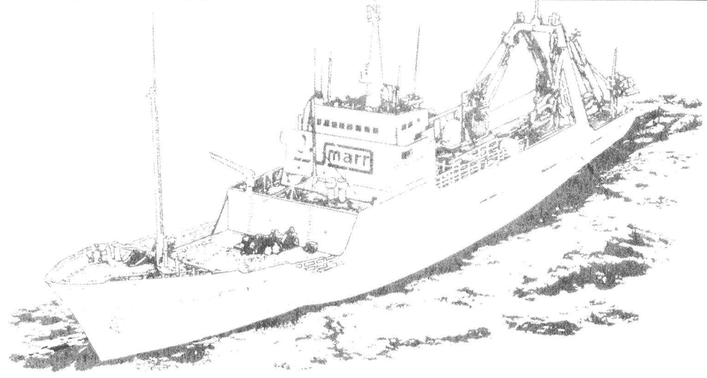
Atlas of the U.S. Exclusive Economic Zone

Gulf of Mexico and Eastern Caribbean Areas

U.S. Geological Survey

Miscellaneous Investigations Series I-1864-A,B

Atlas of the U.S. Exclusive Economic Zone, Gulf of Mexico and Eastern Caribbean Areas



By EEZ-SCAN 85 Scientific Staff

A. Atlas of the U.S. Exclusive Economic Zone, Gulf of Mexico

B. Atlas of the U.S. Exclusive Economic Zone, Eastern Caribbean

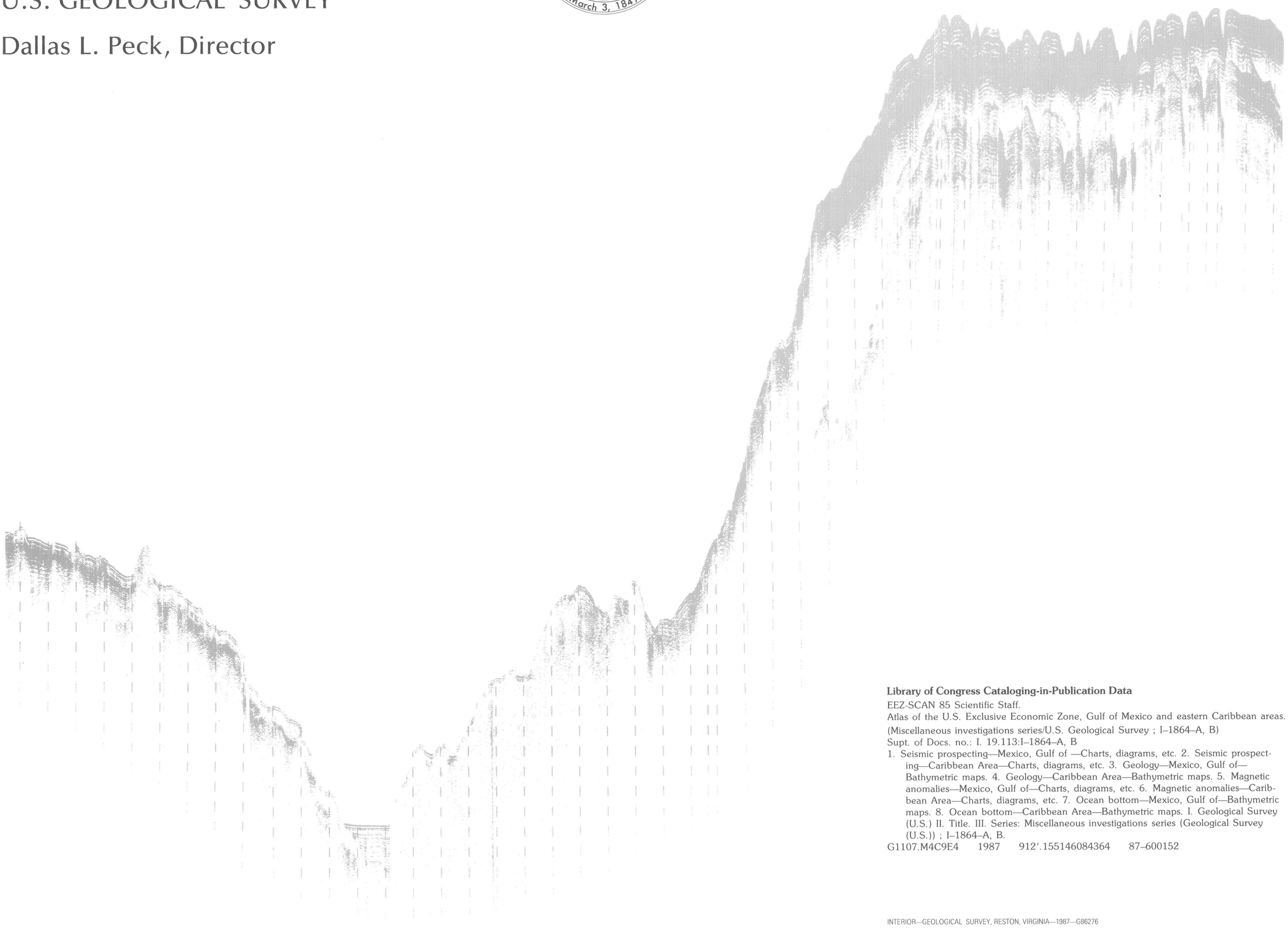
U.S. Geological Survey
Miscellaneous Investigations Series I-1864-A, B
1987

