U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

U.S. Environmental Protection Agency Reference Site on the Farallon Continental Slope off of San Francisco (CA): Characterization of the Seafloor and Shallow Subbottom

By

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INTRODUCTION

The ports within the San Francisco Bay system have long suffered from siltation problems, requiring periodic maintenance dredging to maintain navigable water depths. The US Army Corps of Engineers has overseen dredging of navigable waterways in San Francisco Bay since the 1800's. The Long Term Management Strategy (LTMS), a plan developed by a consortium of public and private entities concerned with safe navigation in San Francisco Bay, estimates that 300- 400 million cubic yards of dredged material from San Francisco Bay projects will need to be disposed of over the next 50 years. Some of this material will be utilized for beneficial re-use projects within the bay, such as wetlands nourishment. A large portion however will still need to be disposed of outside of the bay. The LTMS and the US Environmental Protection Agency (USEPA) consequently designated the "San Francisco- Deep Ocean Disposal Site (SF-DODS)" through the mandatory Federal offshore site designation process. SF-DODS is located approximately 35 km southwest of the Farallon Islands in about 2800 m water depth on the outer continental slope. As part of the designation process for an offshore disposal site, the U.S. Environmental Protection Agency (EPA) also specified a "Reference Site" on the continental slope west of San Francisco. This Reference Site occurs on the middle to lower continental slope west of San Francisco and southwest of the Farallon Islands (Fig. 1). The purpose of this Reference Site is to establish a "standard" against which environmental changes at the San Francisco Deep Ocean Disposal Site (SF-DODS) can be compared as the disposal of dredge spoils proceeds in future years. The Reference Site will be considered representative of the "natural" Farallon slope environment and processes (presumably un-affected by dredge spoils which will <u>not</u> be dumped at this Site).

The continental margin off of central California is a region of rugged and diverse morphology. A broad continental shelf, where water depths seldom are deeper than 120 m, falls gently away from the shoreline adjacent to San Francisco. Approximately 48-56 km (30-35 miles) from the shoreline a natural break in slope occurs between the shallower waters and gentler gradient of the continental shelf and the deeper waters and steeper gradient of the continental slope. This natural break in slope, the "shelfbreak", occurs at about 120-150 m water depth. The continental shelf, landward of the shelfbreak, is characterized by its general lack of physiographic relief; the continental slope on the other hand is characterized by its relatively great topographic relief and rugged morphology. The slope occurs from about 150 m water depth down to about 3500 m water depth where it merges with the deep Pacific Ocean basin.

The USGS conducted cruise E2-94-NC in response to EPA's request to characterize the Reference Site, both acoustically and sedimentologically. This report presents the acoustic characterization of the Reference Site and integrates the acoustic results with the sedimentologic results.

METHODS

In this report we evaluate acoustic and sediment data from USGS cruises F8-90-NC (1990) and E2-94-NC (1994) to characterize the seafloor and shallow subbottom of the EPA Reference Site on the Farallon slope. Side scan sonar data were collected in 1994 with an EG&G SMS-960 Seafloor Mapping System digital side scan sonar utilizing an operating frequency of 100 kHz. High-resolution shallow subbottom seismic reflection profiles were collected in 1994 with an ODEC Bathy-2000 system utilizing a frequency of 3.5 kHz. Approximately 450 km of trackline data were collected in 1994. Acoustic data and equipment systems from 1990 surveys are described in Chin, et. al., (1992). In 1990, side scan sonar data were collected with a 30 kHz SeaMarc 1A system while 3.5 kHz subbottom data were collected with a Raytheon system. Approximately 120 km of 1990 trackline data were collected within the Reference Site. Gravity cores were collected in 1990 using a standard USGS piston coring system. Five cores from the 1990 dataset occur within the Reference Site. In 1994 seven gravity cores were collected with a USGS hydraulically-dampened coring system (Bothner, et. al., 1997).

Side Scan Sonar

The SMS-960 Seafloor Mapping System acquires digital sonographs of the seafloor and applies automatic spatial corrections for slant range and ship speed. This allows for corrections in real time of distortions due to slant range and speed to yield corrected plan views of the seafloor. The sonar data were magnetically taped for subsequent image processing on the USGS-MIPS system.

The acoustic data collected in 1994 were generally poor in quality. The sonar data were collected on only 1-11/2 days of the cruise due to excessively poor operating conditions. The light weight of the towfish, in conjunction with the rough seas, produced minimally acceptable sonar data. The entire 1994 cruise was affected by strong winds, high seas, and poor opearting conditions. The limited areas we did survey with the SMS revealed no major differences from the 30 kHz (SeaMarc 1A) survey of 1990.

3.5 kHz Subbottom

The ODEC Bathy-2000 system was designed to collect seafloor bathymetry and shallow subbottom profiles. The data would allow us to characterize the bottom morphology and the uppermost part of the sediment column immediately below the seafloor within the Reference Site. It would also allow us to delineate unconsolidated sediment to target areas for subsequent gravity coring. The ODEC system used is superficially similar to the Raytheon 3.5 kHz system used on the 1990 surveys. Bathy-2000 consists primarily of an onboard signal processor, power amplifier, and thermal recorder. The system is integrated with the ship's navigation systems. The transducer is housed in a towfish that is deployed via an armored co-axial cable. For the 1994 cruise, the towfish was deployed off the stern of the ship. Hardcopy output was to a Hewlett-Packard, 180 DPI, 16-level inkjet color printer. Profiles were automatically annotated with time, latitude, longitude, and water depth (based on an automatic bottom-tracking function).

Our setup for the ODEC system utilized a HP inkjet color printer. This configuration yields similar results to the 1990 systems except that the intensity of the reflectors is color-coded by the darkness of color utilized (Fig. 2) rather than by how dark/intense the paper is imprinted by the traditional gray scale graphic recorders. The resolution of the ODEC profiles is roughly equivalent to that of the 1990 profiles, about 1-2 m; the exception is in areas where extreme swell severely distorts the record.

Our procedure in analyzing the ODEC profiles was to note the acoustic character of the shallow subbottom and the thickness of the strata we judged to be unconsolidated within the Reference Site. Unconsolidated sediment is the sediment that in most cases should be obtainable by gravity coring during sampling operations. The sediment is typically loosely arranged and un-cemented. Acoustically, unconsolidated sediment is typically transparent to very weakly bedded.

We then sought to verify interpretations made from the ODEC 3.5 kHz profiles by comparison to previous (1990) subbottom profiles obtained in the study area. A trackline map of the 1990 survey revealed several tracklines that traversed the Reference Site (Fig. 3). We focused on the 4.5 kHz profiles since they revealed the highest resolution and the greatest stratigraphic detail (Fig. 4). In areas where the respective tracklines from 1990 and 1994 either crossed or were in proximity to one another, interpretations for acoustic stratigraphy, nature of the shallow subbottom, and thickness of unconsolidated sediment were compared and refined. Our final conclusions on the acoustic character of the Reference Site were then based on the best available evidence derived from the 1990 and 1994 datasets.

