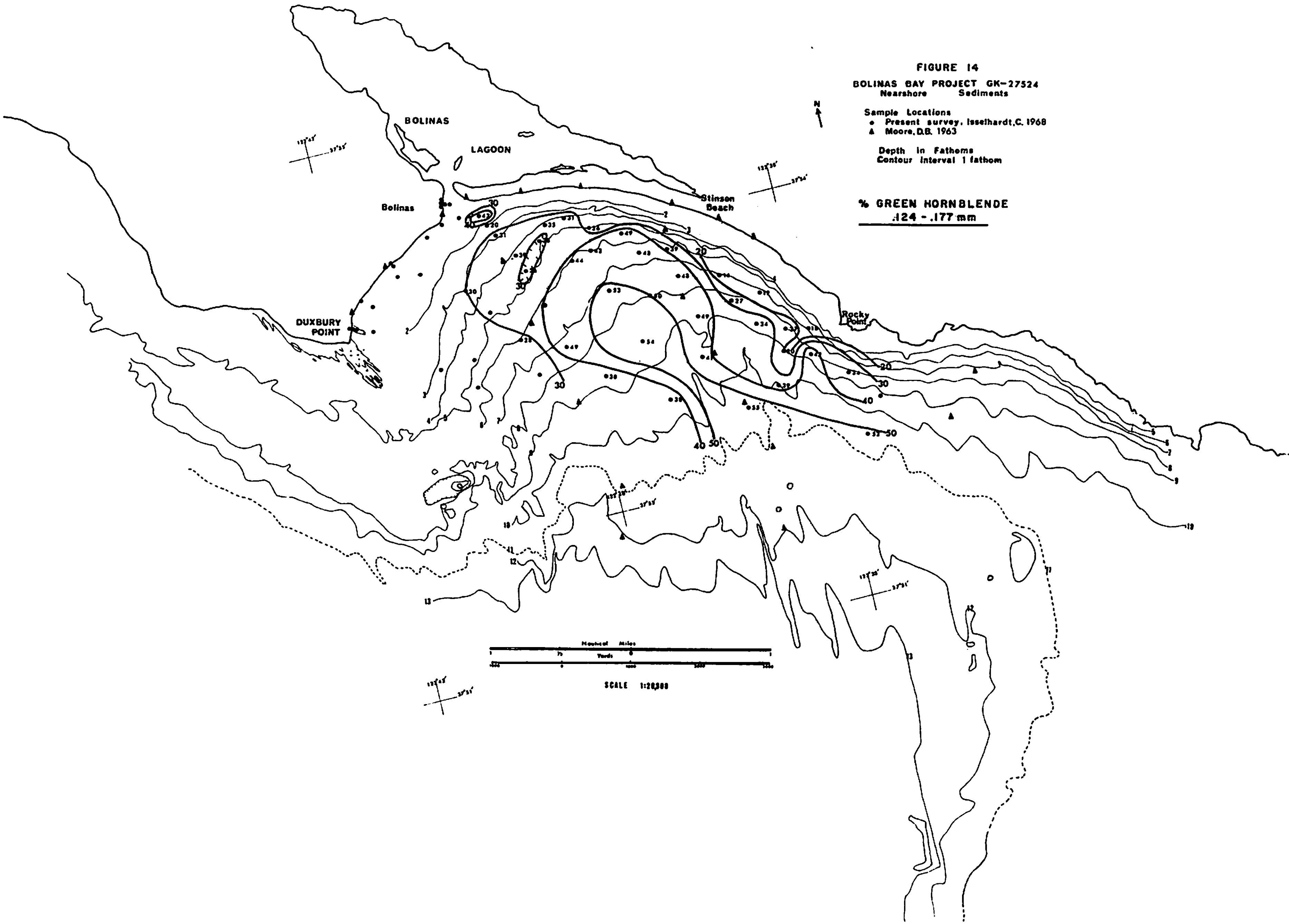


FIGURE 14
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% GREEN HORNBLENDE
.124 - .177 mm
N
BOLINAS
LAGOON
Bolinas
Stinson Beach
DUXBURY POINT
Rocky Point
SCALE 1:20,000

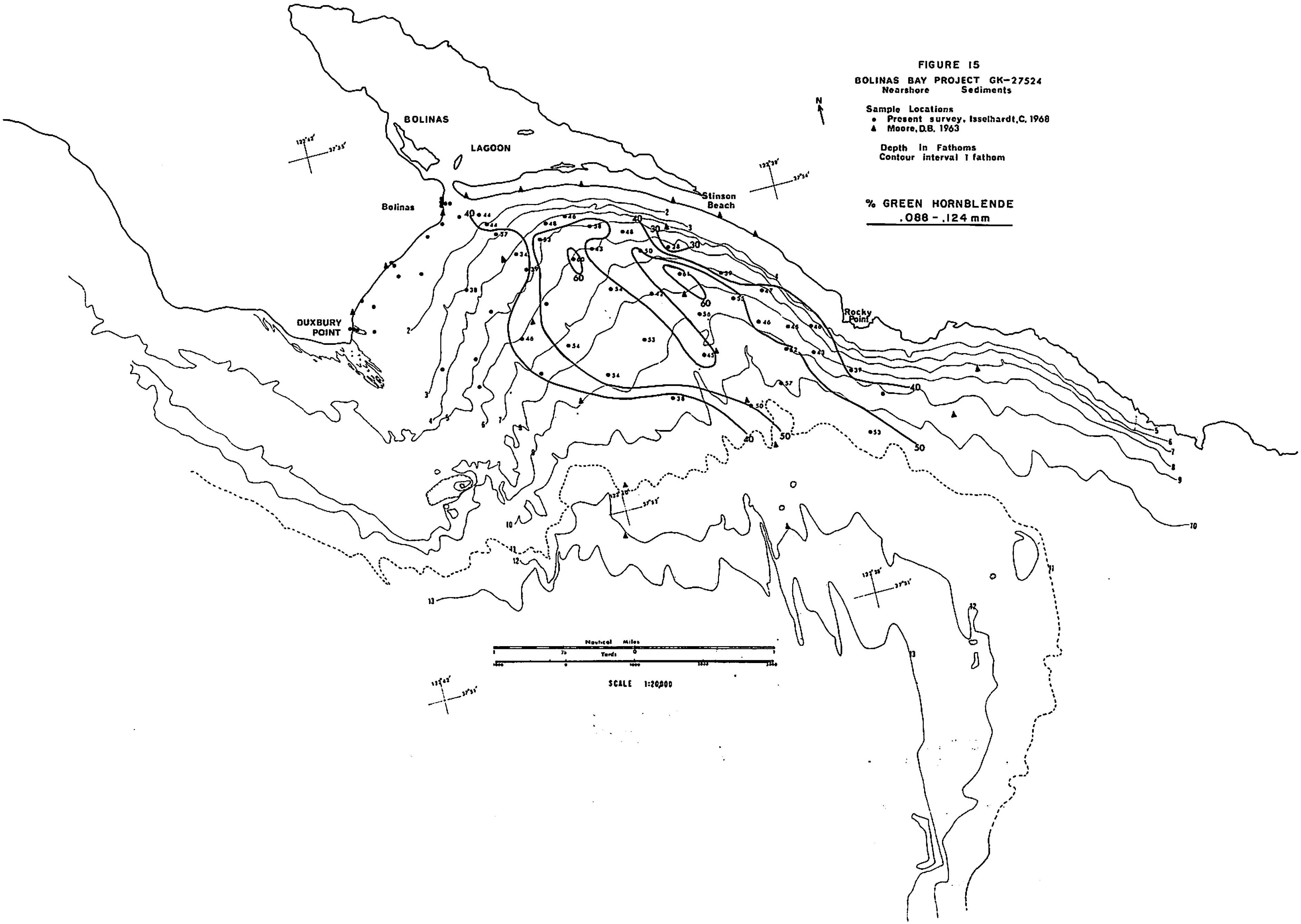


FIGURE 15
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% GREEN HORNBLENDE
.088 - .124 mm
BOLINAS
LAGOON
Bolinas
Stinson Beach
DUXBURY POINT
Rocky Point
N
SCALE 1:20,000

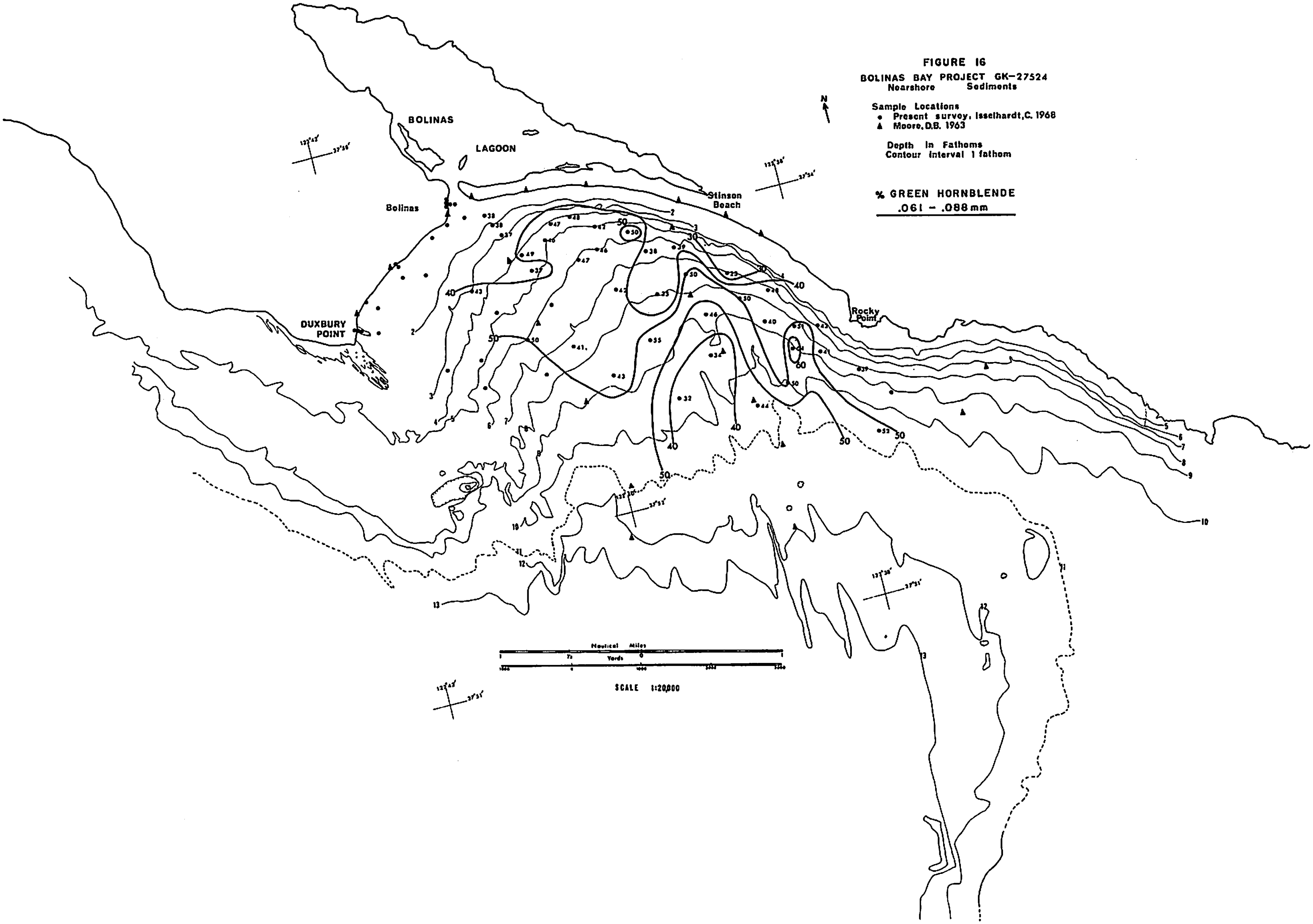


FIGURE 16
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% GREEN HORNBLENDE
.061 - .088 mm
BOLINAS
LAGOON
Bolinas
DUXBURY
POINT
Stinson
Beach
Rocky
Point
N
Nautical Miles
Yards
SCALE 1:20,000

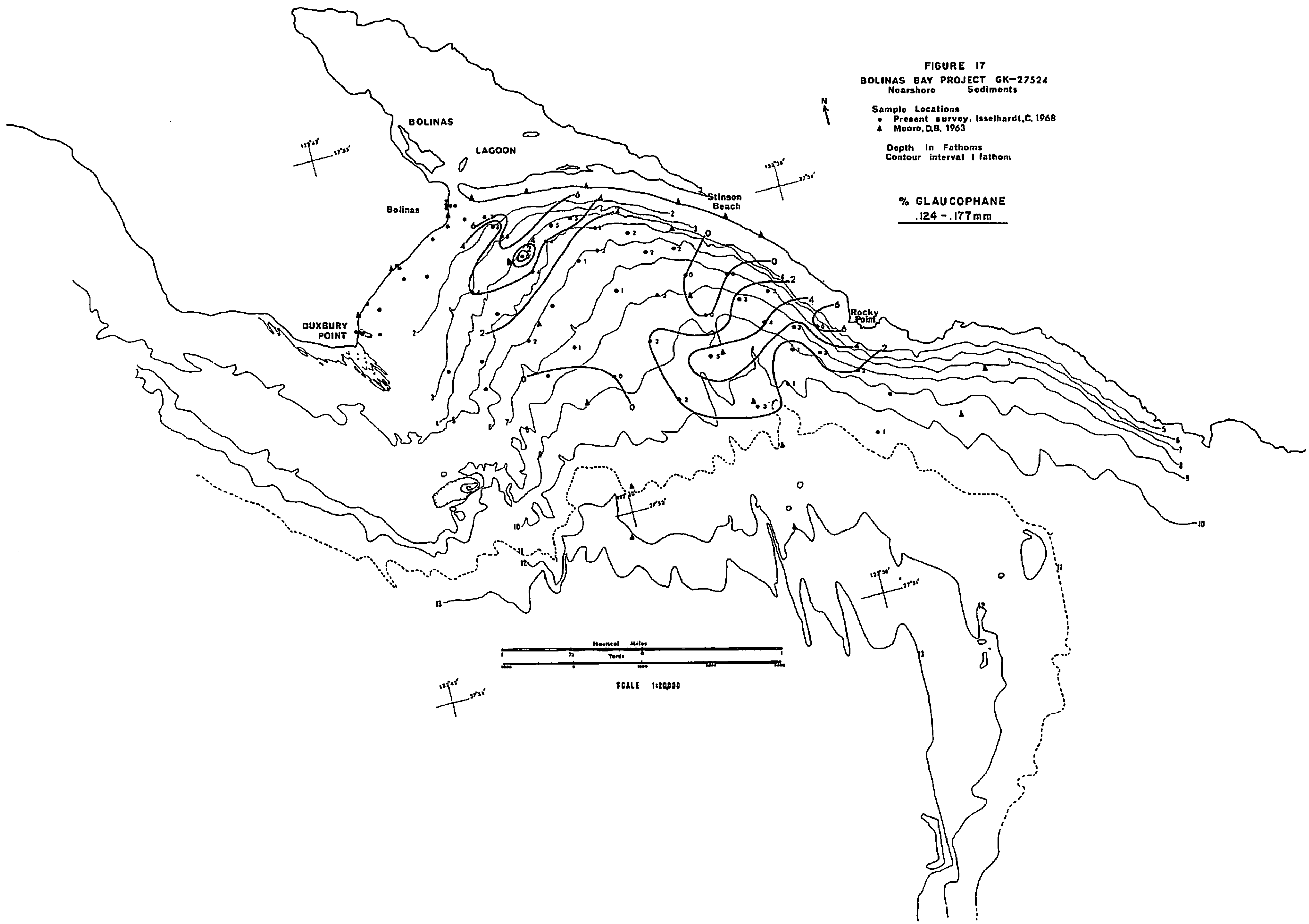


FIGURE 17
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
N
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% GLAUCOPHANE
.124 - .177mm
BOLINAS
LAGOON
Bolinas
Stinson Beach
DUXBURY POINT
Rocky Point
SCALE 1:20,000

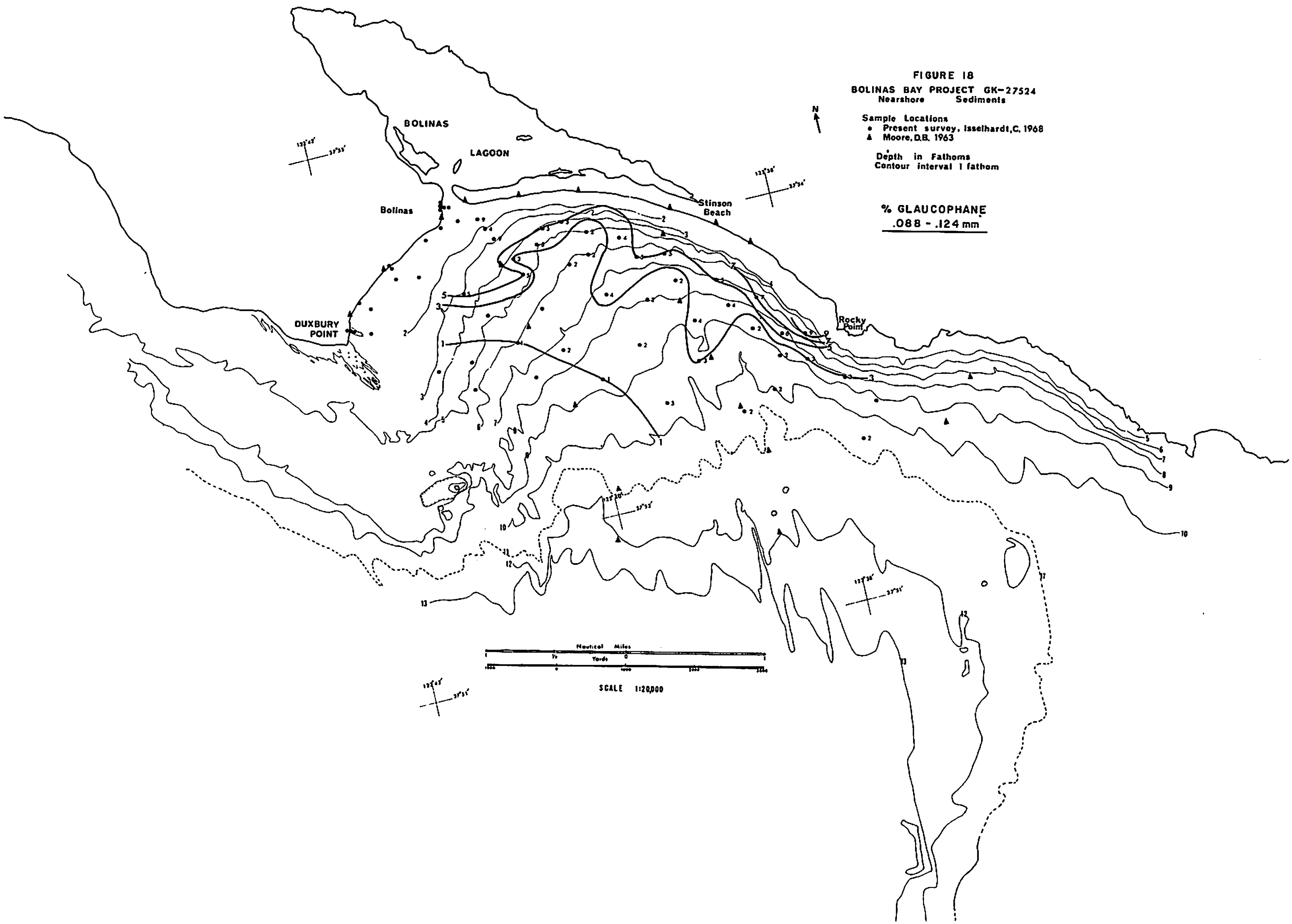


FIGURE 18
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% GLAUCOPHANE
.088 - .124 mm
N
BOLINAS
LAGOON
Bolinas
Stinson Beach
Rocky Point
DUXBURY POINT
Nautical Miles
Yards
SCALE 1:20,000