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director



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THIS PAGE: Seismic-reflection profile across the Puerto Rico Trench. Profile represents about 7,500 meters of relief.

COVER: Oblique view of the Gulf of Mexico and Caribbean Sea from the southeast, adapted from a map by Richard Edes Harrison. Dashed lines indicate extent of areas surveyed in the Gulf of Mexico and off Puerto Rico and the U.S. Virgin Islands.
Cover design by Kevin King and Patricia Forrestel.

FOREWORD

Dallas L. Peck
Director, U.S. Geological Survey

An act of Congress in 1879 established the U.S. Geological Survey (USGS) as a scientific research organization and charged it to conduct an "examination of the geological structure, mineral resources, and products of the national domain." Not until 1962, however, were these examinations extended into the marine realm, when Congress first appropriated funds for offshore investigations by the USGS. During the late 1960's and 1970's, offshore geologic surveys conducted by the USGS rapidly expanded as the result of national and international events such as increased domestic oil and gas exploration and the oil embargo by the Organization of Petroleum Exporting Countries.

On March 10, 1983, President Reagan proclaimed that the ocean area out to 200 nautical miles off the coast of the United States—including the Commonwealths of Puerto Rico and the Northern Mariana Islands, and the island territories of the United States—was the Exclusive Economic Zone (EEZ) of this Nation. The proclamation increased the area of offshore Federal lands to approximately 3.4 million square nautical miles, an area about 30 percent larger than the total onshore area of the United States. As noted by the National Advisory Committee on Oceans and Atmosphere, considering the rate of depletion of the earth's natural resources on land and the potential that the oceans are believed to have for addition to our resource base, the significance of the EEZ to the future of our country may well be greater than that of the Louisiana Purchase of 1803. That act (during the Presidency of Thomas Jefferson) doubled the size of our country and brought with it a vast territorial and resource base on which the United States grew during the 19th century.

In establishing the EEZ, this country has gained access to potentially large energy and mineral resources that may lie on or below the surface of the sea floor. Accordingly, the resources of the EEZ are a potential means of ensuring national economic security by allowing the Nation to become more self-sufficient in strategic and critical minerals. However, the United States must establish a framework for the orderly exploration and development of the EEZ and provide sufficient information regarding the EEZ to allow resolution among competing alternative uses. Private ventures in the EEZ will be encouraged and enhanced both by demonstrations of substantial potential energy and mineral resources and by the provision of regulations that allow normal competitive market forces to operate. In view of the substantial resources that may exist in the EEZ, management of the EEZ will also require adequate protection of the environment during future exploration and development activities.