Sediment Gravity Cores

As a final step to characterizing the acoustic nature of the Reference Site we compared the results of 1994 sampling operations to our interpretations made strictly from acoustic profiles. Sampling results from the 1990 survey were also utilized where relevant. The relatively low (about 30%) recovery rate for 1994 sampling operations has several possible explanations. The USGS hydraulically-dampened gravity core was deployed for the first time on this cruise at full ocean water depths. We chose this coring device in order to obtain the most representative in-situ sediment sample of the seafloor possible (see Bothner, et. al., 1997). The relatively deep water and strong currents (associated with the extremely poor weather conditions) hampered our sampling efforts. The patchy nature of the unconsolidated sediment required that our positioning be exact if we were to successfully obtain sediment at the pre-designated site on our ODEC profile. However, the strong winds and currents usually made it difficult for the vessel to stay on station. Furthermore, at these water depths and with the strong currents present, the coring device very likely did not descend vertically once lowered into the water (ie---when the vessel was presumably directly above the pre-designated sampling site). Although we experienced operational problems, most were early in the cruise and most were resolved to a degree that we felt confident with the results the core device provided--- both in terms of recovery and "no recovery".

RESULTS

Regional Slope Morphology

The continental slope has two contrasting morphologies off the San Francisco Bay region of central California (Fig. 1, 3). The northern part of the Farallon slope, called the "northern province" in Karl, et. al.(1992), is characterized by numerous submarine canyons, gullies, and intervening ridges (Fig. 1, 3). The slope in the southern province is wider (35-45 km), less steep, and less dissected than the northern slope province (Fig. 1, 3). The overall physiography is highly dissected, relatively narrow, and rugged. It ranges in width from about 10 to 15 km. In contrast, the southern part of the Farallon slope, termed the "southern province," is a broad, gently sloping plain that contains Pioneer Canyon (Fig. 3). Pioneer Canyon is the major submarine canyon on the continental slope off this part of central California. The canyon winds its way downslope from a double-headed channel that incises the shelf break. Its sinuous course reveals several channel meanders that have since been abandoned as the canyon switched its course, in much the same way that a subaerial river avulses out of its channel (Fig. 5).

Reference Site Morphology

The Reference Site is situated on a fairly broad, gently sloping plain that occurs immediately north of Pioneer Canyon (Fig. 1). This plain occurs from the shelf break downslope to the lowermost slope, where a break-in-slope occurs--below which is the deep ocean basin floor. The plain, north of Pioneer Canyon, marks the approximate transition zone between the northern and southern slope provinces (Fig. 3) and is approximately the northernmost part of the southern slope province. As opposed to the highly dissected and rugged northern province, this plain is dissected only along its outer edge and slopes gently basinward along its entire length. Two un-named submarine canyons dissect the plain in water depths of about 800 to 1600 m. These un-named canyons do not extend upslope to the shelf break (ie-like Pioneer Canyon); they terminate in about 800-850 m water depth.

Reference Site Acoustic Characterization

Seismic reflection profiles reveal that the Reference Site is characterized by thin, patchy, and discontinuous unconsolidated sediment. This sediment occurs mostly as localized patches or as a discontinuous veneer that drapes older typically well-bedded strata, as identified in a previous study (Chin, et. al., 1992). Subbottom penetration ranged from a few meters to about 25 m on 4.5 kHz profiles. 4.5 kHz profiles indicate that two units of acoustically transparent strata occur over localized parts of the study area (Fig. 6). The uppermost and youngest unit is rarely more than about 2 m thick. The top surface of this unit is the modern seafloor. The lower and older transparent unit attains thicknesses up to about 7 m, but is generally less than 3-5 m. These acoustically transparent units (one or both may be present at different locations) overlie older relatively well-bedded strata that underlie most of the Reference Site. Older strata are generally moderately-to-well bedded and are laterally continuous on acoustic profiles

(Fig. 7). In places, older strata can be continuously traced the entire length and width of the Reference Site. Bedding varies from parallel to sub-horizontal. The bulk of the subbottom is interpreted to be older semi-consolidated to consolidated sedimentary strata (the "moderately- to well-bedded strata"). Locally, older strata are truncated at the seafloor by erosion (as defined by an unconformity in profiles) and in other locations are truncated along the steep flanks of submarine canyons and gullies. Over much of the study area the seafloor mimics the top surface of the older strata, due in large part to the thin or absent unconsolidated sediment veneer (Fig. 7). Locally, this older stratified unit is folded into relatively tight synclines and anticlines.

The 3.5 kHz ODEC profiles (Fig. 2) yield much the same picture as the 4.5 kHz profiles discussed above. A representative acoustic characterization, based on the ODEC data, indicates a patchy and localized distribution of unconsolidated sediment (acoustically transparent) overlying older semi- to consolidated (moderately- to well-bedded acoustically) strata over the study area. The ODEC profiles suggest, like the 4.5 kHz data, that two units may be present within the acoustically transparent unconsolidated sediment layer and that these overlie a moderately-to-well-bedded older unit. ODEC profiles also indicate that one or both of the transparent unconsolidated units may be present locally and that they are typically thin and discontinuous. The uppermost and youngest unit, "yellow" on the ODEC profiles, is usually less than 2 m thick (Fig. 2). The lower transparent unit, "green" in the ODEC profiles, is often thicker than the "yellow". However, the "green" unit rarely attains thicknesses greater than about 5-7 m. These thicknesses correlate well with interpretations derived from the 4.5 kHz data for the acoustically transparent surficial units.

The moderately- to- well-bedded older stratal unit on ODEC profiles, "purple" in color, is most often the basal unit for the ODEC dataset (Fig. 2). Subbottom penetration is usually less than about 25-30 m; the bulk of this represents the older stratified unit. As on 4.5 kHz profiles, we can often trace this older well-stratified unit across the entire length and/or width of the Reference Site--indicating that it is laterally continuous and fairly widespread in its distribution. It is clear from the ODEC profiles that a significant change in acoustic impedance occurs below the "green" (older; acoustically transparent) layer suggesting the "purple" strata are significantly denser (more consolidated/indurated) than either of the surficially transparent layers. These older strata are most likely semi-consolidated to consolidated in nature.

Correlation Of Acoustic Results With Sediment Sampling Results

Acoustic results were compared with unconsolidated sediment sampling data from both 1990 (Fig. 8) and 1994 (Fig. 9). Five of the 1990 gravity cores occur on the boundaries of the Reference Site: 5G5, 5G6, 6G7, 6G8, and 23G27 (Fig. 8). All five of the 1990 gravity cores recovered approximately 2- meters of unconsolidated sediment. The only 1994 core that is located in proximity to a 1990 core is station 3-1; this core site is approximately 200-300 m north of 1990 stations 5G5 and 5G6 (Fig. 9). The core at 3-1 recovered 49 cm of sediment as compared to 2.0 and 2.8 m respectively for the 1990 stations. The maximum recovery for the 1994 dataset was 0.76 m of sediment.

The 1994 gravity cores were predominantly clayey silts (> 60 % mud fraction content for all 7 cores); in contrast, four of the five (23G27 the exception) 1990 gravity cores were predominantly silty sand or sandy silt (> 40% sand fraction content). The only cores located in proximity, between the two datasets, (3-1 and 5G5/6), revealed sand contents that were grossly similar (3-1= 36.5%sand content and 5G5/6= 41%).

The two datasets consist of gravity cores that, with the exception of cores 3-1 and 5G5/6, are no closer in proximity than about 1.5 km (Fig. 8, 9). The relatively sandy composition of the 1990 gravity cores was previously identified in Karl, et. al. (1992) and occurs mainly up-slope of the Reference Site. The sandy veneer is anomalous on the continental slope, where unconsolidated sediment is generally mud (silt and clay). It may represent a relict sediment deposit or possibly a mass-gravity flow derived from further upslope. However, geophysical profiles and side scan sonar show no unequivocal evidence of mass gravity movement where the sandy deposit is located. At this time we do not have sufficient data to adequately explain the origin of the sandy veneer.