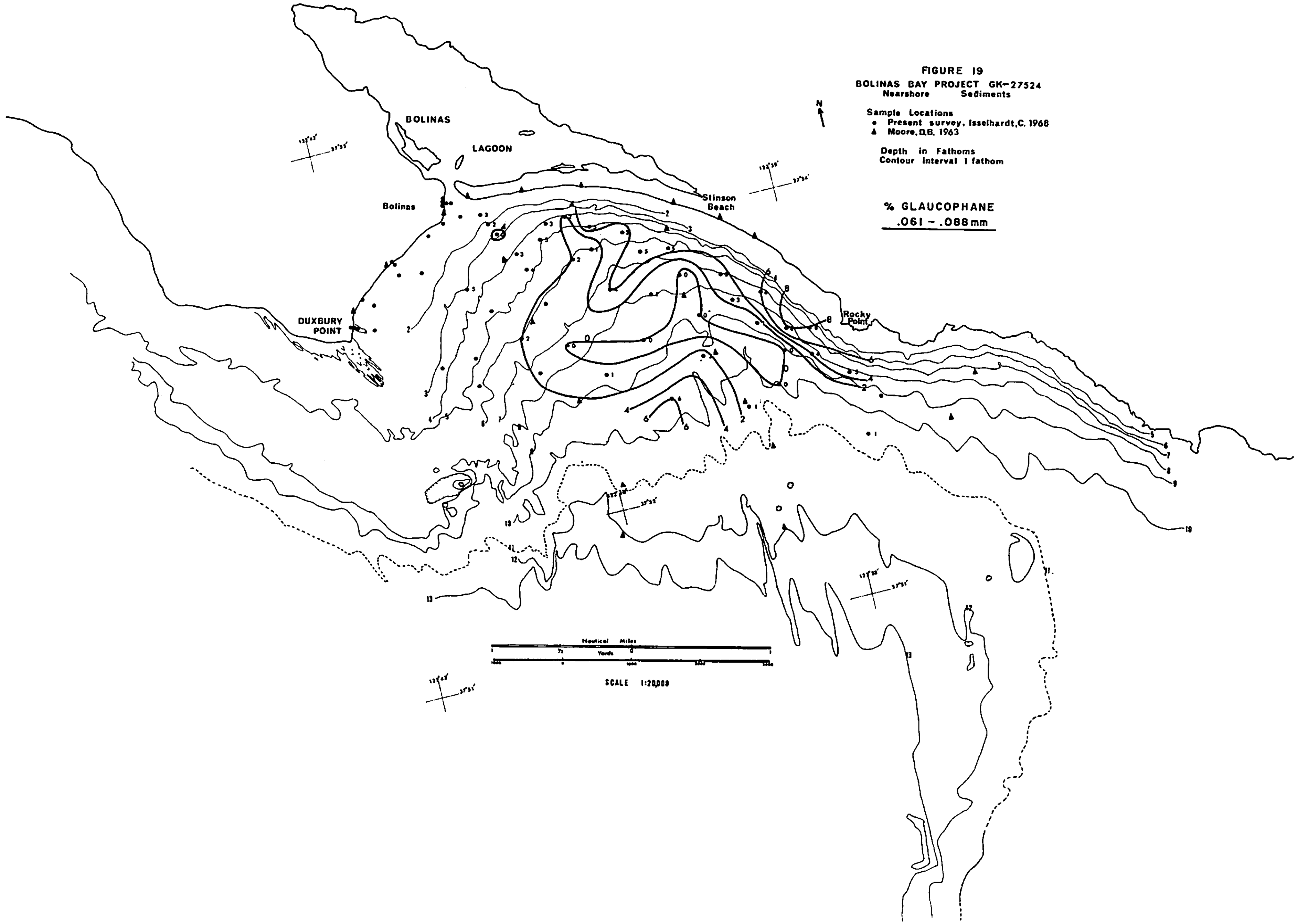


FIGURE 19
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments

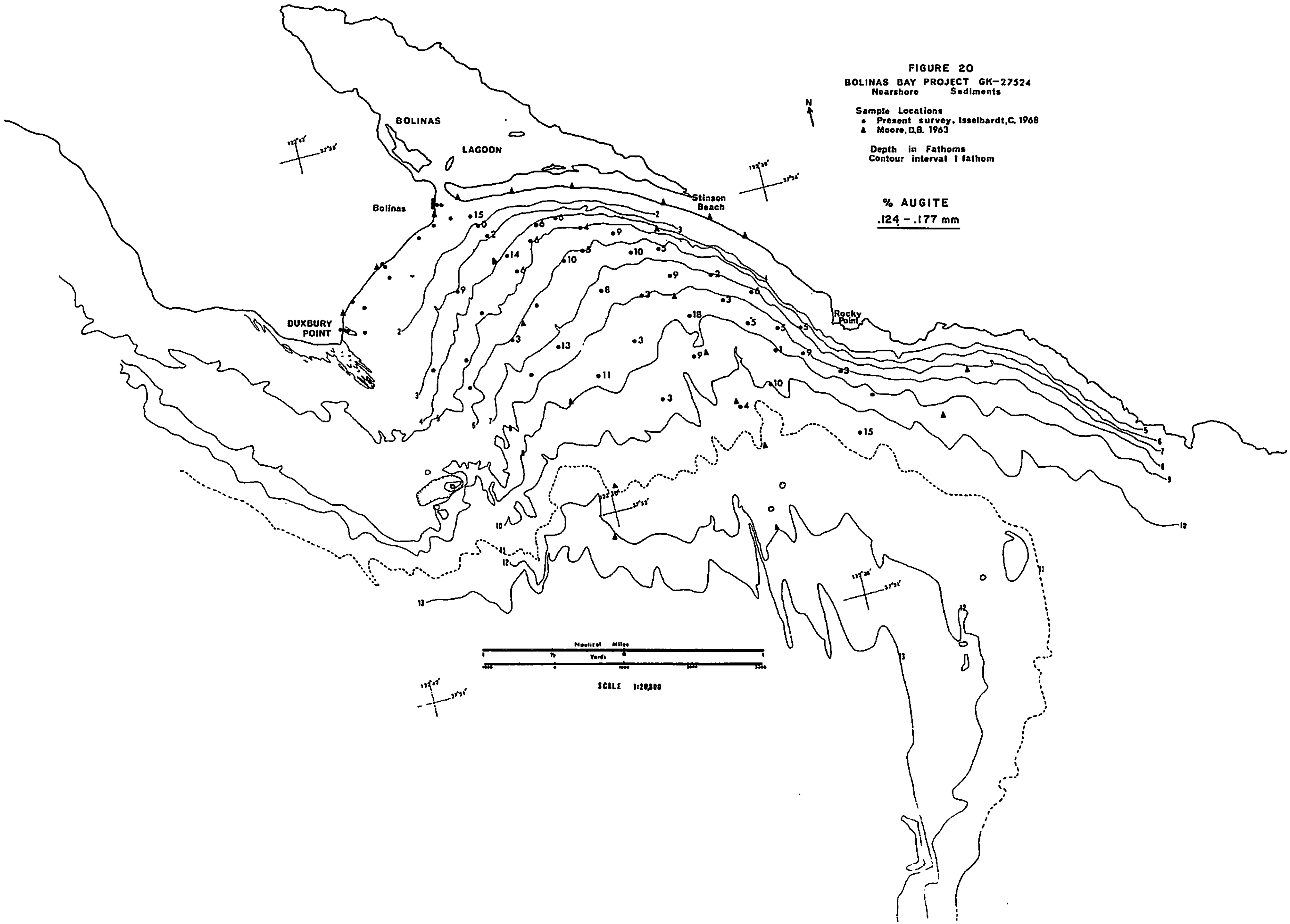


FIGURE 20
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% AUGITE
.124 - .177 mm
N
BOLINAS
LAGOON
Bolinas
DUXBURY
POINT
Stinson
Beach
Rocky
Point
Nautical Miles
Yards
SCALE 1:20,000

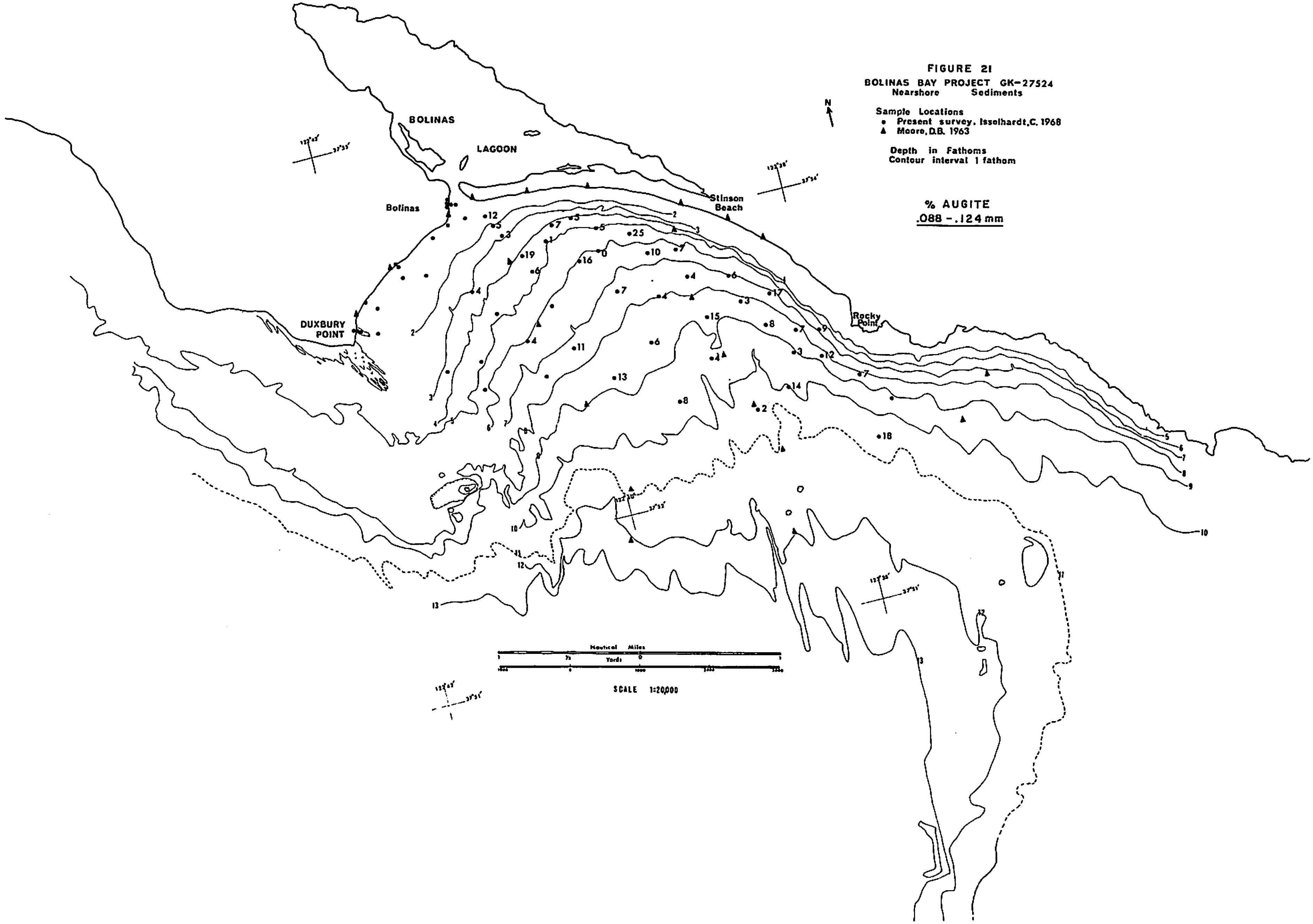


FIGURE 21
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% AUGITE
.088 - .124 mm
N
BOLINAS
LAGOON
Bolinas
DUXBURY
POINT
Stinson
Beach
Rocky
Point
Nautical Miles
Yards
SCALE 1:20,000

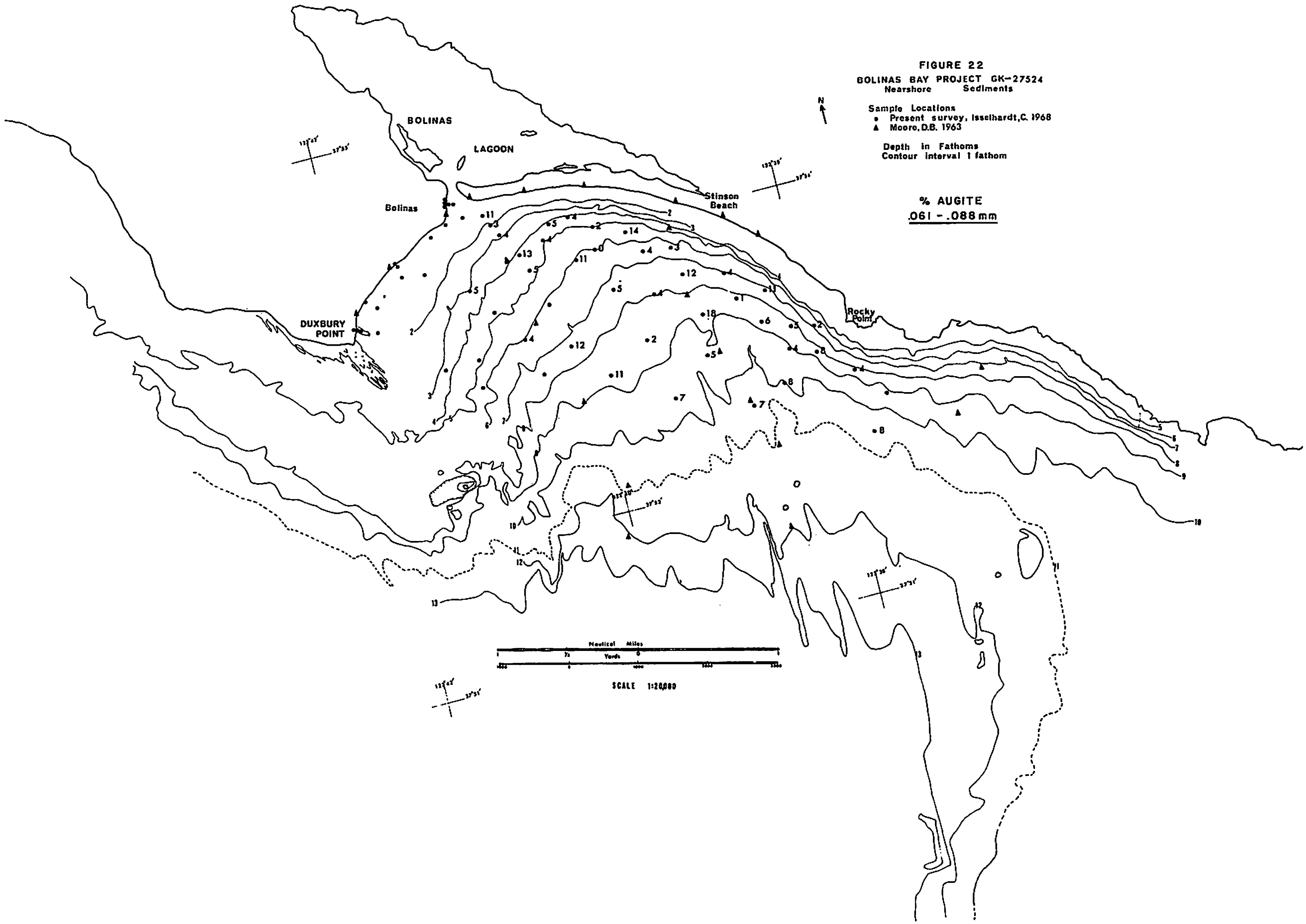


FIGURE 22
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% AUGITE
.061 - .088 mm
N
BOLINAS
LAGOON
Bolinas
Stinson Beach
Rocky Point
DUXBURY POINT
Nautical Miles
Yards
SCALE 1:20,000

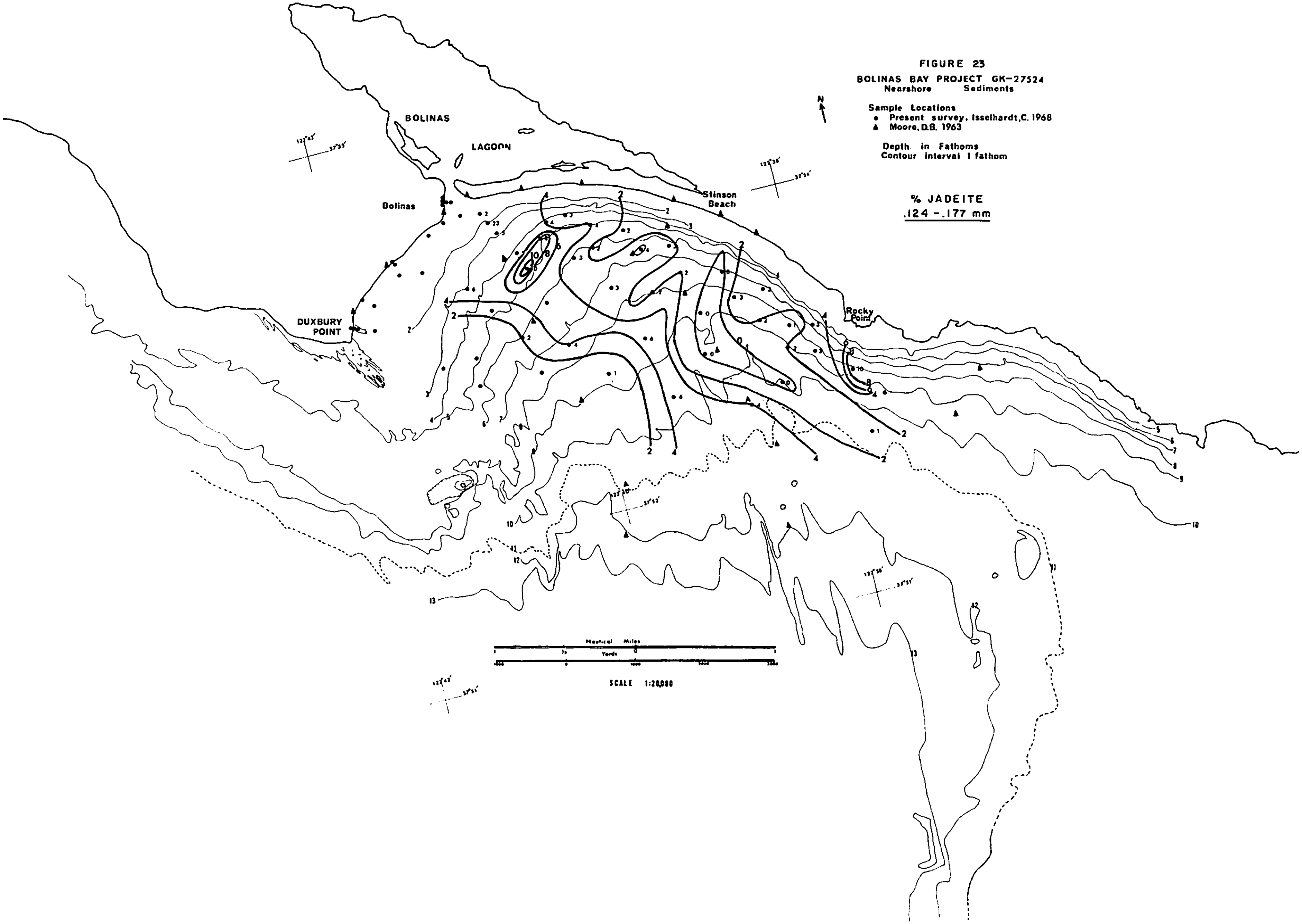


FIGURE 23
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% JADEITE
.124 -.177 mm
N
BOLINAS
LAGOON
Bolinas
Stinson Beach
DUXBURY POINT
Rocky Point
Nautical Miles
Yards
SCALE 1:20,000