The EEZ, by comparison to long-studied onshore areas, clearly is a new frontier. The exploration, characterization, understanding, management, protection, and utilization of this frontier present an exciting challenge to all elements of the U.S. marine community including academia, industry, and government. In meeting this challenge, the USGS has the important role of developing an integrated, comprehensive scientific understanding of the EEZ as a basis for formulation of Government policies. In his State of the Union address of January 25, 1984, President Reagan said "The Department of the Interior will encourage careful, selective exploration and production of our vital resources in an exclusive economic zone within a 200-mile limit off our coasts . . . .". Under the direction of the Secretary of the Interior and the Assistant Secretary for Water and Science, the USGS assumed responsibility for developing and coordinating an EEZ program of national scope. As part of this effort, the USGS marine program in the EEZ provides for the orderly exploration necessary to develop a geologic understanding of these new Federal lands. The EEZ program of the USGS serves the national need by developing or extending our understanding of where mineral or petroleum resources occur, the geologic framework in which such resources may exist, the geologic environmental conditions that may be encountered during their future exploitation, and how their formation in ocean areas can aid in the search for analogous onshore deposits of economic significance.

A logical first step in the exploration of a new frontier is to map it. In April 1984 the USGS, in cooperation with the Institute of Oceanographic Sciences (IOS) of the United Kingdom, initiated Program EEZ-SCAN as a first effort to expand our geologic understanding of the EEZ. This program was created to map the EEZ at a reconnaissance scale using a unique sidescan sonar system developed by IOS. This revolutionary system, known as GLORIA (Geological LOng-Range Inclined Asdic), is capable of mapping large areas of the sea floor on a single pass of the ship. In 1984, GLORIA was used to map the EEZ off California, Oregon, and Washington with spectacular and significant results. During 1985, GLORIA was used to map the EEZ in the Gulf of Mexico and off Puerto Rico and the U.S. Virgin Islands. The results of those surveys are presented in this publication. Over the next four years, EEZ-SCAN will be extended to the EEZ of the Atlantic coast, Alaska, and Hawaii. We believe these surveys will provide the critical "road maps" for future EEZ research.

This publication provides a graphic overview of the EEZ in the Gulf of Mexico and the eastern Caribbean, but it represents only a fraction of the information that must be collected and analyzed in the exploration of the new frontiers. It illustrates how cooperative efforts between governments can successfully deal with the challenges of exploration. Most important, perhaps, the many discoveries illustrated in the atlas remind us that this is a beginning, not an end, to understanding our marine heritage.

I–1864–A

Atlas of the U.S. Exclusive Economic Zone, Gulf of Mexico

Contents, followed by text

Sonar-Imagery Mosaics with Geologic Interpretations and Bathymetry (Sheets 1–16)

Seismic-Reflection Profiles

Magnetic-Anomaly and Bathymetry Profiles

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I–1864–B

Atlas of the U.S. Exclusive Economic Zone, Eastern Caribbean

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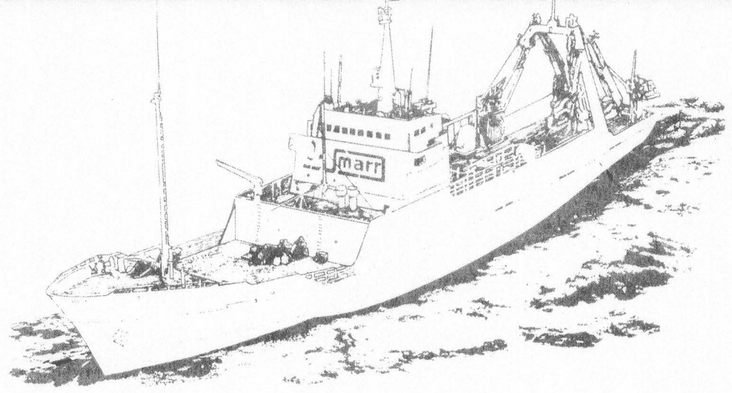