The major reason for both similarities and differences between the 1990 and 1994 datasets relates to the physical character of the seafloor and shallow substrate that occurs in and adjacent to the Reference Site. Unconsolidated sediment, as deduced from both 1990 and 1994 seismic reflection surveys, occurs in thin, discontinuous, localized patches and lenses throughout the Reference Site. This patchy distribution we feel is primarily responsible for the mixed results obtained in sampling operations in 1994. ODEC 3.5 kHz and 4.5 kHz profiles both indicate that unconsolidated sediment (acoustically transparent units in profiles) usually occurs in discontinuous patches and lenses that areally may be only several hundred meters (or less) in size in any direction (Fig. 4, 6). The limited areal extent of many of the sediment patches in the Reference Site was beyond the positioning accuracy we were able to obtain in the rough weather conditions and sea state of the 1994 cruise. Consequently, although our pre-designated sampling site was targeted as unconsolidated sediment (on acoustic profiles), the error associated with the drift of the vessel and the coring device resulted in the coring device landing in areas where there was no unconsolidated sediment (semi-consolidated to consolidated older sediment or possibly crystalline bedrock in some instances at the surface of the seafloor).

SUMMARY

1) The EPA Reference Site is situated on the middle to lower continental slope west of San Francisco (CA). From a regional perspective, it occurs on the northernmost flank of the "southern Farallon slope province." This is a region of the central California continental slope characterized by relatively wide, gently westward dipping, sediment covered plains that are in general not intensely dissected by submarine canyons and gullies. In contrast, the "northern Farallon slope province" is relatively narrow, steeper, highly dissected by submarine canyons and gullies, and has only thin localized veneers of unconsolidated sediment.

2) Acoustic profiles (3.5 kHz and 4.5 kHz) reveal that the Reference Site is characterized by a thin, discontinuous veneer of unconsolidated sediment that occurs in localized patches, many as small as several 100's of meters in any direction. The typical acoustic pattern is a transparent lens that overlies relatively well-bedded older strata or a wholly transparent subbottom. The acoustically transparent lens occurs locally as two units; both are typically thin and discontinuous. Where there is no transparent lens present, the shallow subbottom consists of either wholly transparent older strata (no subbottom penetration) or well-bedded strata cropping-out at the seafloor. There may be some unconsolidated sediment present below the resolution of our acoustic system (1 meter). In places, the well-bedded strata are truncated at the seafloor by an erosional unconformity, indicating a period of erosion or non-deposition that preceded deposition of the youngest slope sediments.

3) Sediment sampling in and adjacent to the Reference Site indicates that the seafloor in this area consists of silty clays and clayey silts (> 50% mud content). However, in water depths less than about 800-1000 m (mostly upslope of the Reference Site), there is a significant sand-sized component (> 25% sand content) in seafloor sediments. The presence of this significant sand-size component may be correlative with the anomalous sandy veneer identified by Karl, et. al., 1992 for surface sediments in this area of the Farallon slope

4) Correlation of the acoustic data and sampling data from the 1990 and 1994 surveys confirm the patchy, localized distribution of unconsolidated sediment throughout the Reference Site.

Acknowledgements

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Karl, H.A., Chin, J.L., Edwards, B.D., and Maher, N.M., 1992, Core descriptions and sedimentologic/stratigraphic analysis: in- Karl, H.A., (ed.) Comprehensive geological and geophysical survey of the Gulf of the Farallones region, Administrative Report for the US Environmental Protection Agency, Nov. 1992, p. 120-145.

Illustrations

Figure. 1-- Index map of the San Francisco Bay area and the adjacent continental margin. The Farallon shelf and slope comprise the subaqueous portion of the continental margin off the San Francisco Bay area. Note how the morphology of the Farallon slope changes just north of the Pioneer Canyon and Reference Site locations.

Figure. 2-- 3.5 kHz seismic reflection profile acquired by ODEC Bathy-2000 system in 1994. Profile crosses the middle-to-upper part of the Reference Site study area. Note that two acoustically transparent layers ("yellow" and "green") overlie an older and harder stratal unit ("purple"). Very little to no subbottom penetration occurs below the "purple" unit.

Figure. 3-- Map of 1990 tracklines on which 4.5 kHz seismic reflection profiles were acquired by a transducer mounted on a SeaMarc 1A towfish. 30 kHz side scan sonar profiles were collected simultaneously. Note the location of the Reference Site within the larger 1990 EPA Regional study area. These data were collected to characterize the regional Farallon slope. Also note the northern and southern geomorphic provinces of the Farallon slope.

Figure. 4-- 4.5 kHz seismic reflection profile obtained in 1990 showing representative acoustic stratigraphy in and adjacent to the Reference Site. Two acoustically transparent surficial units overlie an older fairly well-bedded unit (and/or a wholly transparent older acoustic unit). The base of the lower surficial unit and the top of the older well-bedded unit is an angular unconformity that locally becomes a disconformity. To the "left" of the profile, the transparent units pinch out and an older stratal unit crops out at the seafloor with little to no unconsolidated sediment present ("wholly transparent" acoustic signature). The older stratal unit to the "left" may be either a different facies of the older stratal unit to the "right" or possibly a completely different stratal unit as suggested by the lack of subbottom penetration, lack of inclined reflectors, and the general change in acoustic character. It is also possible that the older well-bedded stratal unit to the "right" pinches out against the wholly transparent older unit (at or about where the surficial transparent units pinch out). The pinch out of the surficial unit(s) is common in and adjacent to the Reference Site---yielding a characteristic patchy distribution to the unconsolidated sediment. Note the limited areal extent of the unconsolidated sediment lens.

Figure. 5-- SeaMarc 30 kHz side scan sonar mosaic image (obtained in 1990) of the Farallon slope which includes Pioneer Canyon and Pioneer Seamount. The EPA Reference Site is located on the northern flank of Pioneer Canyon. Pioneer Canyon follows a relatively sinuous course across the continental slope from the shelfbreak to the deep ocean basin. Note the abandoned meanders (hi-lited in yellow), most of which occur on the southern side of the modern canyon. These are features that identify the former course(s) of the canyon; they were abandoned when the canyon shifted to a new position---much as subaerial rivers and streams do onshore. The small submarine canyons that incise the lower part of the Reference Site do not show such meanders and are relatively straight.

Figure. 6-- 4.5 kHz seismic reflection profile obtained in 1990 that is located in the Reference Site showing the two acoustically transparent surficial layers. These strata overlie a relatively well-bedded older unit. The base of the lowermost surficial unit is in places an angular unconformity and in other places is a disconformity. On the "left" and "right" sides of the profile there is very little to no surficial layer (unconsolidated sediment) such that the older well-bedded unit may crop out at the seafloor. Note that the older unit exhibits a "rolling" morphology, possibly due to structural folds.

Figure. 7-- 4.5 kHz seismic reflection profile (obtained in 1990) located in the Reference Site. The profile shows a very thin to absent acoustically transparent surficial layer and the "rolling nature" of the older underlying stratified unit. Note that the seafloor mimics the morphology of the older stratified unit, partly because the acoustically transparent layer is thin or absent.

Figure. 8-- Map of 1990 gravity core locations from USGS cruise F8-90-NC. Small inset box shows the location of the EPA Reference Site study area. The 1990 dataset includes several gravity cores that occur within the Reference Site; most however occur outside the boundaries of the 1994 study area. Note that the 1990 core set covers a much larger area of the continental slope than the 1994 core set (Fig. 9).