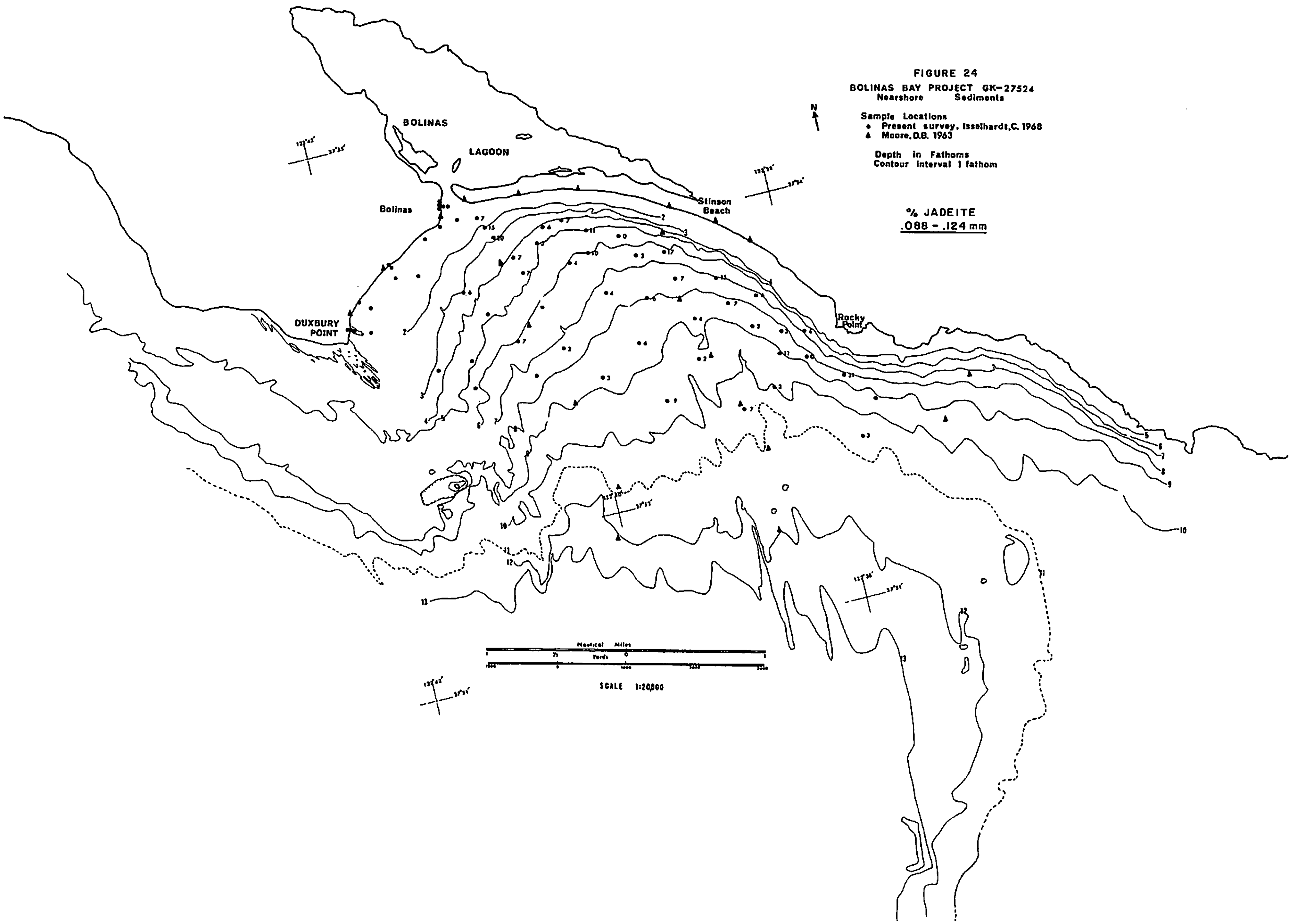


FIGURE 24
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
N
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% JADEITE
.088 - .124 mm
BOLINAS
LAGOON
Bolinas
Stinson Beach
DUXBURY POINT
Rocky Point
SCALE 1:20,000

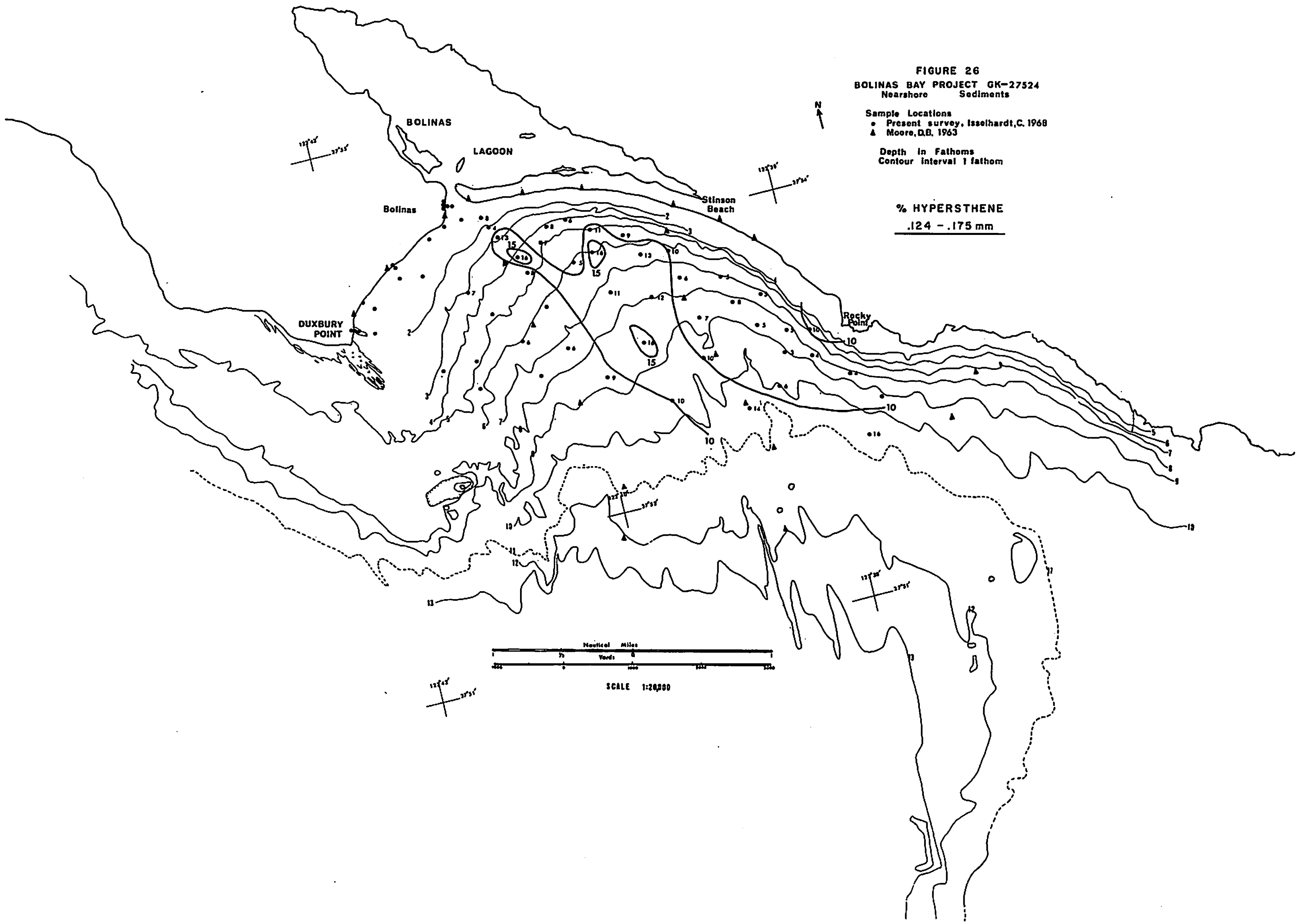


FIGURE 26
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% HYPERSTHENE
.124 - .175 mm
N
BOLINAS
LAGOON
Bolinas
DUXBURY POINT
Stinson Beach
Rocky Point
SCALE 1:20,000
Nautical Miles
Yards

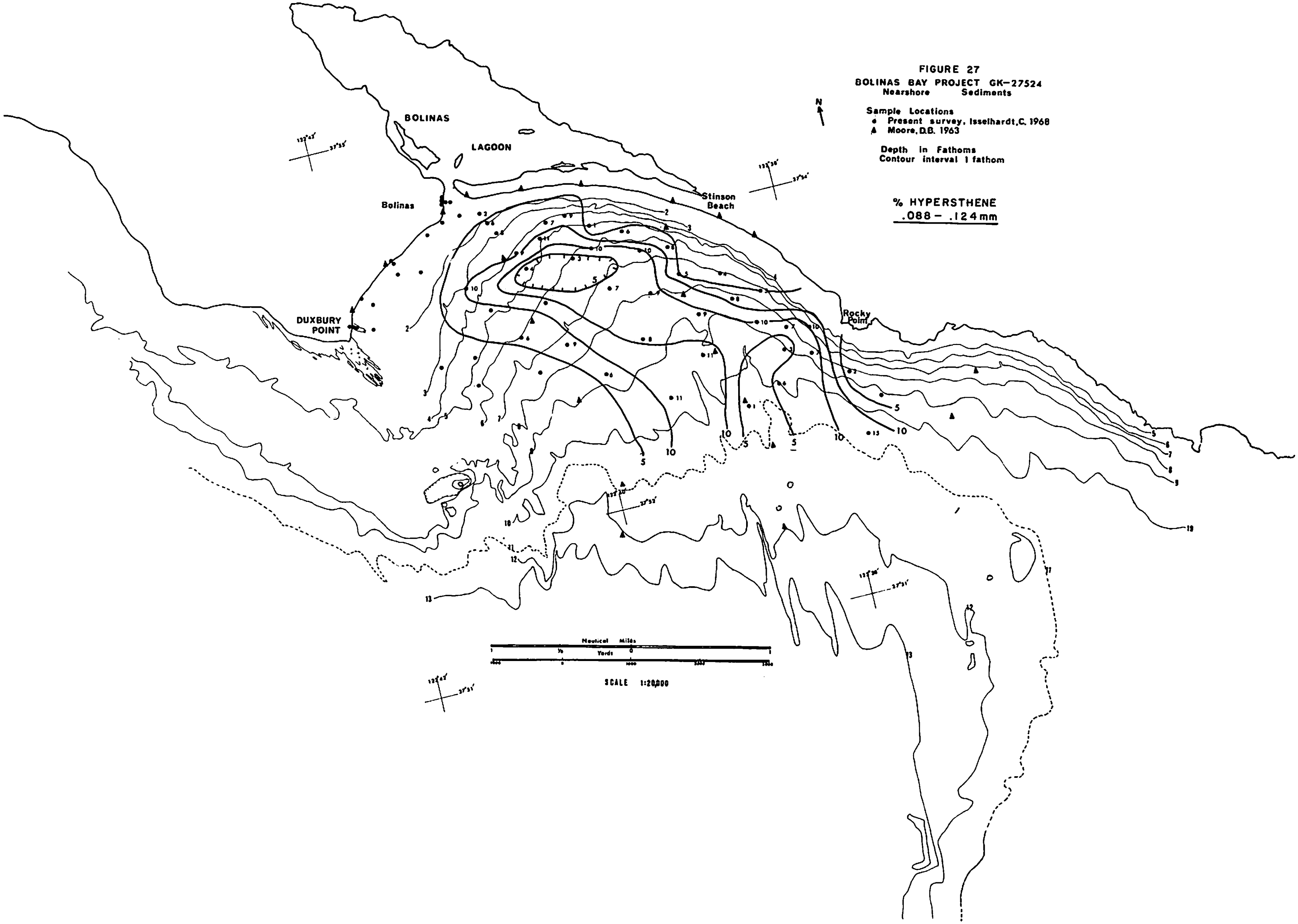


FIGURE 27
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
Present survey, Isselhardt, C. 1968
Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% HYPERSTHENE
.088 - .124 mm
BOLINAS
LAGOON
Bolinas
DUXBURY
POINT
Stinson
Beach
Rocky
Point
N
Nautical Miles
Yards
SCALE 1:20,000

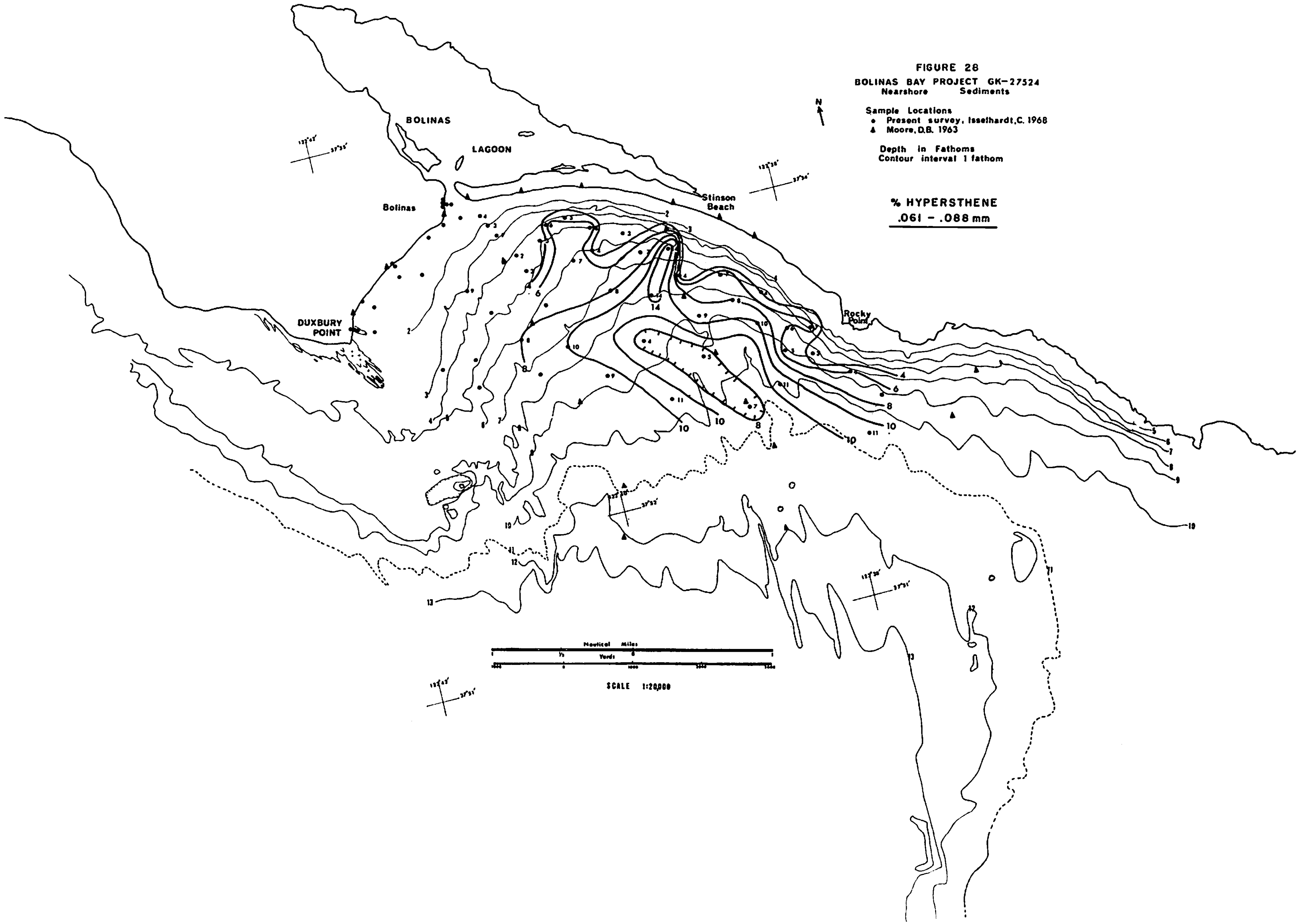


FIGURE 28
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments

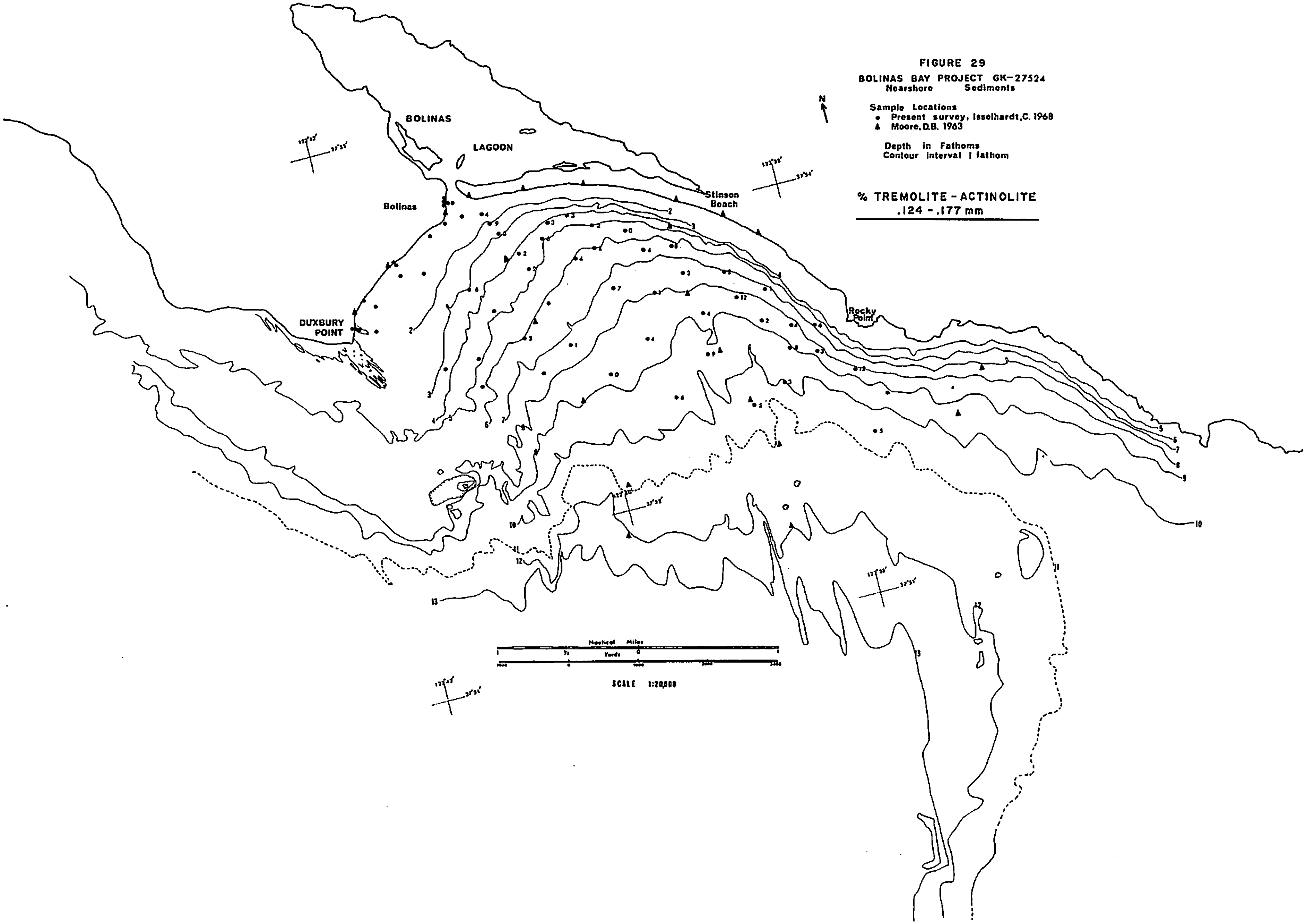


FIGURE 29
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
N
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% TREMOLITE - ACTINOLITE
.124 - .177 mm
BOLINAS
LAGOON
Bolinas
DUXBURY
POINT
Stinson
Beach
Rocky
Point
Nautical Miles
Yards
SCALE 1:20,000