By EEZ-SCAN 85 Scientific Staff

U.S. Geological Survey
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INTRODUCTION

On March 10, 1983, President Reagan signed a proclamation establishing an Exclusive Economic Zone (EEZ) extending 200 nautical miles seaward from the coasts of the United States, the Commonwealths of Puerto Rico and the Northern Mariana Islands, and the U.S. territories and possessions. Within this zone, the United States claimed jurisdiction over the seabed and its resources (fig. 1). As part of its mission to map the federal lands and to determine their resource potential, the U.S. Geological Survey (USGS) began a program in 1984 to provide maps of the EEZ. The reconnaissance-scale mapping tool that the USGS selected was the long-range sidescan-sonar system, GLORIA (Geological LOng-Range Inclined Asdic), owned and operated by British colleagues at the United Kingdom's Institute of Oceanographic Sciences (IOS).

Sidescan sonar was selected as the mapping tool because it can be used to obtain information on geologic processes. The intensity of the back-scattered sound from the sea floor is a function of the gradient or slope of the sea floor, of the microtopography or surface roughness, and of the sediment characteristics such as texture or induration. Because sidescan sonar provides information from a swath of sea floor, large areas can be mapped quickly.

In the summer of 1984 the USGS began its sidescan-sonar survey of the EEZ off the coasts of Washington, Oregon, and California. In 100 days, the EEZ was mapped from the Canadian to the Mexican border, extending from the continental shelf edge (approximately 200 meters (m) water depth) to the seaward boundary. Results of this survey were published by the USGS in the *Atlas of the Exclusive Economic Zone, Western Conterminous United States* (EEZ-SCAN 84 Scientific Staff, 1986) (fig. 2). Continuing the mapping effort in the late summer and fall of 1985, the USGS conducted surveys of the EEZ in the Gulf of Mexico and around Puerto Rico and the U.S. Virgin Islands.

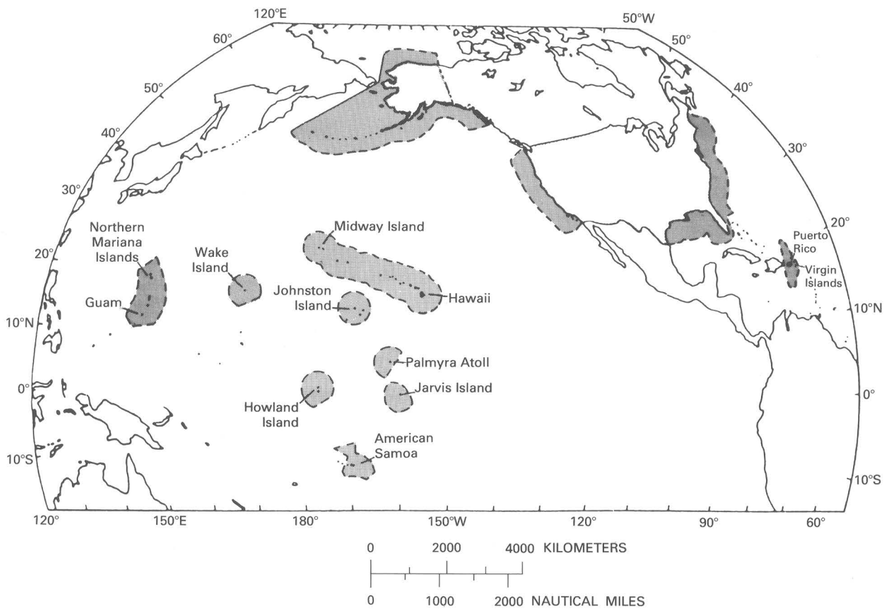

Figure 1—Exclusive Economic Zone (EEZ) of the United States, Commonwealth of Puerto Rico, Commonwealth of the Northern Mariana Islands, and United States overseas territories and possessions (outlines of map are approximate).