Figure. 9-- Map of 1994 hydraulically-dampened gravity core locations within the EPA Reference Site from USGS cruise E2-94-NC. Compare this map to Fig. 8. Bathymetry in meters.

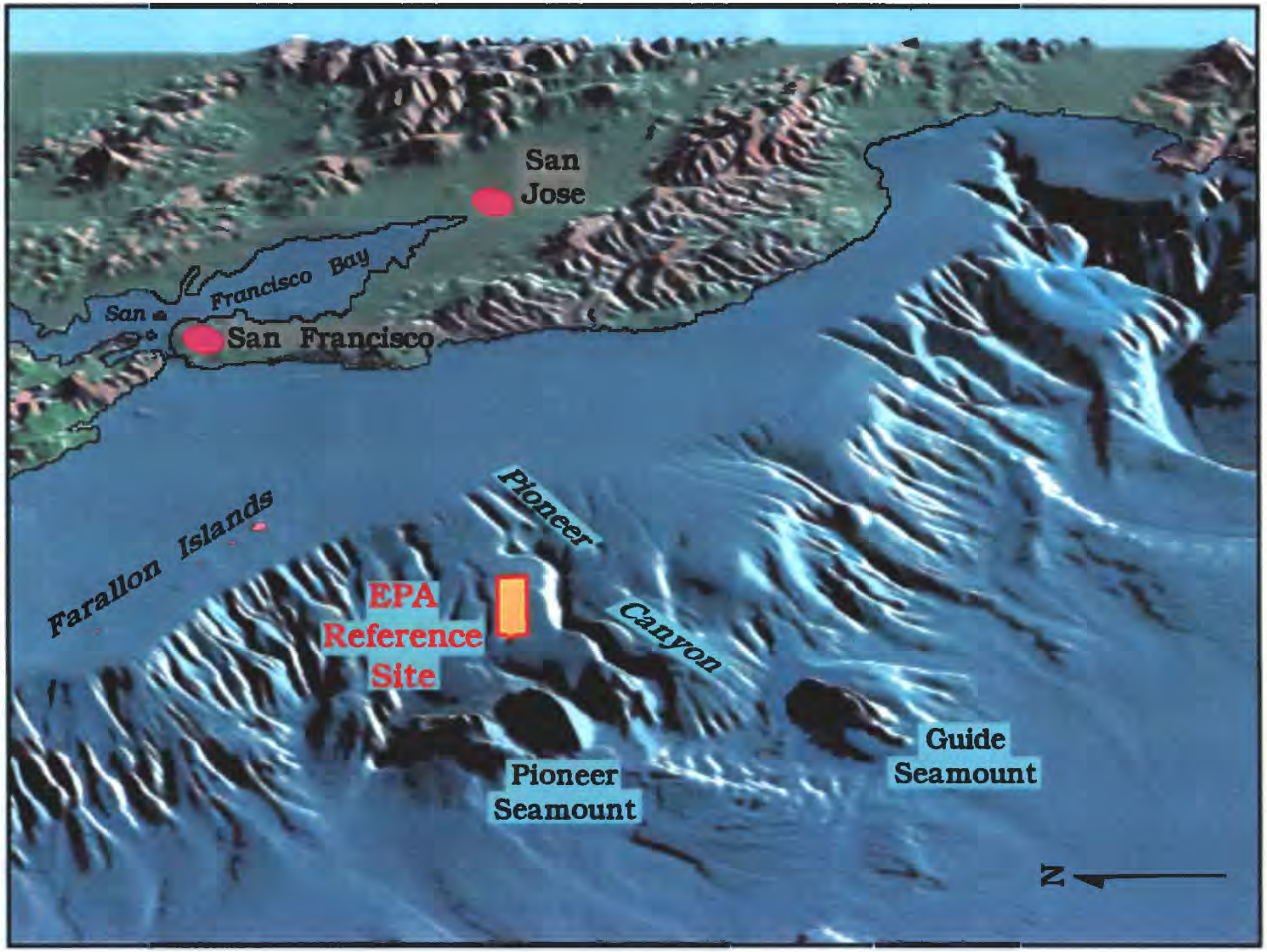
San
Jose
San Francisco Bay
San Francisco
Farallon Islands
Pioneer Canyon
EPA
Reference
Site
Pioneer
Seamount
Guide
Seamount
N

FIGURE 1

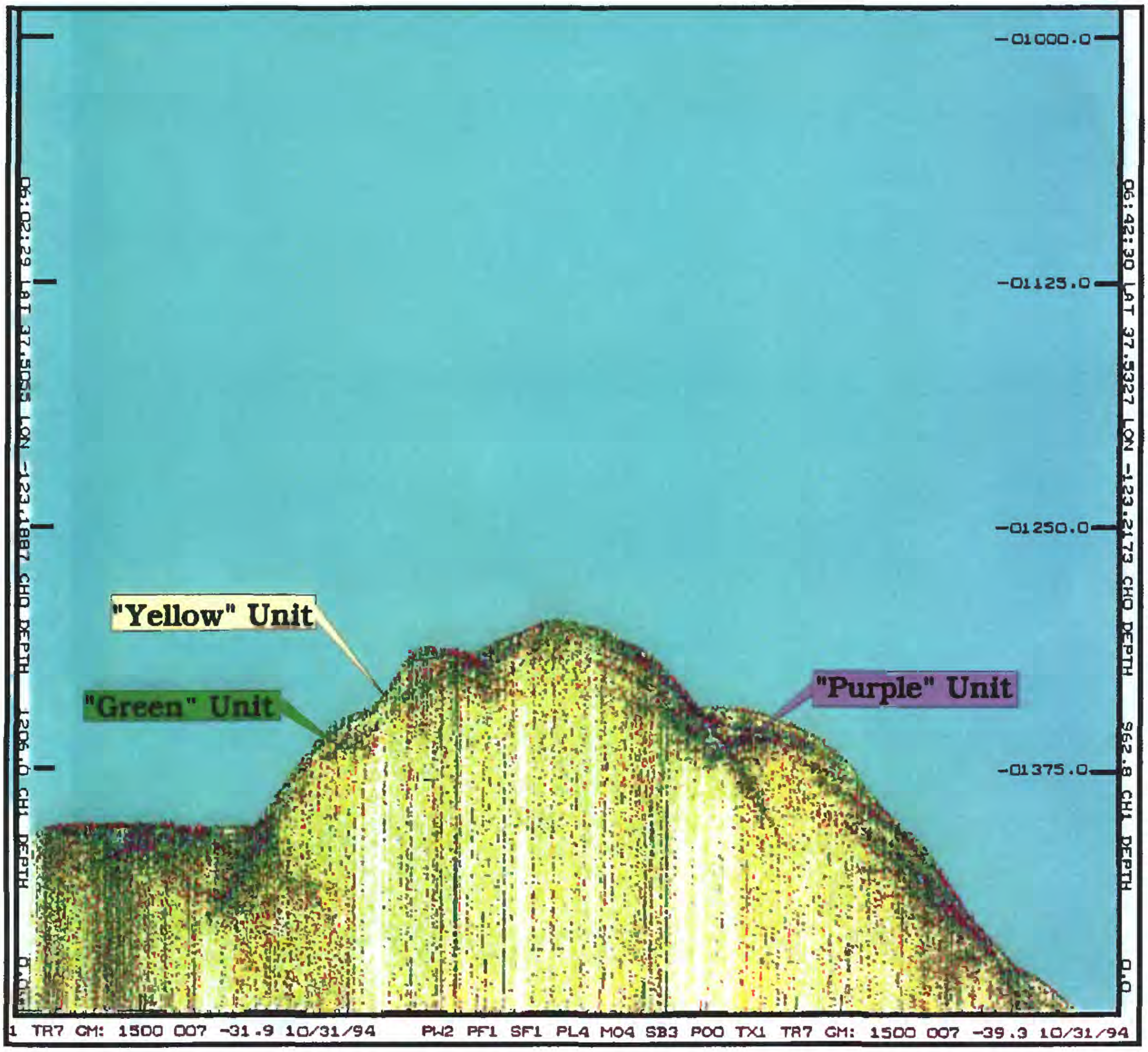
-01000.0
-01125.0
-01250.0
-01375.0
"Yellow" Unit
"Green" Unit
"Purple" Unit
1 TR7 GM: 1500 007 -31.9 10/31/94 PW2 PF1 SF1 PL4 MO4 SB3 POO TX1 TR7 GM: 1500 007 -39.3 10/31/94