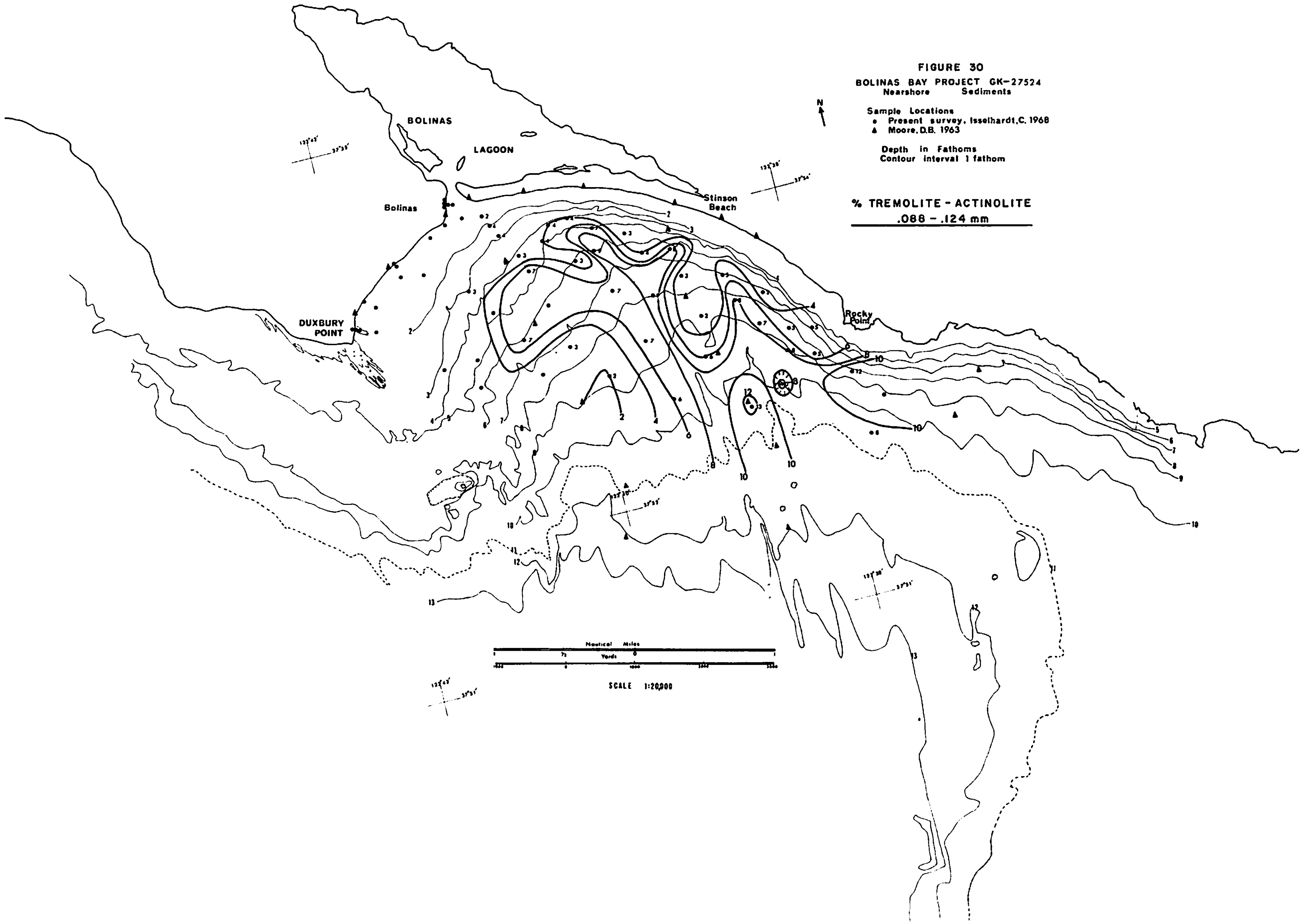


FIGURE 30
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% TREMOLITE - ACTINOLITE
.088 - .124 mm
N
BOLINAS
LAGOON
Bolinas
Stinson Beach
DUXBURY POINT
Rocky Point
Nautical Miles
Yards
SCALE 1:20,000

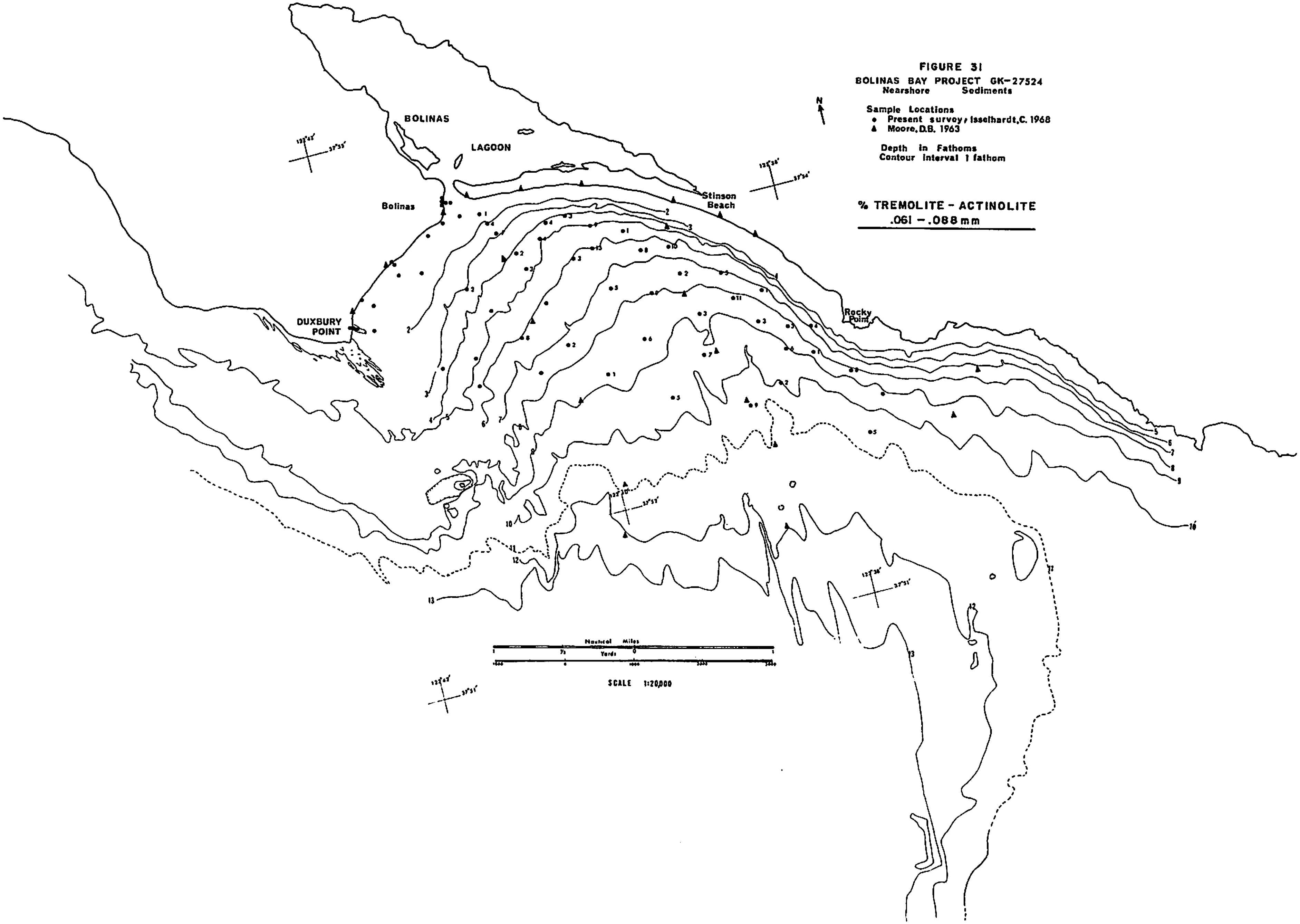


FIGURE 31
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% TREMOLITE - ACTINOLITE
.061 - .088 mm
N
BOLINAS
LAGOON
Bolinas
Stinson
Beach
DUXBURY
POINT
Rocky
Point
Nautical Miles
Yards
SCALE 1:20,000

for the minerals glaucophane and jadeite, one near Rocky Point, and the other near the mouth of the entrance to Bolinas Lagoon. This is shown well on all the maps of glaucophane distribution (Figs. 17-19) and on Figs. 23 and 25 for jadeite distribution. Figure 13 for clinozoisite-epidote distribution and Fig. 26 for hypersthene distribution also show this trend in the vicinity of Rocky Point. The clinozoisite-epidote and the hypersthene maps, along with Fig. 19 for glaucophane distribution, show only the high mineral concentration near Rocky Point, and not the one near the entrance to Bolinas Lagoon. It is possible that the distinctness of the mineral composition near Rocky Point is emphasized by selective sorting. This area has the steepest topographic gradient in the bay and waves striking Rocky Point could be responsible for spreading beach sediment into deep water.

The two major trends are contiguous, and reveal a consistent pattern in the mineral content distributions (Fig. 32). High mineral contents in the areas near Rocky Point and near the entrance to Bolinas Lagoon are matched by low mineral contents in the middle of the bay, and vice-versa. On a few maps a high mineral concentration is apparent in the southwest edge of the sample area, near Duxbury Reef, but it includes only a few samples, and probably does not reflect provenance. Sample 2012 is the most unusual of these. Sample 1972, near the entrance to Bolinas Lagoon is clearly of aberrant mineral composition, and is also not a good indicator of provenance.

These trends in mineral concentration reveal two different mineralogic suites. The linear mid bay tongue is formed by higher concentrations of the minerals green hornblende and hypersthene. This is a natural

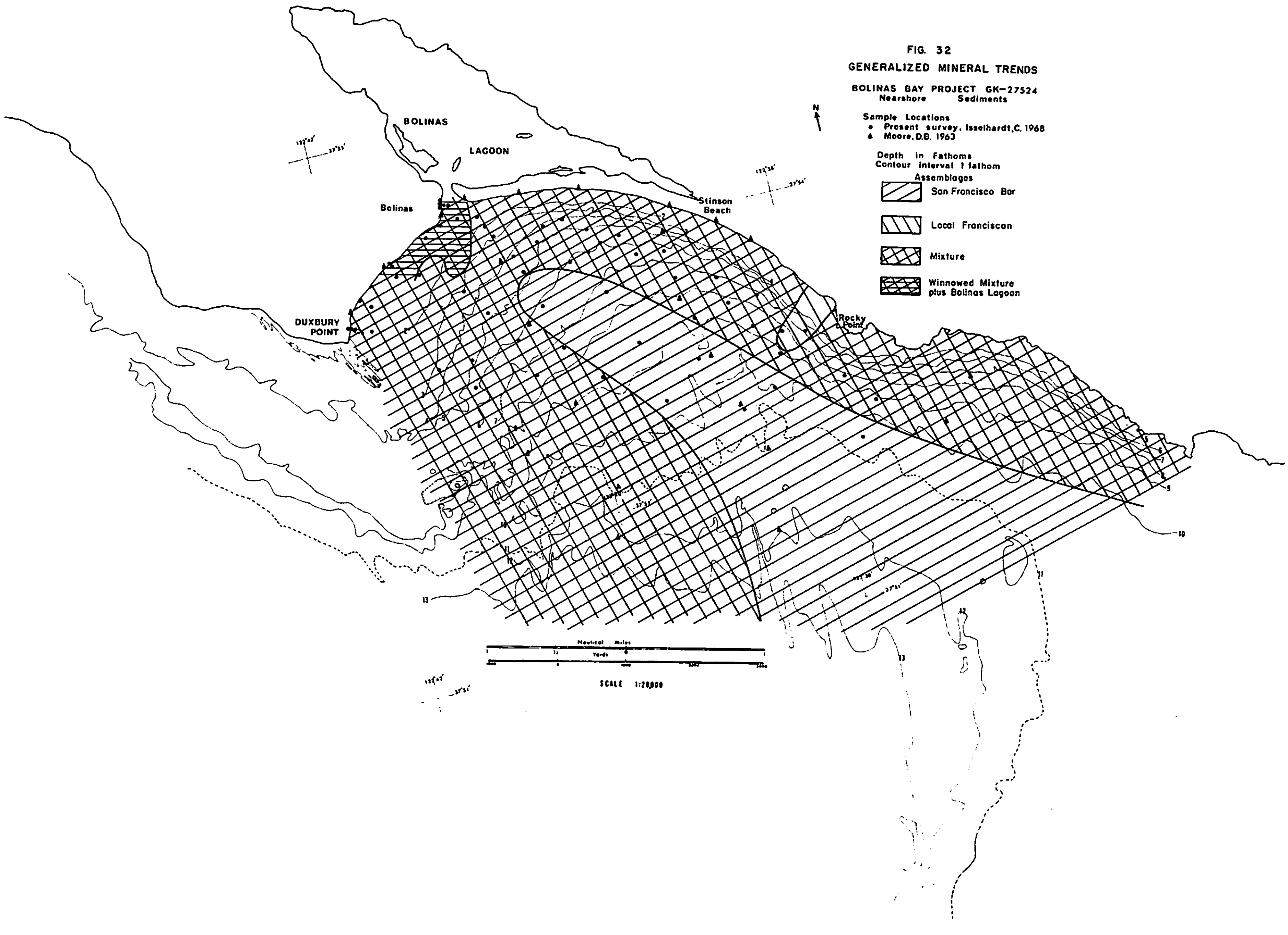


FIG. 32
GENERALIZED MINERAL TRENDS
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments

association of minerals, inasmuch as the two minerals have similar concentration patterns throughout the bay. The highs near Rocky Point and the entrance to Bolinas Lagoon are formed by the minerals glaucophane and jadeite. This also is a natural mineral association inasmuch as their distribution patterns are the same throughout the bay. The only mineral group that has high concentrations in both trends is clinozoisite-epidote (Fig. 13), which has higher concentrations near Rocky Point and on the mid-bay tongue. This appears in only one of the three size fractions. No explanation can be given for this distribution. The minerals tremolite-actinolite and augite do not show discernible trends.

2) Generic End Members

In order to identify possible mineralogical provinces in the vicinity of Bolinas Bay, three generic end members are erected representing volcanic, plutonic, and metamorphic rock sources. The choice of minerals to represent each end member is subjective but hopefully based on adequate information from known paragenesis of rock types (Deer, Howie & Zussman, 1966), known regional assemblages (Moore, 1965; Cherry, 1966), and existing mineral suites in Bolinas Bay (Isselhardt and others, 1969). The three end members are based on the minerals hypersthene (volcanic), green hornblende (plutonic), and glaucophane plus jadeite (Franciscan metamorphics). The weight per cent for each sample was recalculated assuming hypersthene plus green hornblende plus glaucophane plus jadeite = 100%. Thus each component was calculated as follows:

$$\text{volcanic} = \frac{\text{hypersthene}}{\text{hypersthene + green hornblende + glaucophane + jadeite}}$$

$$\text{plutonic} = \frac{\text{green hornblende}}{\text{hypersthene + green hornblende + glaucophane + jadeite}}$$

$$\text{Franciscan metamorphic} = \frac{\text{glaucophane + jadeite}}{\text{hypersthene + green hornblende + glaucophane + jadeite}}$$

Ideally, each component should be of the same order of persistence (Pettijohn, 1957) to eliminate a differential weathering effects on the resistance of minerals, and of the same hydraulic radius (Briggs, 1962), so that the value for each component represents the amount of contribution at the source and is not an artifact of sorting by size. The effects of these factors, however, are not important in the suite of samples from Bolinas Bay, and do not require special consideration in this study.

The data plotted on triangle diagrams for .124 - .177 mm (Fig. 33), .088 - .124 mm (Fig. 34), and .061 - .088 mm (Fig. 35) indicate that separate mineralogical provinces in Bolinas Bay are not readily apparent on the basis of bulk heavy mineral composition. This means that there has been homogenization of heavy mineral assemblages from various sources within the hydraulic regime of the bay.

Major differences cannot be seen in the bulk heavy mineralogy of the sediments, but trends in the distribution of the minerals are apparent, and can be related to different sources. Distribution maps of the Franciscan metamorphics end member (glaucophane-jadeite) are presented in Figs. 36, 37, and 38. There is a gradient in the distribution of glaucophane-jadeite, with high concentrations near the entrance to Bolinas Lagoon and Rocky Point, and low concentrations in the center of

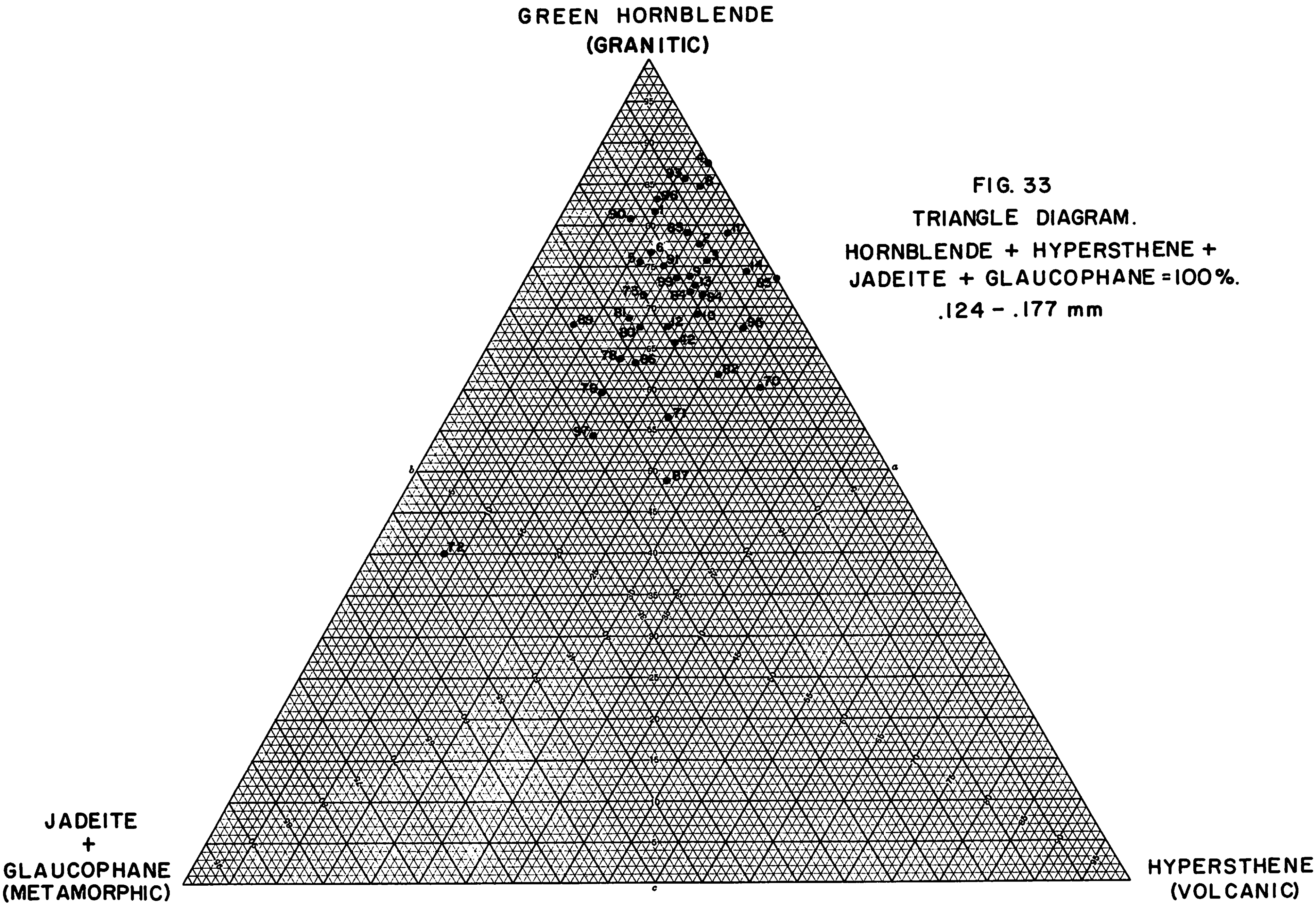


FIG. 33
TRIANGLE DIAGRAM.
HORNBLENDE + HYPERSTHENE + JADEITE + GLAUCOPHANE = 100%.
.124 – .177 mm

GREEN HORNBLENDE
(GRANITIC)