FIGURE 2

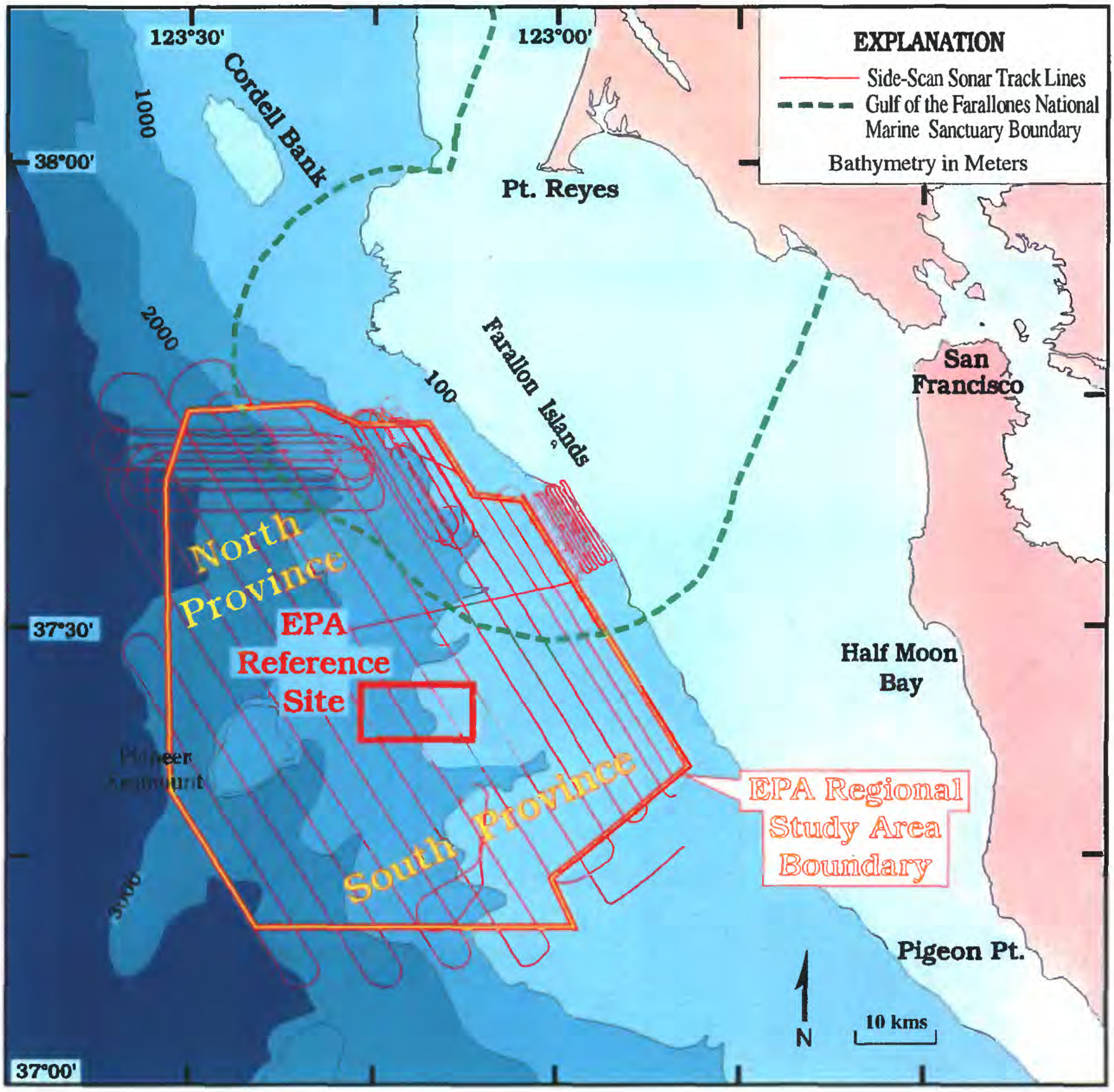
EXPLANATION
Side-Scan Sonar Track Lines
Gulf of the Farallones National Marine Sanctuary Boundary
Bathymetry in Meters
123°30'
123°00'
38°00'
37°30'
37°00'
Cordell Bank
1000
2000
3000
100
Pt. Reyes
Farallon Islands
San Francisco
Half Moon Bay
Pigeon Pt.
North Province
South Province
EPA Reference Site
Pioneer Seamount
EPA Regional Study Area Boundary
N
10 kms

FIGURE 3

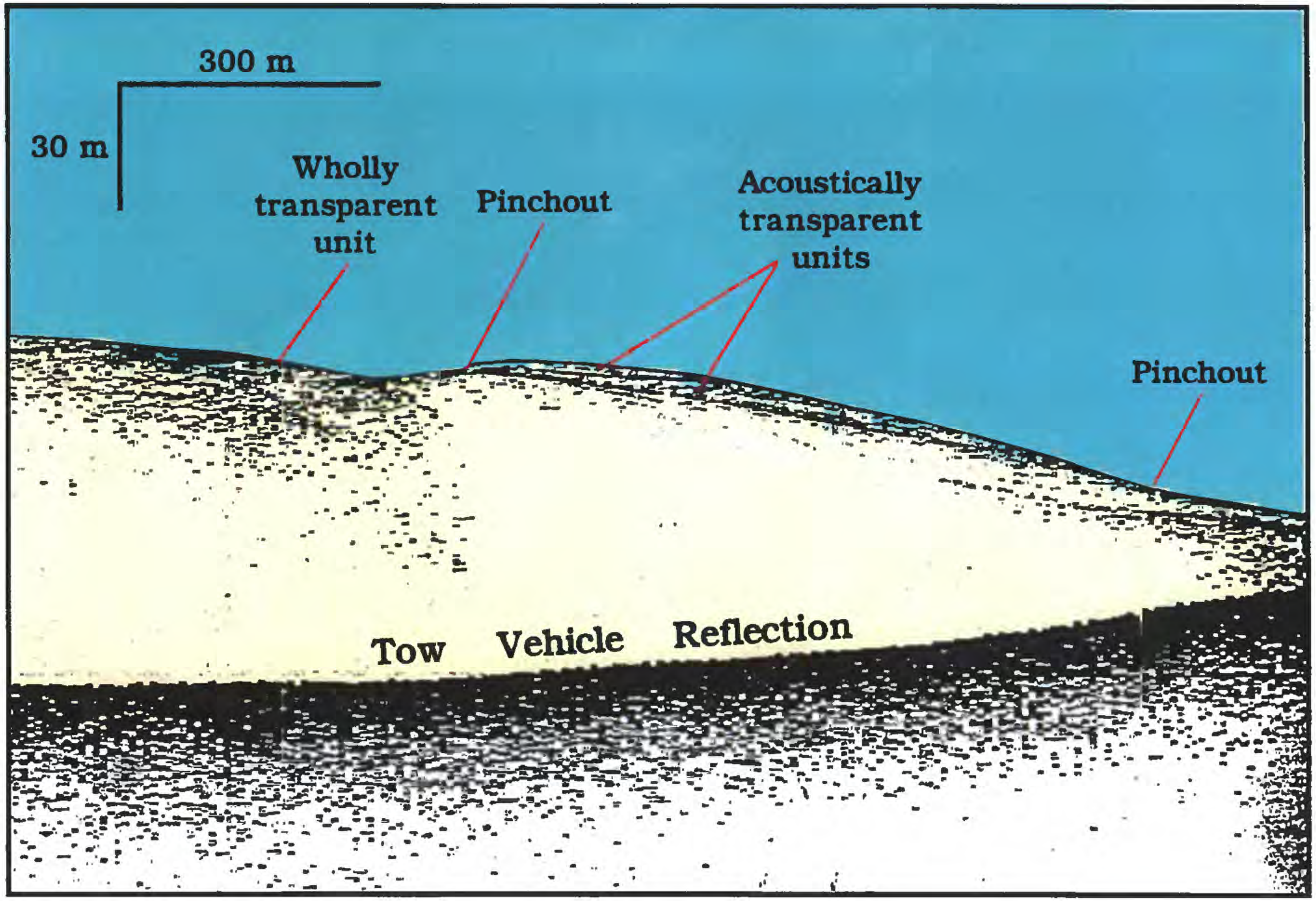
300 m
30 m
Wholly transparent unit
Pinchout
Acoustically transparent units
Pinchout
Tow Vehicle Reflection

FIGURE 4

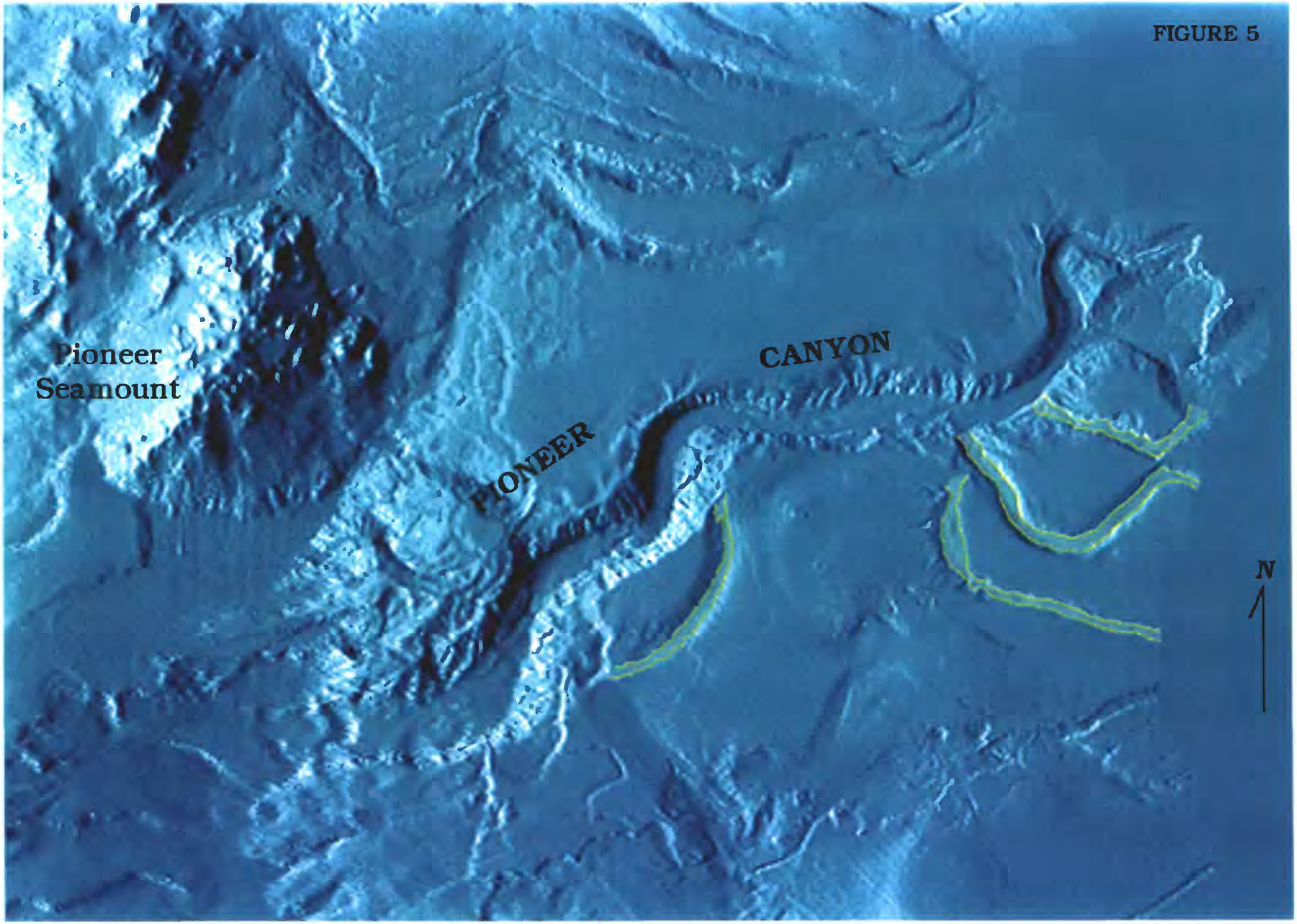

FIGURE 5

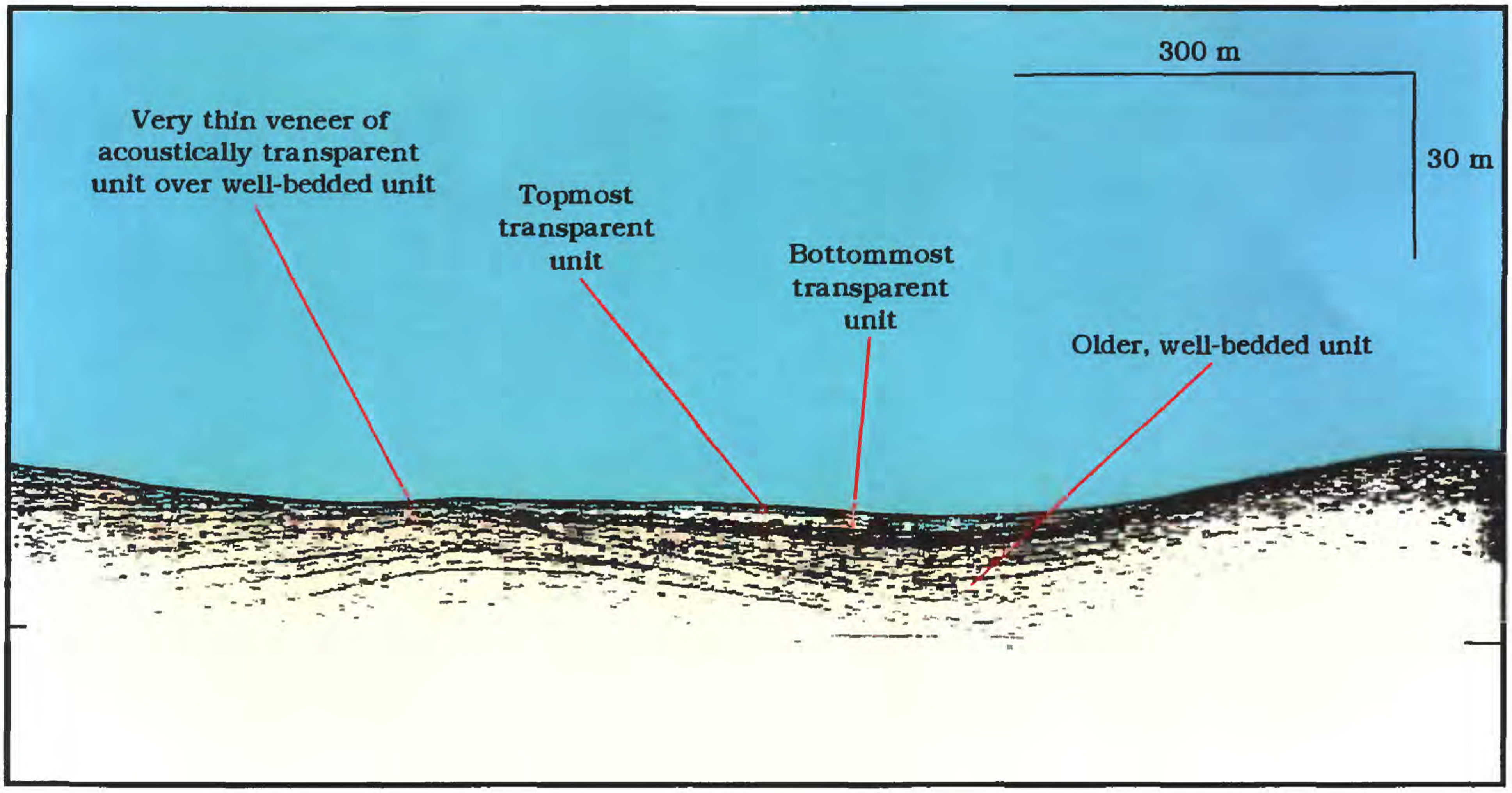
300 m
30 m
Very thin veneer of
acoustically transparent
unit over well-bedded unit