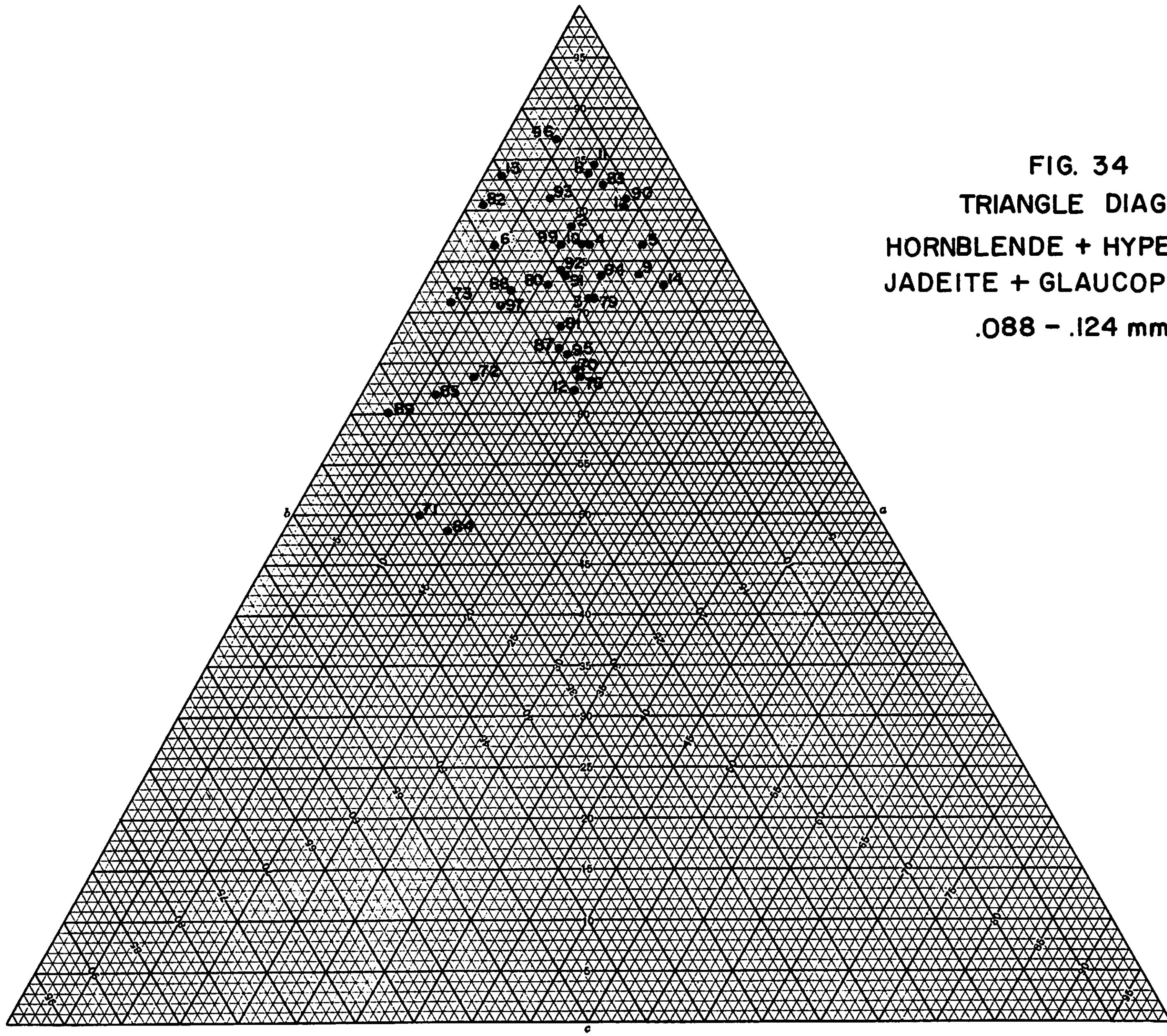


FIG. 34
TRIANGLE DIAGRAM.
HORNBLENDE + HYPERSTENE +
JADEITE + GLAUCOPHANE = 100%.
.088 - .124 mm

JADEITE
+
GLAUCOPHANE
(METAMORPHIC)

HYPERSTHENE
(VOLCANIC)

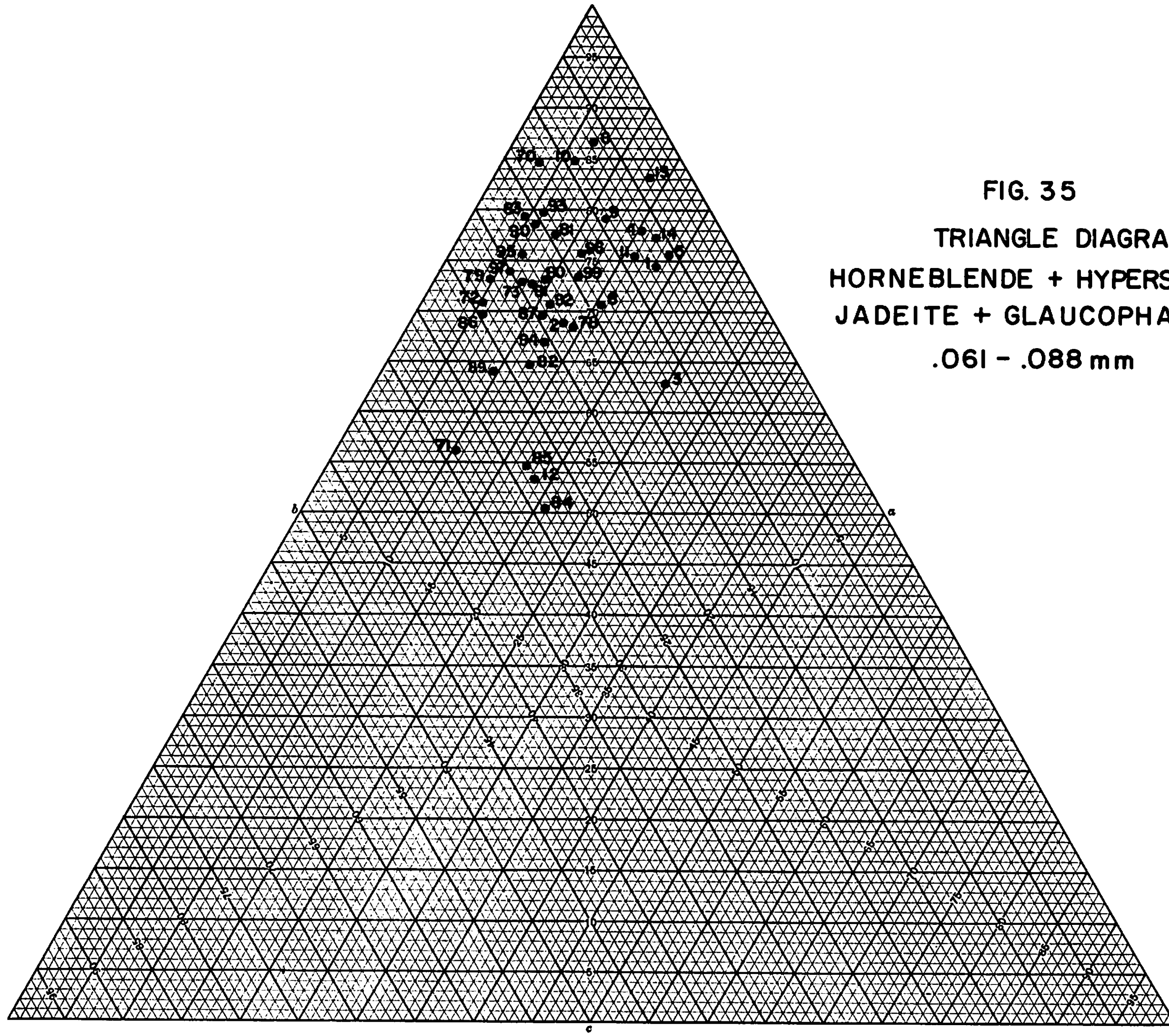


FIG. 35

TRIANGLE DIAGRAM.

HORNEBLENDE + HYPERSTHENE +
JADEITE + GLAUCOPHANE = 100%.
.061 - .088 mm

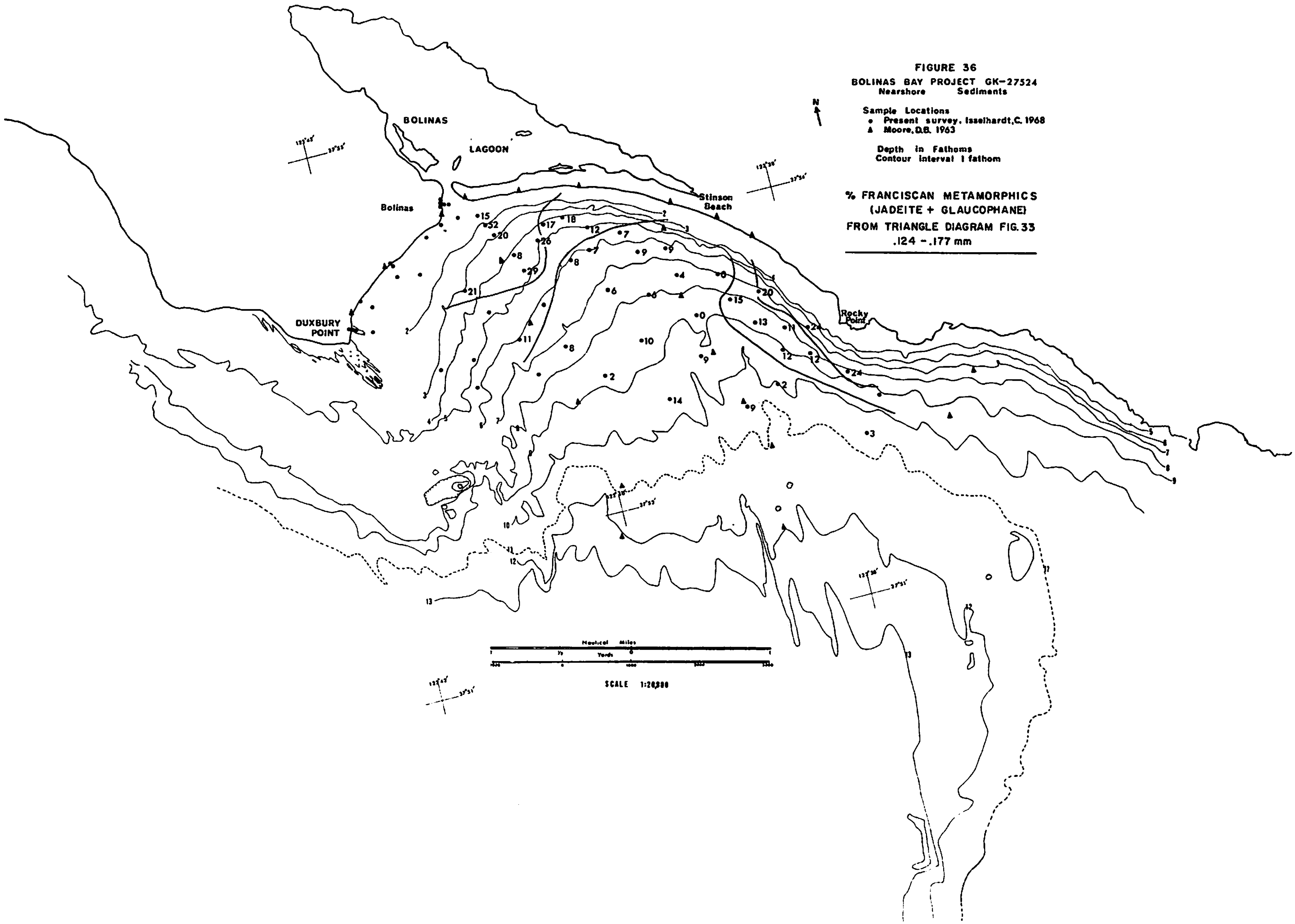


FIGURE 36
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% FRANCISCAN METAMORPHICS
(JADEITE + GLAUCOPHANE)
FROM TRIANGLE DIAGRAM FIG. 33
.124 - .177 mm
N
BOLINAS
LAGOON
Bolinas
DUXBURY
POINT
Stinson
Beach
Rocky
Point
Nautical Miles
Yards
SCALE 1:20,000

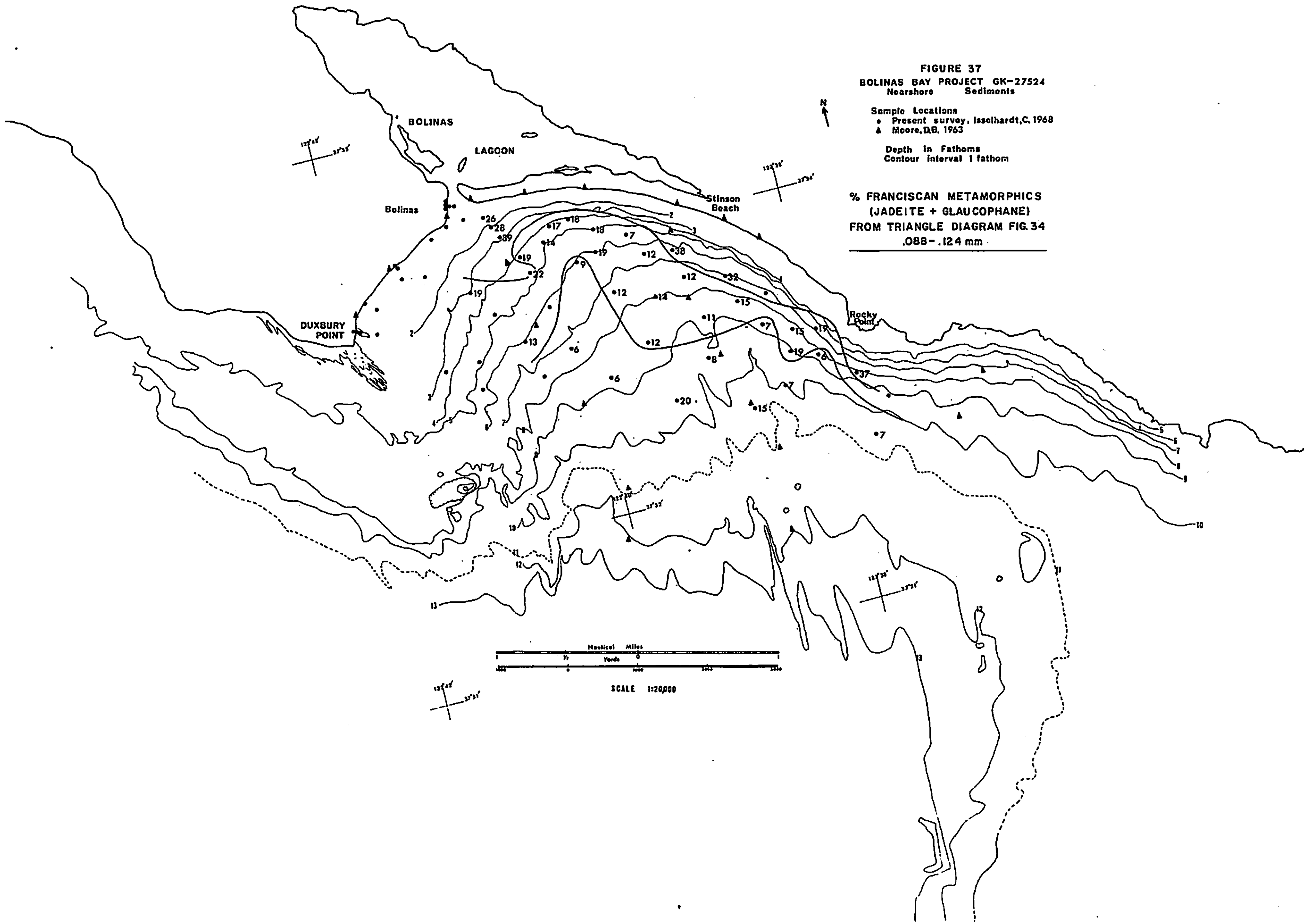


FIGURE 37
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
N
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% FRANCISCAN METAMORPHICS
(JADEITE + GLAUCOPHANE)
FROM TRIANGLE DIAGRAM FIG. 34
.088 - .124 mm
BOLINAS
LAGOON
Bolinas
Stinson Beach
DUXBURY POINT
Rocky Point
Nautical Miles
Yards
SCALE 1:20,000

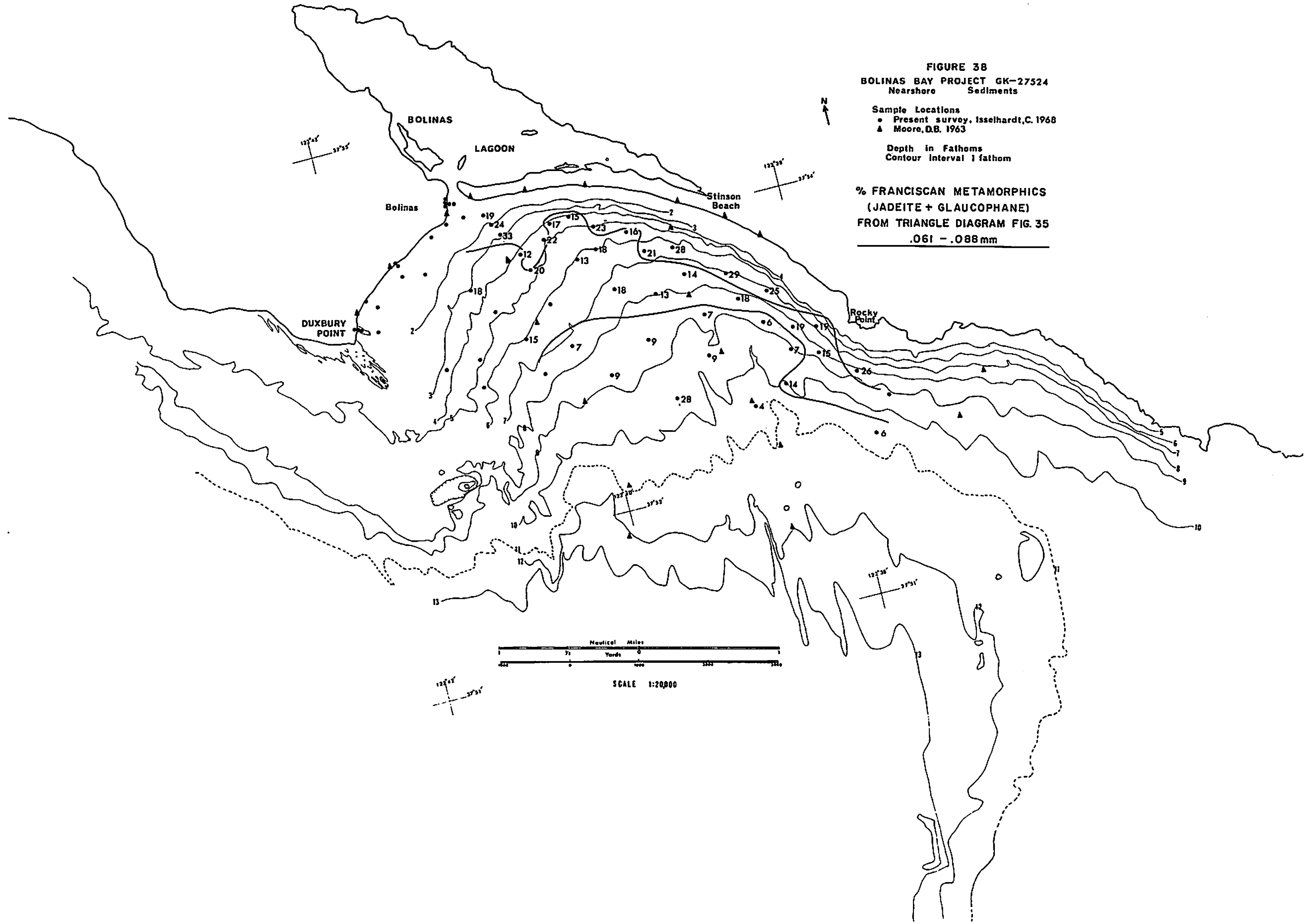


FIGURE 38
BOLINAS BAY PROJECT GK–27524
Nearshore Sediments

% FRANCISCAN METAMORPHICS
(JADEITE + GLAUCOPHANE)
FROM TRIANGLE DIAGRAM FIG. 35
.061 – .088 mm

the bay. These areas of high concentration occur at places where sediment derived from Franciscan Fm. rock enters the bay, indicating significant contributions of sediment from these sources. This trend in the Franciscan metamorphics end member is nearly identical to the trends seen in the distribution maps of unmodified mineral percentages.