Topmost
transparent
unit
Bottommost
transparent
unit
Older, well-bedded unit

FIGURE 6

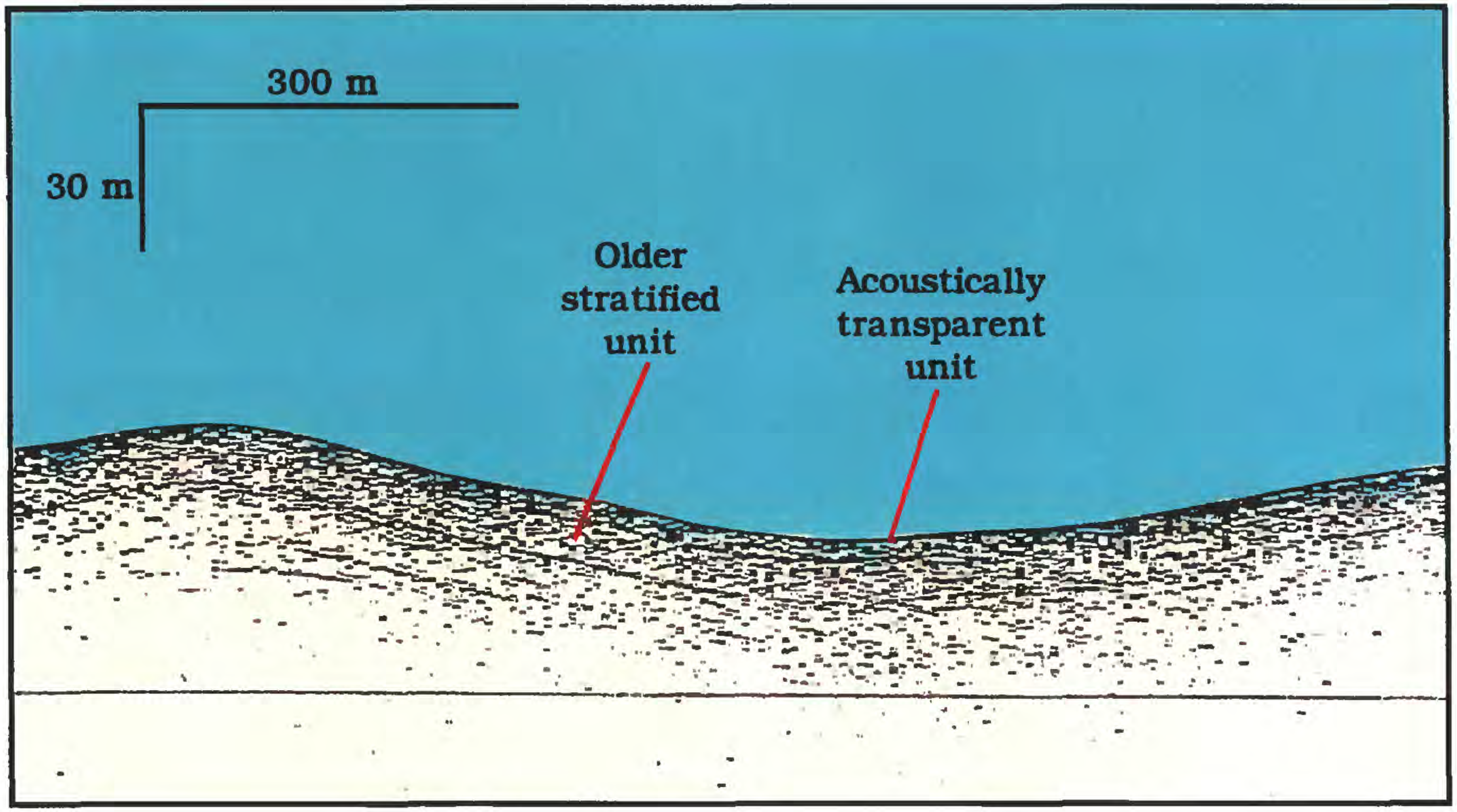
300 m
30 m
Older stratified unit
Acoustically transparent unit

FIGURE 7

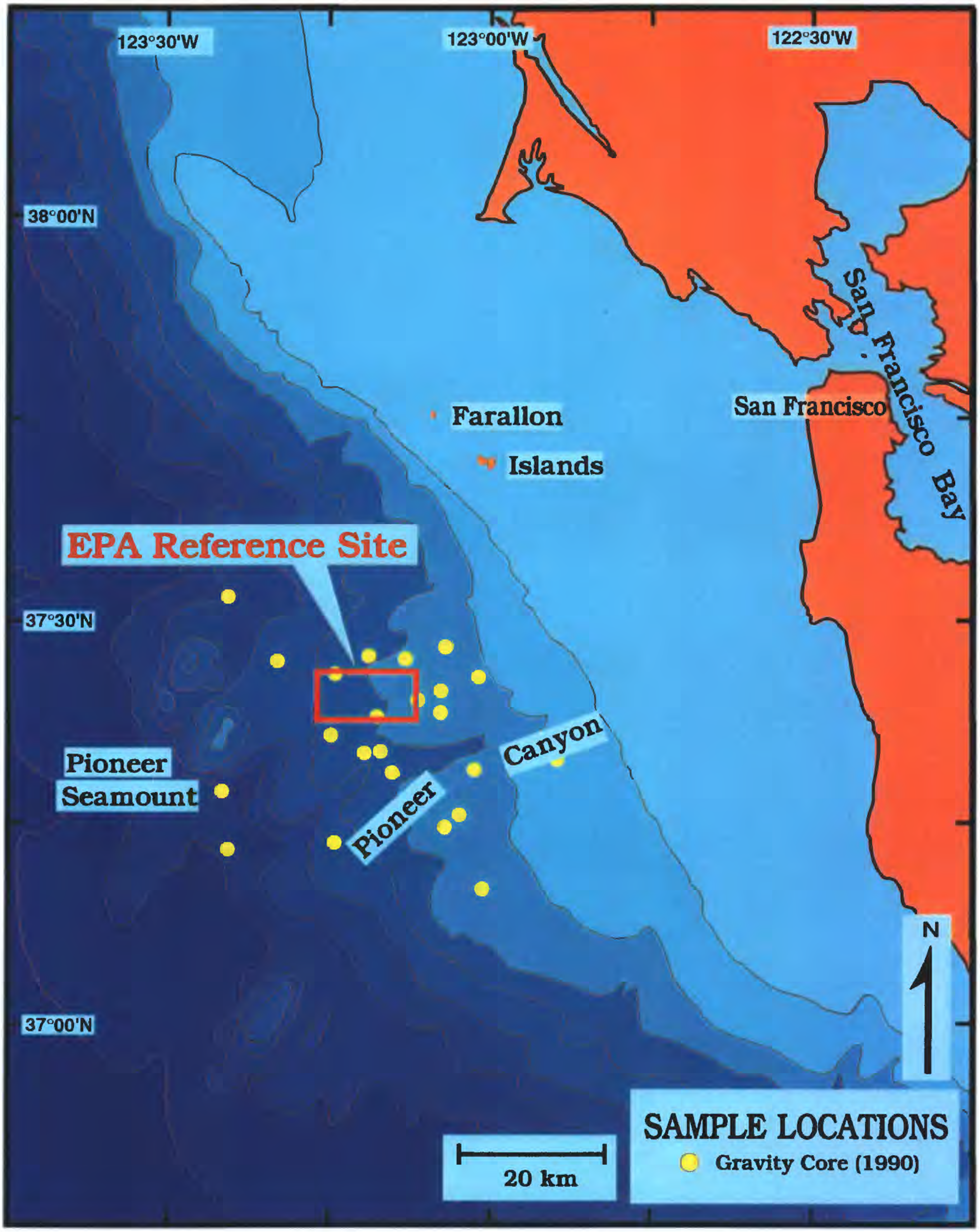
123°30'W
123°00'W
122°30'W
38°00'N
37°30'N
37°00'N
San Francisco Bay
San Francisco
Farallon
Islands
EPA Reference Site
Pioneer
Seamount
Pioneer
Canyon
N
SAMPLE LOCATIONS
Gravity Core (1990)
20 km

FIGURE 8

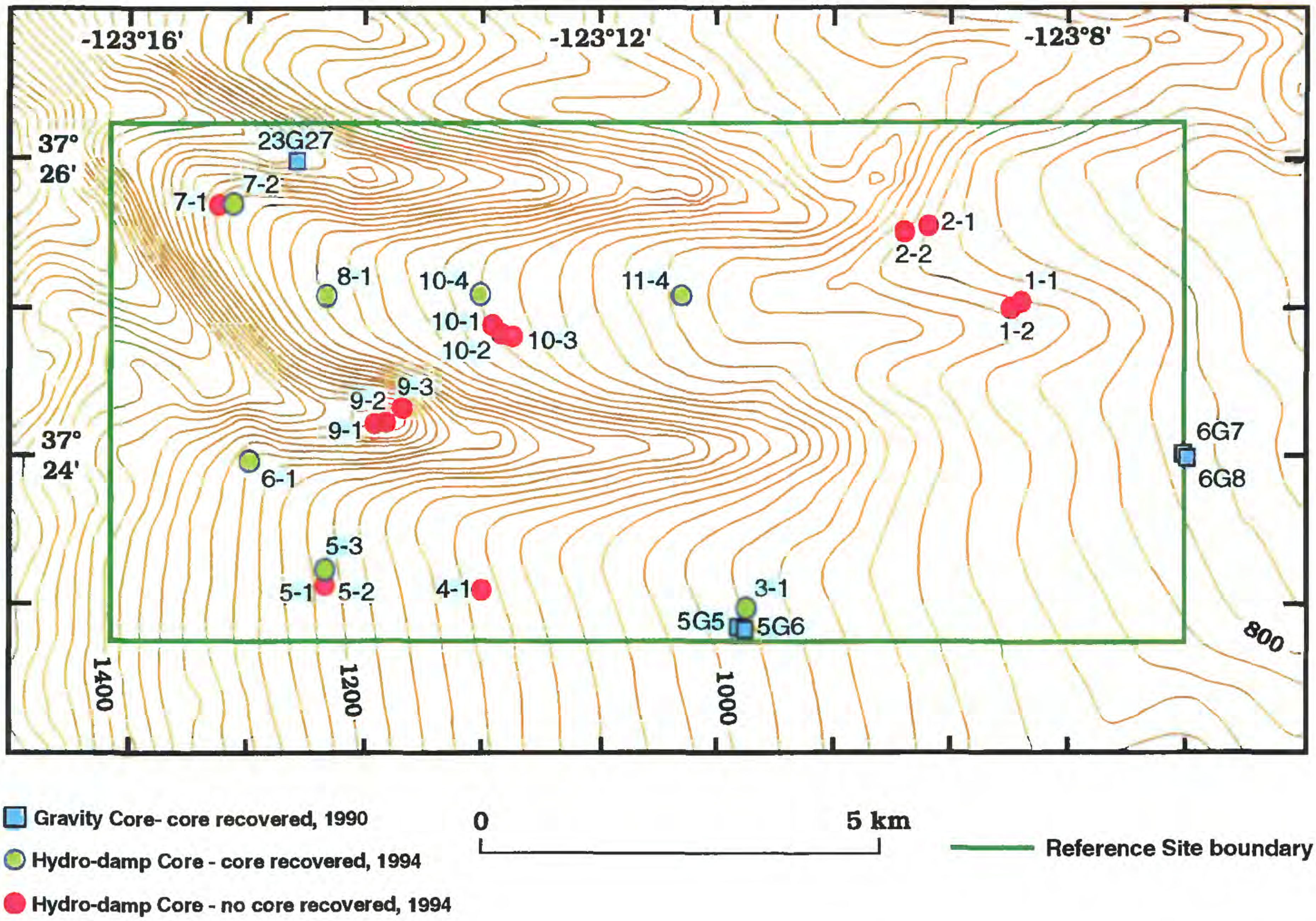
-123°16'
-123°12'
-123°8'
37° 26'
37° 24'
23G27
7-1
7-2
8-1
10-4
10-1
10-2
10-3
11-4
2-1
2-2
1-1
1-2
9-1
9-2
9-3
6-1
5-1
5-2
5-3
4-1
3-1
5G5
5G6
6G7
6G8
800
1000
1200
1400
Gravity Core- core recovered, 1990
Hydro-damp Core - core recovered, 1994
Hydro-damp Core - no core recovered, 1994
0
5 km
Reference Site boundary

FIGURE 9