Moore (1965) in his study of continental shelf sediments west of Marin and San Francisco counties defined two heavy mineral provinces within our area; an aragonite-augite province and an aragonite-hornblende province (Fig. 39). His provinces are based on a much larger area of study, but the sampling is much sparser than in this study. The boundary between Moore's two provinces cuts through the southwest corner of the Bolinas Bay study area. Most of the Bolinas Bay samples are in Moore's aragonite-augite province. The exact boundaries of Moore's provinces are not those of the mineral trends in this study, but the hornblende rich province of Moore does include the areas of richest hornblende content in this study.

For our purposes we distinguish one mineralogic province, with localized compositional variation that reflects sources or sediment to the bay. The major one is the mid-bay tongue that is based on green hornblende and hypersthene, and the other includes the high concentration of glaucophane and jadeite near Rocky Point and near the entrance to Bolinas Lagoon.

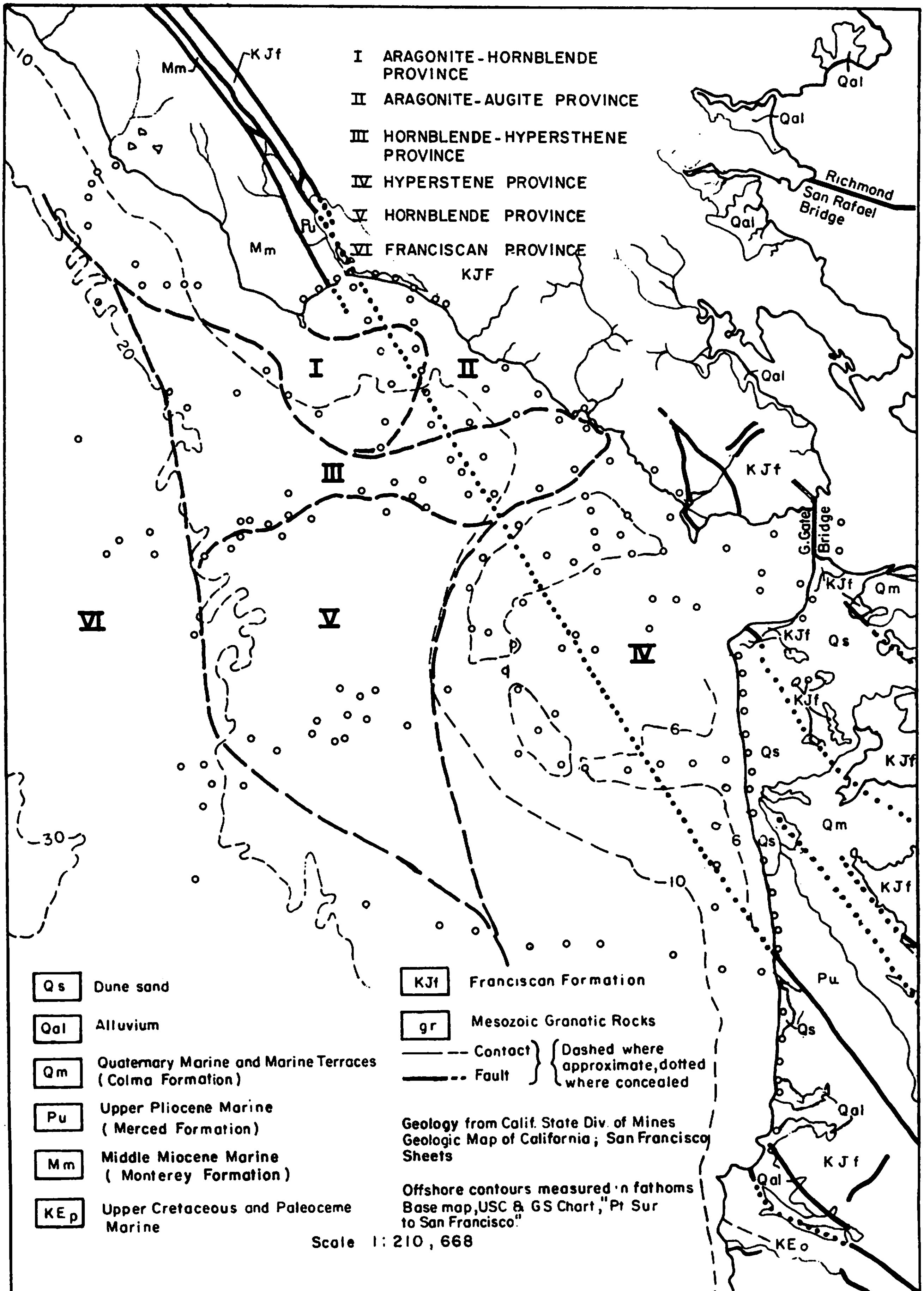


FIG. 39 SEDIMENTARY PETROGRAPHIC PROVINCES
(FROM MOORE, p. 49, 1965)

IV. PROVENANCE

A. Possible Sources

Several potential sources for the sediments of Bolinas Bay are:

(1) Webb Creek drainage, which empties directly into Bolinas Bay

(2) drainage area of Bolinas Lagoon, with sediment transported from the lagoon into Bolinas Bay by tidal action

(3) sea cliff erosion of cliffs between Duxbury Reef and the town of Bolinas

(4) San Francisco Bar, with sediments transported into Bolinas Bay by northward flowing bottom currents

(5) Franciscan rocks south of Bolinas Bay - sediments brought into the bay by northward longshore drift

(6) Monterey shale and granitic rocks north of Duxbury Point - sediments brought into the bay by southward longshore drift.

Webb Creek, draining Franciscan terrain, is the only stream that empties directly into Bolinas Bay. Sediments in Bolinas Bay adjacent to the mouth of Webb Creek contain high concentrations of glaucophane and jadeite, and show that Webb Creek sediments are of typical Franciscan mineralogy.

Most of the streams in the immediate area of the bay first drain into Bolinas Lagoon (Fig. 3), which empties into Bolinas Bay through a tidal channel at the west end of Sea Drift Spit near the town of Bolinas. Helley (in Ritter, 1969) noted that the largest drainage into the Lagoon is by Pine Gulch Creek, which has tributaries both in

Franciscan rocks (Copper Mine Gulch) and in tertiary sedimentary rocks (McCormick Creek). Other small streams flow into the lagoon from areas of Franciscan rocks.

Circulation in the lagoon is being studied (Ritter, 1969) and preliminary results indicate that during flood tide the high velocity flows are from the entrance eastward (Fig. 40), while during ebb tide the high velocity flows are from the west side south of the Pine Gulch Creek delta towards the entrance (Fig. 41). This suggests that Pine Gulch Creek sediments have the best chance to escape deposition in the lagoon and be deposited in Bolinas Bay.

The mineralogy of bottom sediments in the lagoon (Helley, in Ritter, 1969) indicates that Pine Gulch Creek principally contributes Monterey shale sediments to the lagoon, which swamps the contribution from the smaller streams with exclusively Franciscan drainage (see Fig. 42). Helley found the lowest concentration (10-20%) of Franciscan minerals associated with high concentration (33-66%) of Monterey shale fragments (Fig. 43).

The Bolinas Cliffs are actively eroding and supply large amounts of sediment to Bolinas Bay annually. Helley (in Ritter, 1969) cites an annual rate of cliff erosion of 2.3 feet per year (determined by A. J. Galloway). The sea cliffs fronting on Bolinas Bay are 7000 feet long and are at least 120 feet high, and would give an annual yield of sediment of 72,000 cubic yards. The cliffs are composed mostly of Monterey shale, with lesser exposures of Merced Formation near the town of Bolinas.

The San Francisco Bar, to the south of Bolinas Bay, contains a very

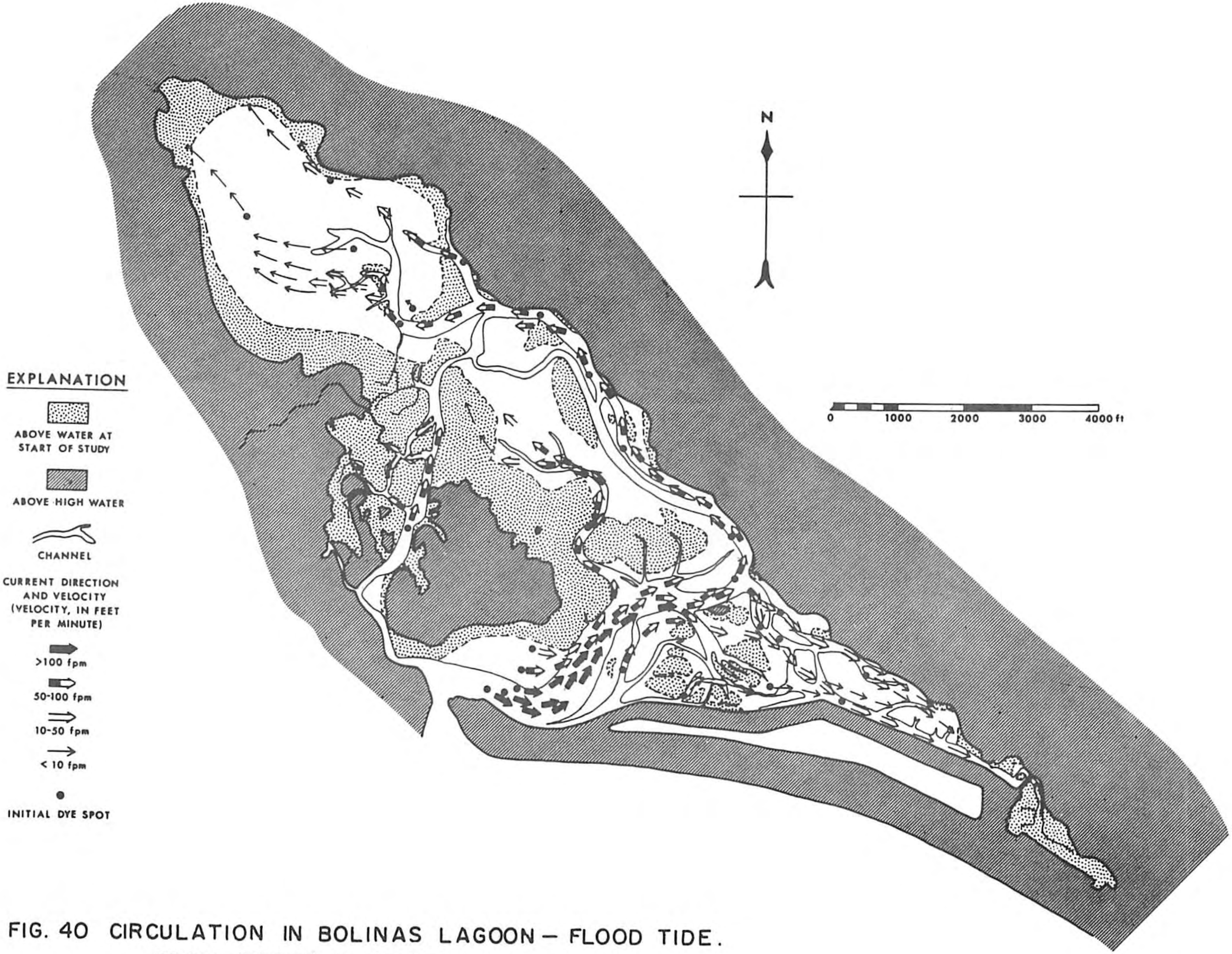


FIG. 40 CIRCULATION IN BOLINAS LAGOON – FLOOD TIDE.
FROM RITTER (p. 36, 1969)

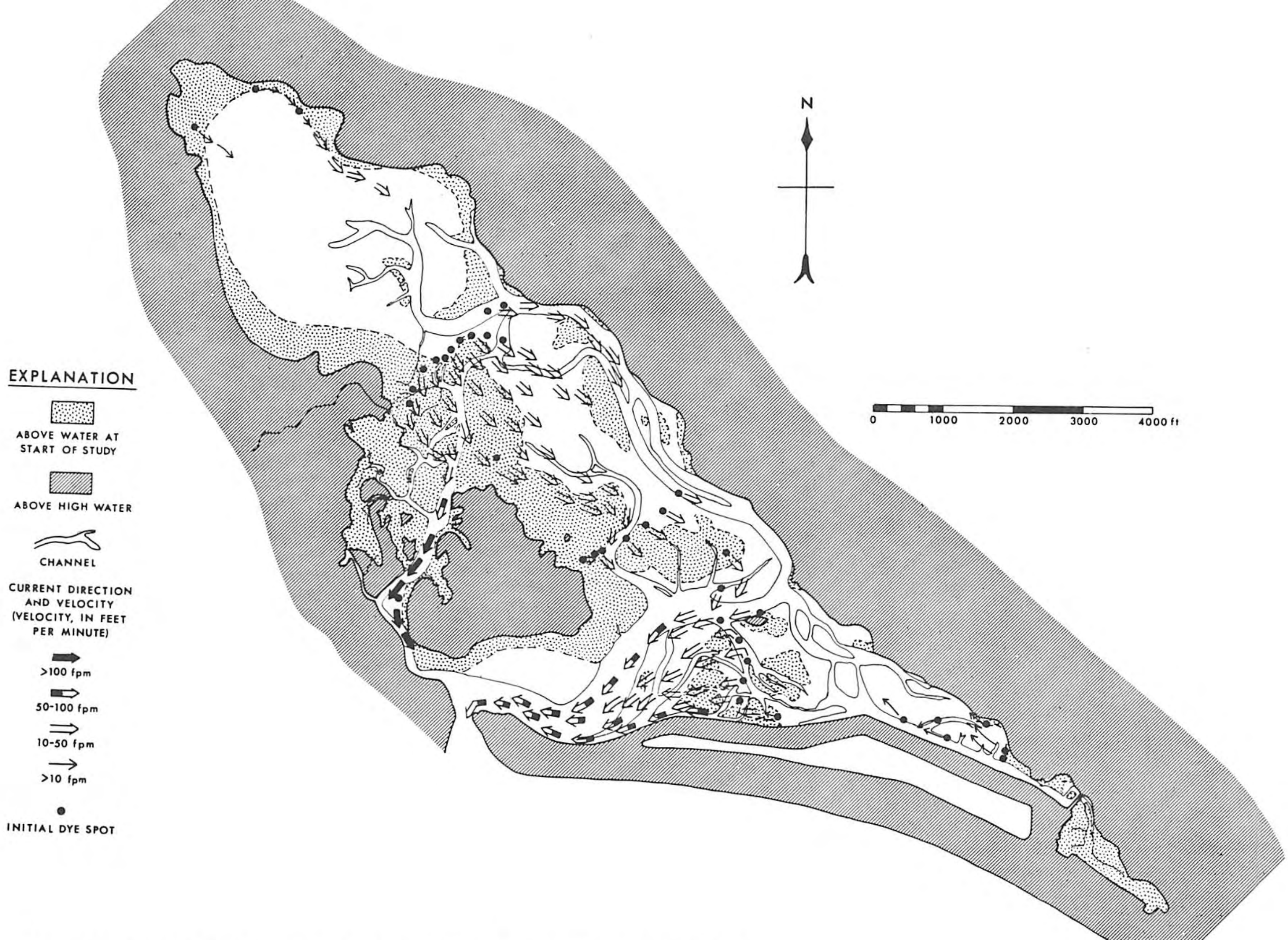


FIG. 41 CIRCULATION IN BOLINAS LAGOON - EBB-TIDE.
FROM RITTER (p.37, 1969)

FIG. 42
FROM HELLEY (IN RITTER, P. 55, 1969)

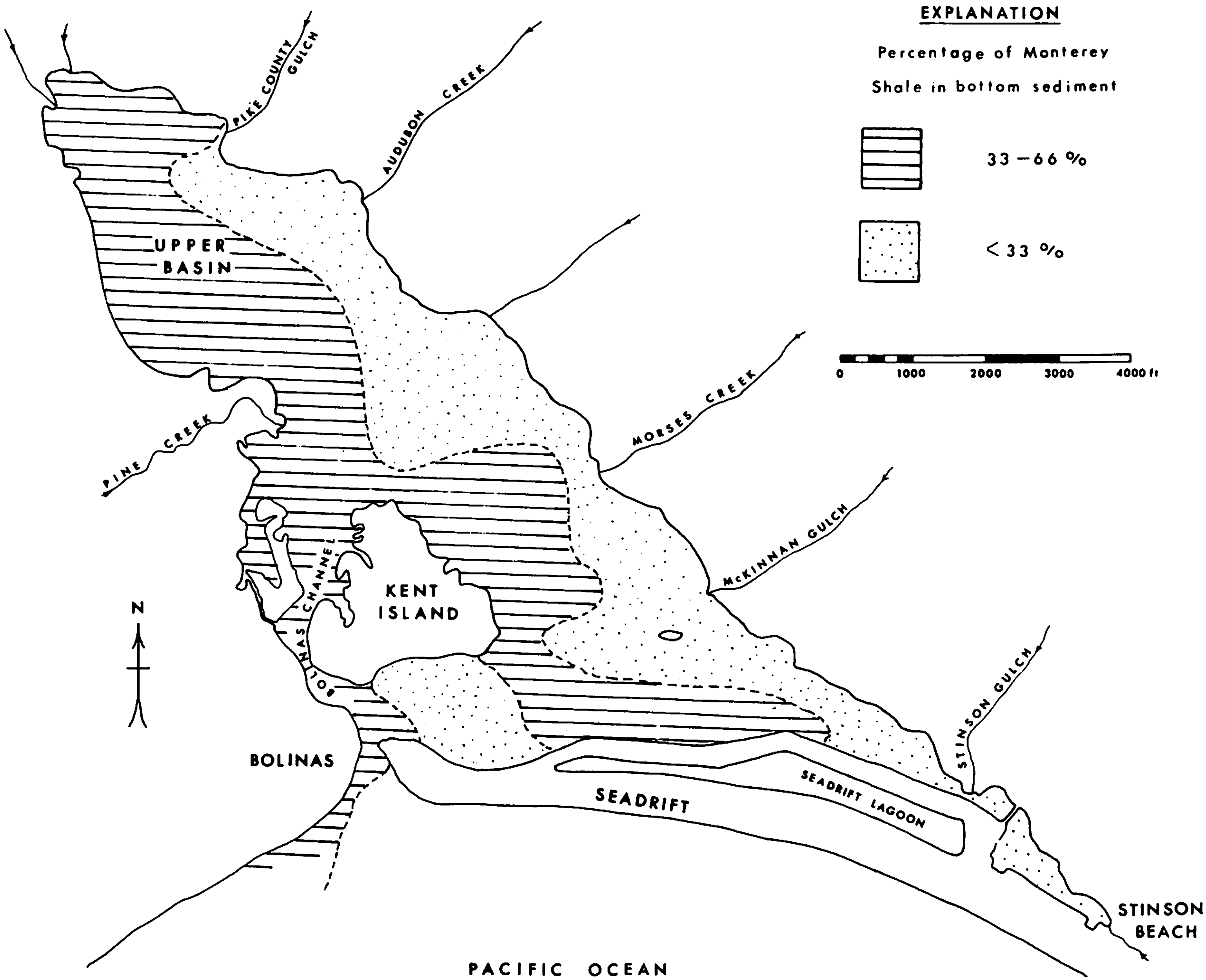
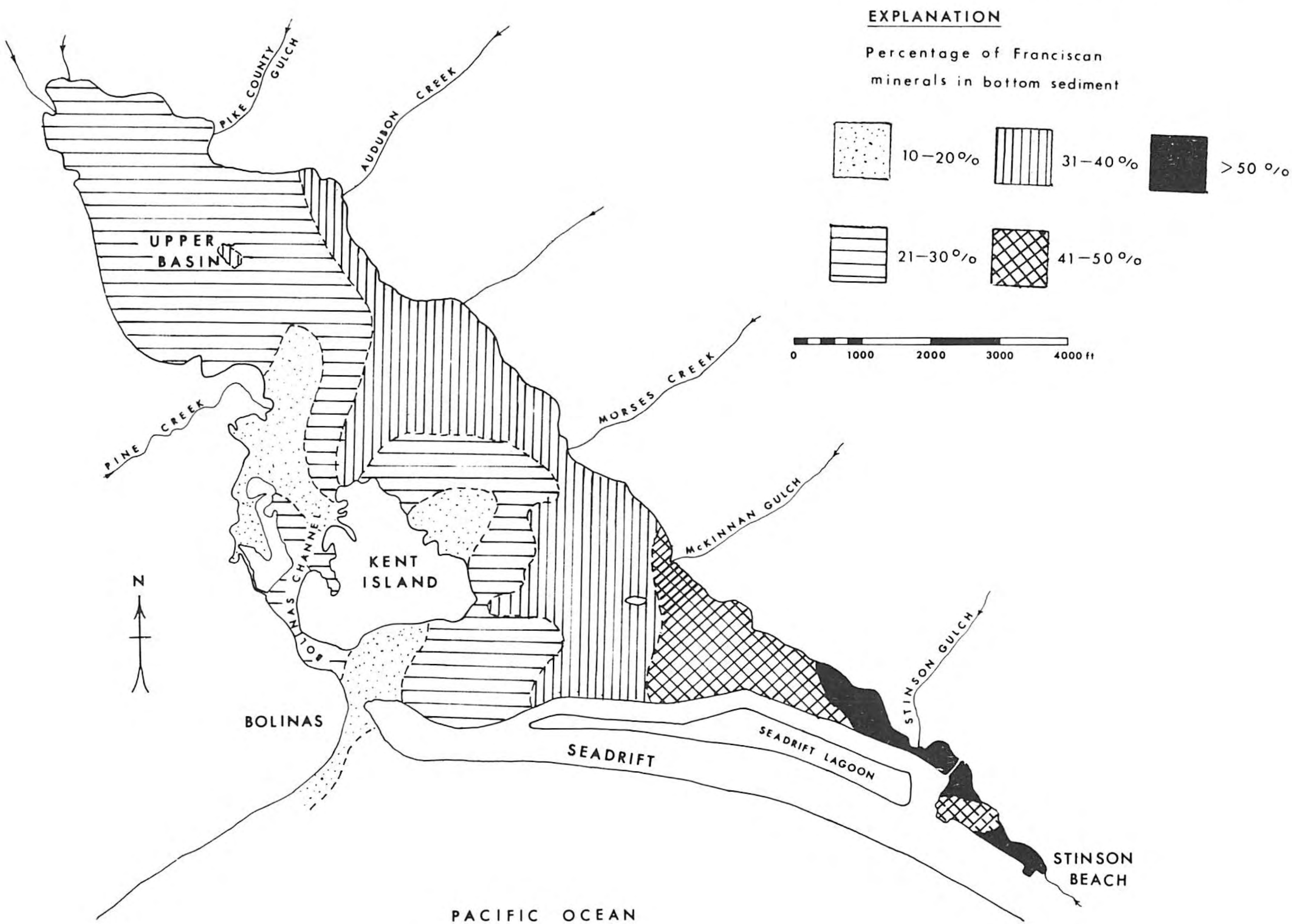


FIG. 43

FROM HELLEY (IN RITTER, p. 56, 1969)



large reservoir of unconsolidated sediment,part of which is brought into Bolinas Bay by tidal currents. Sediments of the San Francisco Bar are characterized by higher concentrations of augite and hypersthene than are found in marine sediments to the northwest or south (Moore, 1965). Sediments of the bar are derived from the Central Valley drainage area which contain large amounts of volcanic rocks and volcanic sediment which is the source of the hypersthene (Hall, 1966). Part of the sediments in Bolinas Bay are characterized by similar high concentrations of augite and hypersthene and thus are probably derived directly from the San Francisco Bar, carried by the northward flowing Coast Eddy Current (U. S. Coast Pilot, No. 7, 1968, p. 152).

The San Francisco Bar is formed of sediment brought to the Pacific through the Golden Gate from the Central Valley drainage area. U. S. Geological Survey estimates (in Holman and Schultz, 1963, p. 4) of the sediment entering San Francisco Bay are from 7.2 to 9.6 million cubic yards per year. Table 1 shows the rates of sedimentation of San Francisco Bay and Bar for the past 101 years (Holman and Schultz, 1963). With the present rate of sedimentation, 2.9 to 5.3 million cubic yards of sediment per year passes through the bay and off the Bar. A portion of this volume must move north into Bolinas Bay by northward flowing currents.

The sea cliffs south of Bolinas Bay, between Rocky Point and Point Bonita, are another possible source for sediments in Bolinas Bay. Sediment derived from them might enter the bay by longshore drift, or by bottom currents. Sediments derived from these rocks have a typical Franciscan mineralogy. The amount of sediment entering Bolinas Bay

Table 1. SAN FRANCISCO BAY AND BAR SEDIMENTATION*

San Francisco Bay - past 101 years (1855-1956)

Accretion:	997.2 X 10^6 cubic yards
Loss:	384.7 X 10^6 cubic yards
Net Sedimentation:	612.5 X 10^6 cubic yards
Rate:	6.06 X 10^6 cubic yards/year

San Francisco Bay - past 56 years (1900-1956)

Accretion:	452.4 X 10^6 cubic yards
Loss:	261.7 X 10^6 cubic yards
Net Sedimentation:	190.7 X 10^6 cubic yards
Rate:	3.41 X 10^6 cubic yards/year

San Francisco Bar - past 101 years (1855-1956)

1855-1873	- 1.66 X 10^6 c.y./year	- 29.9 X 10^6 c.y.	- scour
1873-1884	-16.53 X 10^6 c.y./year	-181.8 X 10^6 c.y.	- scour
1884-1900	+ 4.83 X 10^6 c.y./year	+ 77.2 X 10^6 c.y.	- sedimentation
1900-1956	+ 0.88 X 10^6 c.y./year	+ 49.5 X 10^6 c.y.	- sedimentation

1855-1956 - 0.84 X 10^6 c.y./year

* data from Homan and Schultz (1963, p. 6)

from this source appears to be small. Material carried northward by longshore drift would be blocked or directed seaward by the irregular shoreline, and its character would be masked by mixing with the San Francisco Bar sediments.

The sea cliffs north of Duxbury Point are another possible source of sediment to Bolinas Bay. However, Cherry (1966) noted negligible longshore drift in this area. Duxbury Reef acts as a barrier to sediment movement into the bay. The reef forms a continuous barrier on the sea floor extending about two miles out into the ocean and acts as a baffle which traps sediment, or as a barrier to deflect it to the south. The reef completely blocks sediment movement into the shallow part of Bolinas Bay from the coastline to the northwest, and probably keeps it out of the bay entirely.

B. Major Mineralogic Trends

The mineral distribution maps reveal distinctive mineral suites adjacent to the mouths of Bolinas Lagoon and Webb Creek, and a distinctive mineral suite in the south portion of the bay, near the San Francisco Bay Bar. This distribution reveals that Bolinas Lagoon, Webb Creek, and the San Francisco Bar supply sediment to Bolinas Bay of distinctive composition, and their influence can be seen in the composition of bay sediments. Of the three sources, the San Francisco Bar is the dominant one, judging from its area of influence.

The minerals that show distribution trends in Bolinas Bay are hypersthene, green hornblende, glaucophane, and jadeite. Hypersthene and green hornblende are associated with Bay Bar sediments, and glaucophane and jadeite are associated with Franciscan sediments.

Moore (1965) shows that the primary source of hypersthene is landward of the Golden Gate, and that there is a high concentration of hypersthene on the Bar and decreasing concentrations to the north toward Bolinas. Hypersthene appears not to have any source at Bolinas Bay, as it is rare in the tertiary sedimentary formations on Point Reyes, and is rare in the Franciscan Formation. The principle supplier of hypersthene to the San Francisco Bay Bar is the Sacramento River, with some also coming from the Napa River, both of which empty into San Francisco Bay (Moore, 1965).

Hornblende also has the highest concentrations near the Bay Bar, and according to Moore's (1965, Fig. 10) data this is the best source for hornblende in Bolinas Bay. Hornblende is not abundant on Marin County beaches, and therefore doesn't appear to be coming from the Franciscan Formation or the tertiary sedimentary formations in large quantities, although these units do contain hornblende.

The minerals glaucophane and jadeite are entirely restricted to the Franciscan Formation in their occurrence. Their presence in the sediment of Bolinas Bay indicates a source in the Franciscan rocks bordering the bay.

V. SEDIMENT REGIME

A. Sediment Sources

The data from mineralogical studies presented in this report permit us to distinguish two major and one minor source(s) of sediment for Bolinas Bay. A fourth source, of nondiagnostic mineral composition, is known from studies of sea cliff erosion. The first source is Bolinas Lagoon, which supplies sediment of a distinctive mineral composition characterized by glaucophane and jadeite. Bolinas Bay sediments near the entrance to Bolinas Lagoon are of this composition, and there is a limited eastward dispersal of sediment from this source.

The other major source is the unconsolidated sediments of San Francisco Bar, south of Bolinas Bay, characterized by hornblende and hypersthene. Sediments derived from this source cover a large area in the southeast and central portions of the bay, in areas of the bay closest to the bar. Sediment from the bar enters Bolinas Bay from the southeast, and is mixed with sediment from other sources. This sediment is moved into the bay by bottom currents in the deeper parts of the bay, in depths probably of 50-80 feet, where topographic gradients are low. This sediment does not enter the bay by longshore drift, and does not entar depths that lie within the regime of the surf zone (approx. 0-30 feet).

A third, and minor, source of sediment is Webb Creek near Rocky Point. Sediment with a Franciscan glaucophane-jadeite mineral composition enters Bolinas Bay at this place, and is spread a short distance to the north, west, and south of the point. The limited and equal distribution of sediment from Webb Creek shows that sediment bypassing around Rocky Point, from either the north or the south, is relatively unimportant. As a result, longshore drift on a long term basis is unimportant in sediment movement in the vicinity of Rocky Point. This supplies further evidence that sediment transported into Bolinas Bay from the San Francisco Bar enters through the deeper portions of the bay, outside the surf zone.

A fourth source of sediment, although indistinguishable by heavy mineral content, is present in the northwest corner of the bay. The sea cliffs between the town of Bolinas and Duxbury Reef are rapidly eroding at the present and deliver sediment directly into the bay. The relative importance of this source cannot be determined on the basis of heavy mineral data, but estimates of 72,000 cubic yards of erosion per year indicate that this is a major source of sediment.

B. Sediment Transport

The sedimentary budget of Bolinas Bay is a function of (1) the volume, size distribution, and entry point of material introduced into the bay, and (2) the volume, size distribution,and exit areas for material leaving the bay. Within the bay these sediment fluxes are governed by (3) bottom currents which distribute the sediment, and (4) the bottom configuration which modifies the hydraulic regime causing transportation or deposition of sediment in a given area. The above four factors also, at least in part, are time dependent; some seasonal like the volume of stream discharge, or semi-diurnal like tidal fluctuations of the bottom currents. Thus, in order to understand the complete sediment flux in Bolinas Bay, it would be necessary to take serial bottom samples with the change of season and the tide. Obviously this was not done, because of the expense and the time needed to finish such a project. However, the sampling program was planned as close as possible to the time of maximum sediment flux during (a) maximum sediment introduction (towards the end of the winter rainy season), (b) maximum tidal range (near the spring equinox), and (c) maximum storm swell conditions and maximum longshore drift (winter). Accordingly, the interpretations derived from these analyses of the bottom sediments, strictly speaking, are limited to the end of March. However, Johnson (1969) has shown that the changes in bottom configuration are limited to shallow areas near the mouth of the lagoon. Therefore, the mineralogic distributions shown in this report probably are valid for the generalized annual picture for the entire bay.

C. Sediment Budget

As noted in the section on provenance, the major source of the sedimentary cover is San Francisco Bar. Secondary to this is the sediment from Bolinas Lagoon, and of least importance is Webb Creek. For the Bolinas Cliffs the rate of retreat of the cliffs is known, and volumes of sediment can be roughly determined.

As cited earlier in this report, the Bolinas Cliffs are presently eroding at a rate of 2.3 feet per year. Computing the area of cliff face subject to erosion, the resultant sediment yield to the ocean is determined to by approximately 72,000 cubic yards per year.

Ritter (1969) made measurements of the amount of sediment transported through the mouth of Bolinas Lagoon for one complete tidal day, a period of 25 hours, on October 24-25, 1967. Most of the sediment was moved during the major ebbtide, and the resultant of all portions of the tidal cycle was a net removal of about 330 tons of sediment from the lagoon for a 25 hour period. Projecting this over a full year, and using a density of 79 pounds per cubic foot, which Ritter (1969) determined to be the average density of sediments in Bolinas Lagoon, the resultant is a sediment yield of about 32,500 cubic yards per year. This figure is used as a minimum value of yearly sediment yield. The measurements were made at the end of the California dry summer season, when sediment yield is low. High sediment yields are associated with periods of high water runoff during the winter, which our calculations do not allow for, although it may be counterbalanced to a small degree by dry summer months with a lower sediment yield. A safe estimate would be an average of about 50,000 cubic yards per year.

No data on the amount of water flow, or suspended sediment content, is available for Webb Creek, so an estimate of the sediment yield is made on the basis of the areal distribution of sediments derived from this source in the sediment cover of Bolinas Bay. A rough estimate of between 1,000-10,000 cubic yards per year can be made on this basis. Sediment yield of Webb Creek is augmented by sea cliff erosion of Rocky Point, which may provide as much, or more, sediment as Webb Creek proper. In any event, this source is not a major source of sediment to Bolinas Bay.

An estimate of the volume of sediment entering Bolinas Bay from San Francisco Bar can be made from the computed volume of sediment passing over San Francisco Bar. Sediment is transported over the bar at a rate of 2.9-5.3 million cubic yards per year. Assuming a fairly even radial dispersal off the bar, about 20% of this total will move towards Bolinas Bay, or about 800,000 cubic yards per year. Assuming that 25% of this amount will actually reach Bolinas Bay, with the remainder moving into deeper water, the resultant total is 200,000 cubic yards of sediment per year. Comparing the relative areal distribution of sediment in Bolinas Bay from each source, with a standard of about 50,000 cubic yards of sediment per year from Bolinas Lagoon, 200,000 cubic yards per year is a reasonable estimate of sediment yield to Bolinas Bay from San Francisco Bar.

Estimates of sedimentary inputs into Bolinas Bay are summarized in Table 2.

Table 2. ESTIMATED ANNUAL SEDIMENT INFLUX INTO BOLINAS BAY

Source	Volume	Authority
Bolinas Cliffs	72,000 cu. yards	rate from Galloway
Bolinas Lagoon	32,500 cu. yards	Ritter
Webb Creek	1-10,000 cu. yards	this report
San Francisco Bay	200,000 cu. yards	estimation Holman & Schutz
TOTAL	314,500	
	315,000 cubic yards/year	

Figure 44 shows postulated sediment flux and non-tidal currents for the end of the winter season in Bolinas Bay. As seen in Fig. 44, the orientation of the heavy mineral provinces is not adequately explained by the non-tidal currents in Bolinas Bay. This is particularly true for the lobe of high hornblende-hypersthene emanating from the

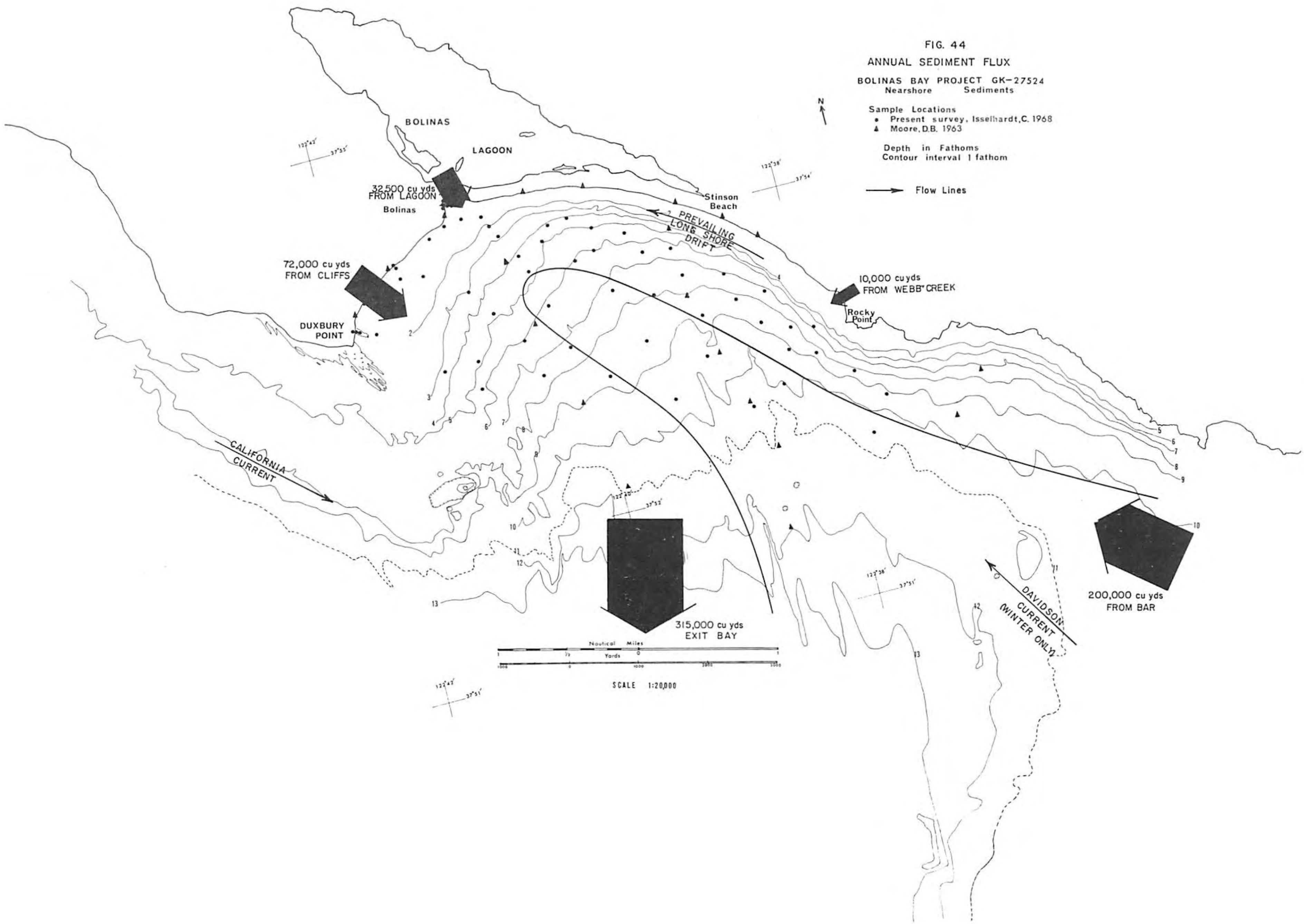


FIG. 44
ANNUAL SEDIMENT FLUX
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
N
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
Flow Lines
BOLINAS
LAGOON
32,500 cu yds FROM LAGOON
Bolinas
Stinson Beach
PREVAILING LONG SHORE DRIFT
72,000 cu yds FROM CLIFFS
10,000 cu yds FROM WEBB CREEK
Rocky Point
DUXBURY POINT
CALIFORNIA CURRENT
DAVIDSON CURRENT (WINTER ONLY)
200,000 cu yds FROM BAR
315,000 cu yds EXIT BAY
Nautical Miles
Yards
SCALE 1:20,000

Potato Patch Shoals of the San Francisco Bar. The influence of the tides in governing the sediment distribution in Bolinas Bay is postulated as a two step process.

I. During flood tide in the lagoon (Fig. 45), the flow of water and entrained sediment to the northwest is at a maximum as (a) the Coast Eddy Current, (b) the Davidson Current, (c) longshore drift by wave refraction around Duxbury Reef, all act in consort with the incoming tide in the lagoon. Apparently the axis of transport is directed approximately along the 50 foot (8-9 fathom) line as shown by the orientation of the hornblende-hypersthene lobe.

II. During ebbtide in the lagoon (Fig. 46), the outflow from the lagoon combines with or produces the southwest return gyre of the Coast Eddy Current, which is reinforced to the southwest off the tip of Duxbury Reef by the California Current. The leading edge of the counterclockwise gyre, (a) entrains material from local sources which mixes with lagoonal material from the ebbtide on the southwest side, but (b) maintains on the inner side of the gyre the compositional integrity of the sediment brought from the San Francisco Bar. The gyre thus produces a northwest oriented lobe of San Francisco Bar material surrounded on three sides by sediments from local source areas.

The above models are based on an input from various sources of 315,000 cubic yards annually to Bolinas Bay (Table 2). Johnson (1969) has shown that the bottom configuration in deeper water does not change throughout the year. Thus, there is no net aggradation-degradation in Bolinas Bay. This implies quasi-equilibrium with a balancing outflow

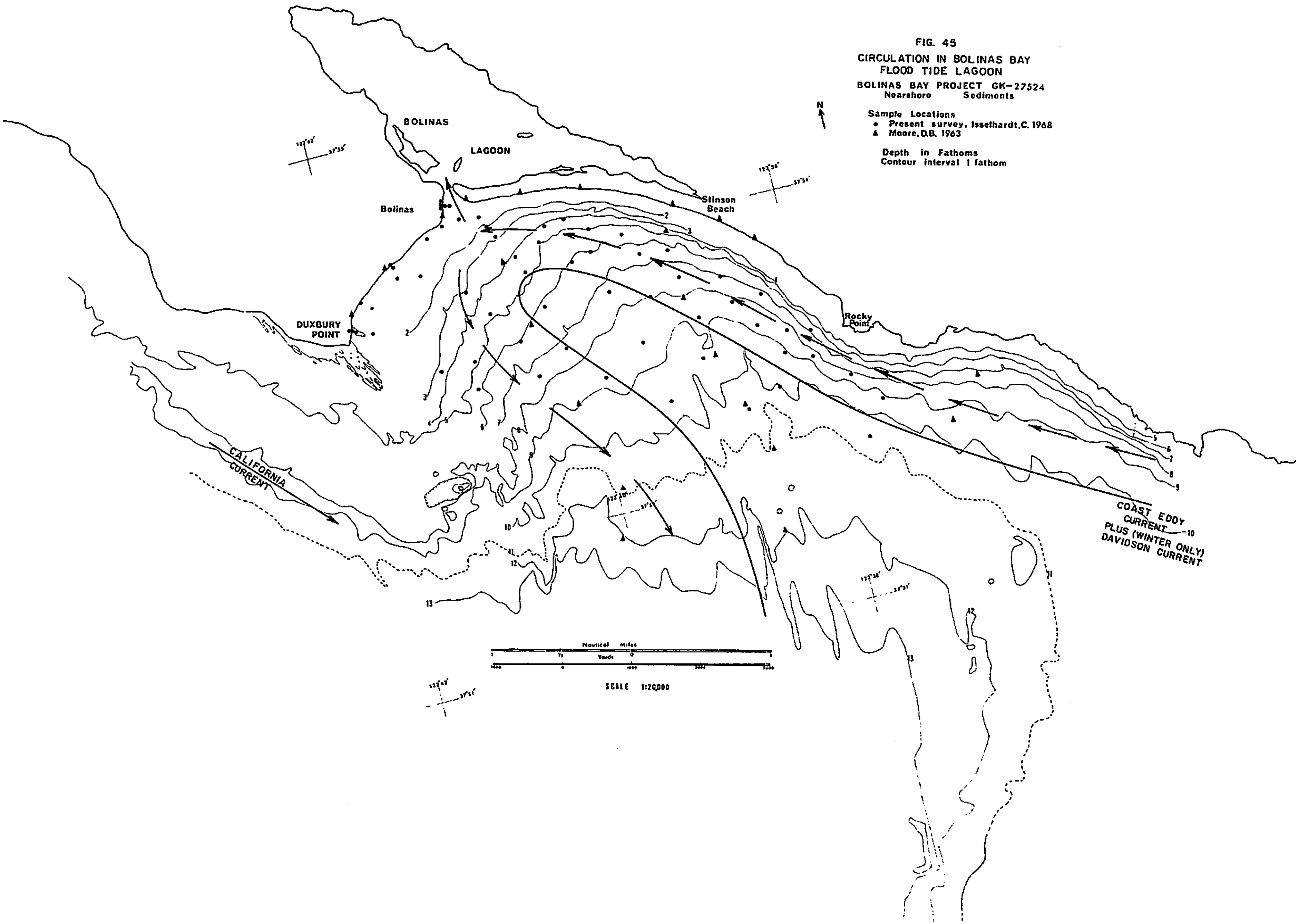


FIG. 45

CIRCULATION IN BOLINAS BAY
FLOOD TIDE LAGOON

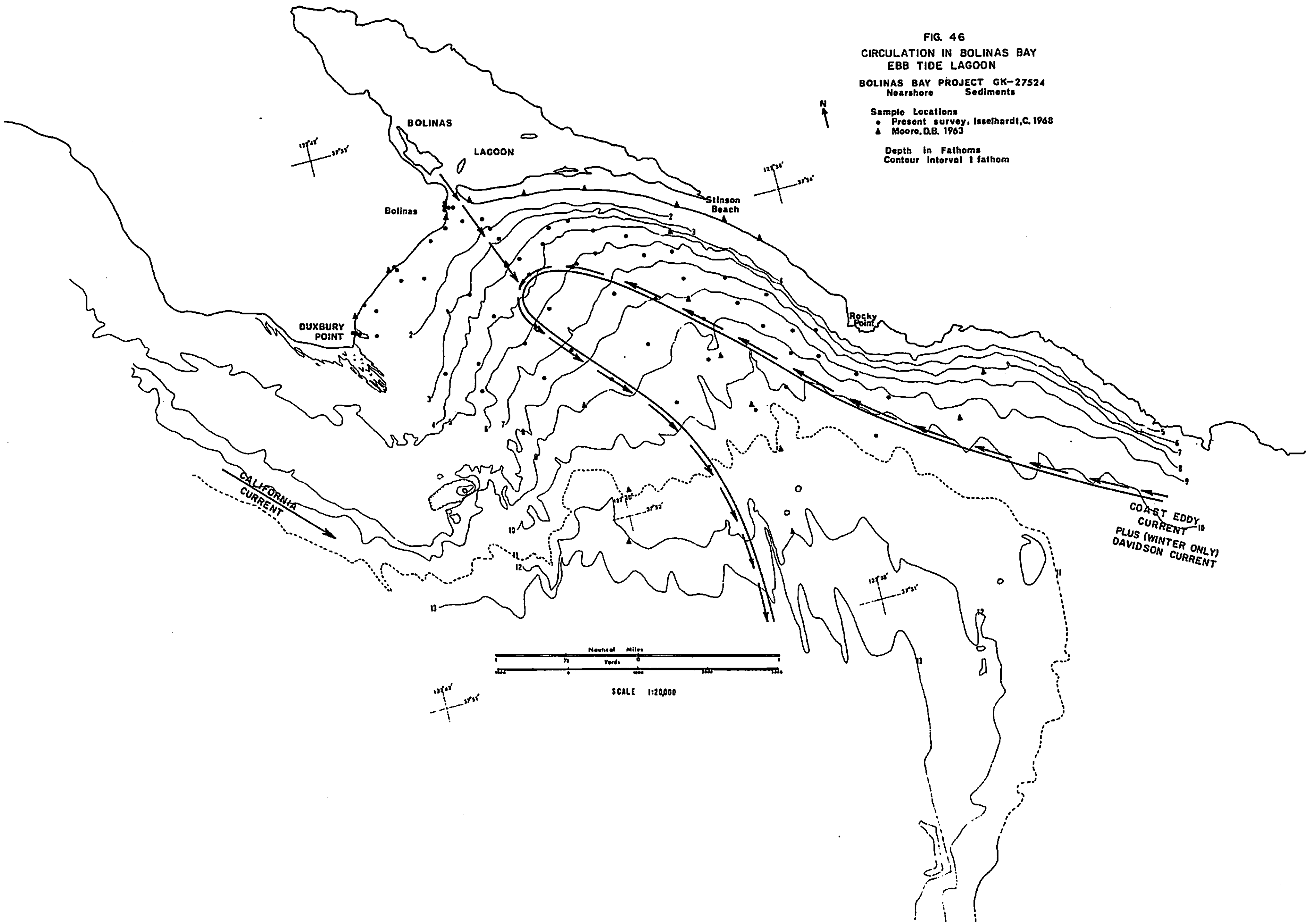


FIG. 46

CIRCULATION IN BOLINAS BAY
EBB TIDE LAGOON

BOLINAS BAY PROJECT GK-27524
Nearshore Sediments

of approximately 315,000 cubic yards annually. With sediment added along the counterclockwise gyre (a) from the southeast from the San Francisco Bar, (b) from the northeast from Webb Creek, and (c) from the northwest from the lagoon and cliff erosion, the logical exit is to the southwest to deeper water on the shelf. This is indicated on the bathymetry map by (1) the steep seaward gradients in the channel adjacent to Duxbury Reef, and (2) two small channels emptying into the embayment which separates the bay from Potato Patch Shoals.

APPENDIX I

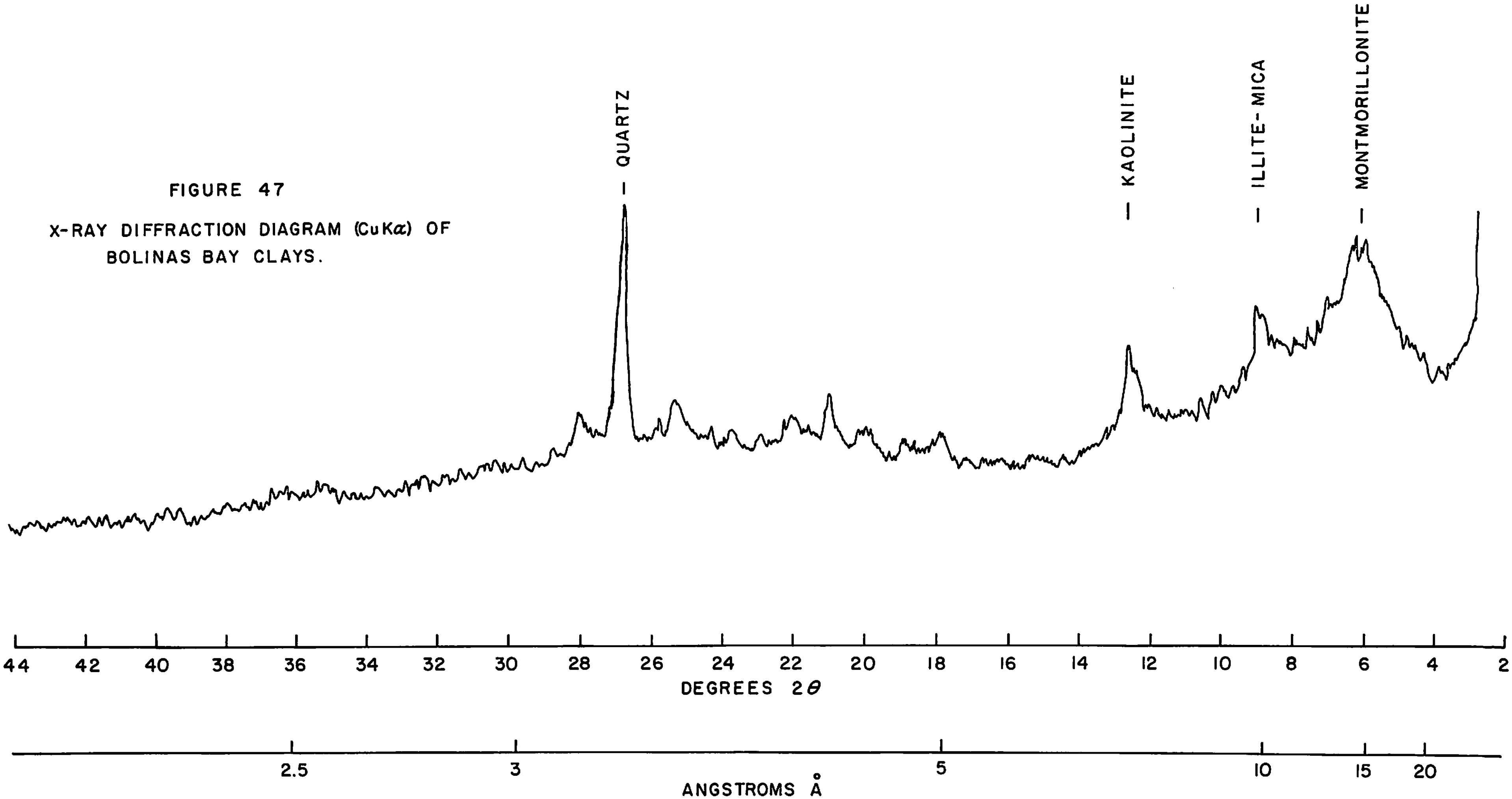
CLAY MINERALOGY

The sediments in Bolinas Bay have an average grain size that falls within the sand size range or coarse silt size range, and consequently have a very low clay content. The clay content is highest in the finer grained sediments that accumulate in the center of the bay in deep water. The clay content is no greater than a few per cent in any of the samples.

X-ray diffraction analyses (see Fig. 47 for typical example) indicate the clay content is similar for all the sediment samples in Bolinas Bay. Montmorillonite is the dominant clay mineral, and kaolinite is the second most abundant, usually of about half the quantity of montmorillinite, and illite-mica is consistently present in small amounts. The clay mineral composition is identical to clay mineral composition of marine sediments in Monterey Bay (Yancey, 1968), and in Half Moon Bay. The proportions of these clay minerals and the compositions are identical in sediments of the three areas. In no cases have significantly different clay compositions been found in marine sediments on the Central California continental shelf. This conclusion must be verified by further work, but the gross clay mineralogy is very similar for a large portion of the continental shelf in this region.

FIGURE 47

X-RAY DIFFRACTION DIAGRAM (CuKα) OF BOLINAS BAY CLAYS.



APPENDIX II

CARBONATE CONTENT AND DISTRIBUTION

This is a summary of a report by Christopher Jackson (1969) prepared for a geological oceanology course given in the Dept. of Civil Engineering at the University of California, Berkeley. The samples used for the report were splits of the same samples collected for the mineralogical and grain size analyses of this report.

The method of analyses was by EDTA chelation of Ca and Mg ions of a powdered bulk sample (Bisque, 1961), where

$$\% \text{ calcareous material} = \frac{\text{gram molecular wt. } CaCO_3 \times \text{mM(Ca + Mg)} \times 100}{10^3 \text{mM/mole} \times 1 \text{ gram sample}}$$

This formula assumes all Ca and Mg are in carbonate shell material and does not account for any exchangeable Ca or Mg from clays. However, with the high visible shell content in the samples, the principle sites for Ca and Mg must be in carbonate shell and the clay sites may be ignored with small error. The data is plotted in Fig. 48.

The areal distribution of the carbonate content of the sediments in Bolinas Bay is a function of several variables. The most important of these are sediment grain size, water depth, topographic gradient, and wave agitation. In general, there is an inverse relationship between water depth and carbonate content, which is paralleled by an inverse relationship between sediment grain size and carbonate content. These patterns are modified by topographic gradients and differential wave protection.

The highest concentration of carbonate content occur in the eastern part of the bay, in deep waters, at the foot of a high topographic

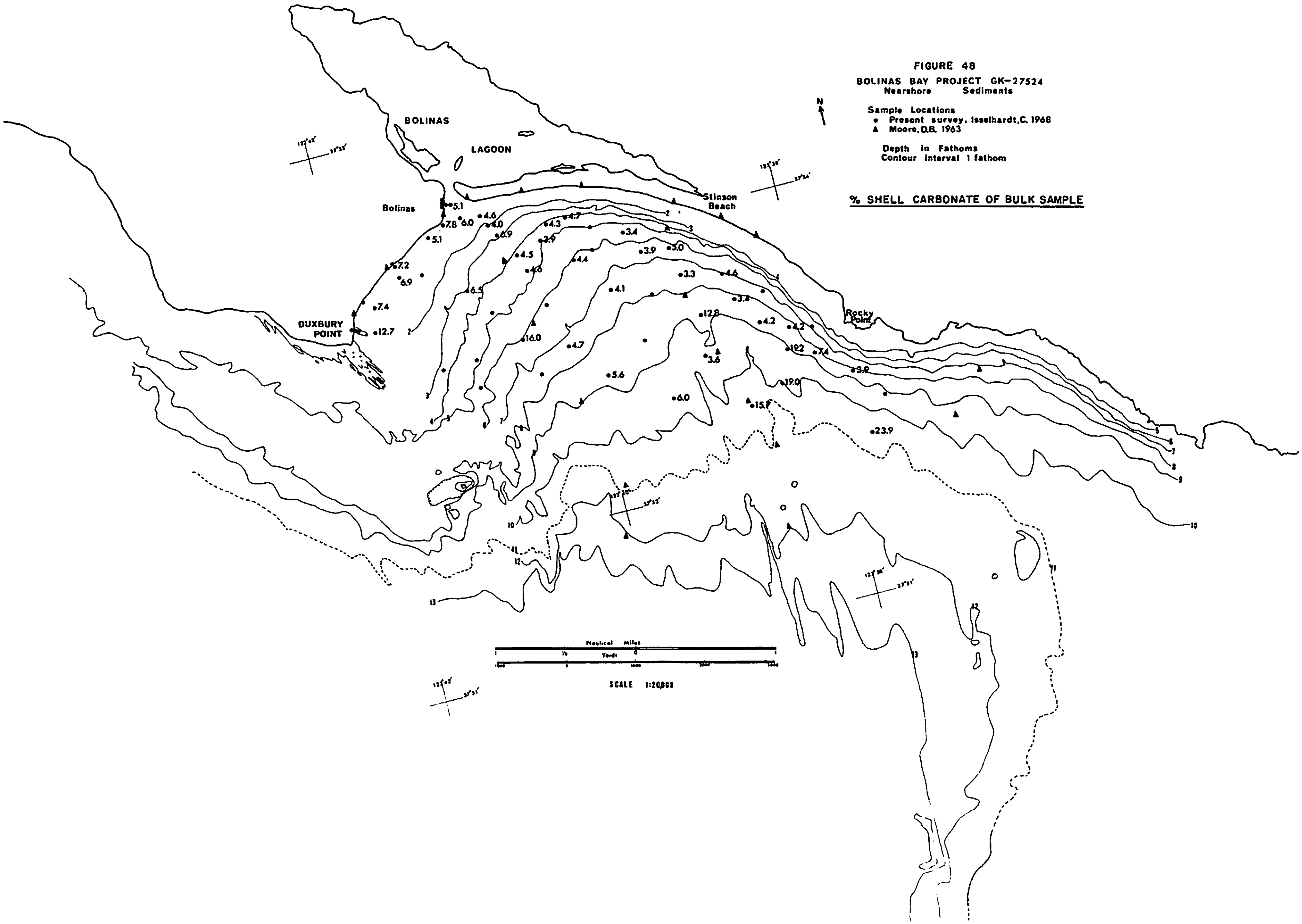


FIGURE 48
BOLINAS BAY PROJECT GK-27524
Nearshore Sediments
N
Sample Locations
• Present survey, Isselhardt, C. 1968
▲ Moore, D.B. 1963
Depth in Fathoms
Contour interval 1 fathom
% SHELL CARBONATE OF BULK SAMPLE
BOLINAS
LAGOON
Bolinas
Stinson Beach
Rocky Point
DUXBURY POINT
5.1
7.8
6.0
4.6
4.0
5.1
6.9
4.3
4.7
3.9
3.4
4.5
4.6
4.4
3.9
3.0
7.2
6.9
6.5
4.1
3.3
4.6
7.4
12.7
3.4
12.8
4.2
4.2
16.0
4.7
19.2
7.4
3.6
5.6
3.9
19.0
6.0
15.7
23.9
Nautical Miles
Yards
SCALE 1:20,000

gradient. Moderately high carbonate contents occur in the center of the bay in deep water and on a low topographic gradient. The lowest carbonate content occurs in shallow water; areas in which the sediment grain size is coarse, and wave agitation is strong. Samples adjacent to the Bolinas Cliffs, where wave agitation is reduced, contain moderate carbonate contents.

Some factors which influence the carbonate content of sediments in large ocean basins, such as salinity, temperature, and nutrient content of the water, appear not to vary enough within the bay to cause variation in carbonate content.

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