DATA COLLECTION

1982 and 1985 Surveys

Sixty-seven days in 1985 divided into three cruise legs were spent mapping in the Gulf of Mexico (fig. 3). This study abutted an area surveyed with the GLORIA system in 1982 as part of Outer Continental Shelf geohazards work that focused on the Texas-Louisiana continental slope. Also in 1982, preliminary work for the Deep Sea Drilling Project (DSDP) Leg 96 site surveys was done on the Mississippi Fan in the eastern Gulf. Combining the data from the 1985 and 1982 surveys provides sidescan-sonar coverage of the EEZ in the Gulf of Mexico from just seaward of the shelf edge to a maximum water depth of 3,600 m. In addition to the sidescan imagery, seismic-reflection profile data and total-magnetic-field data were collected along the ship tracks during much of the surveys.

Legs 1, 2, and 3 of the 1985 survey focused on the western, central, and eastern Gulf of Mexico respectively (fig. 3). Leg 1 departed from Miami, Fla., crossed to the western Gulf, and ended in New Orleans, La. Leg 2 began in New Orleans and ended in Tampa, Fla.; and Leg 3 started from Tampa and finished in Key West, Fla. The 1982 survey, begun in New Orleans, ended in Miami.

Primary navigation for the 1982 and 1985 data collection was with loran-C, except on Leg 3 when transit satellite and Global Positioning System (GPS) were used. Transit satellite fixes, and, in 1985, GPS data, were also logged for comparison on Legs 1 and 2. Our estimate of the positional accuracy of the loran-C navigation is expected to be no worse than ± 200 m.

Tracklines of the MV *Farnella*, the ship used for the survey in the Gulf of Mexico, are shown on p. A6 and A7 (figs. 10 and 11). The Julian day (consecutive day of the year, starting with January 1 as Julian day 1) is annotated on the tracklines twice each day, the time is Greenwich Mean Time and is annotated every 12 hours (hr), and every hour is marked by an arrowhead that gives the direction of profiling. The 1982 survey was conducted from Julian day 33 to 55, and the 1985 survey from Julian day 219 to 295 (fig. 3). Orientation of the tracklines is in general parallel to the trend of the bathymetric contours. Trackline spacing was determined so that overlap of sidescan data from adjacent tracks was achieved. The pronounced thermocline in the Gulf of Mexico during the summer months reduced the swath width of the 1985 survey, which required a closer trackline spacing than that chosen during the 1982 survey. Because of the reduced swath width in shallow water, the sidescan imagery coverage in the western and eastern Gulf begins seaward of the shelf edge.

GLORIA II Sidescan-Sonar System

The GLORIA system is a long-range sidescan-sonar tool developed by IOS specifically to map the morphology and texture of sea-floor features in the deep ocean. Sidescan-sonar images (sonographs) are a record of the acoustic backscatter properties of the sea floor. These images of the sea floor are formed by transmitting sound pulses from two sets of transducers in a towed vehicle which look to port and starboard, respectively. The transducers are tuned so that their beams form a narrow arc (2.7°) in the horizontal plane and a broad arc in the vertical plane. Each transmitted sound signal thus insonifies a narrow band of sea floor from directly beneath the towed vehicle out perpendicular to the ship's track to the maximum range the acoustic signals travel to both sides. By varying the interval between the emission of pulses (20, 30, or 40 seconds (s)), the widest possible swath of sea floor mapped is 30, 45, or 60 kilometers (km), respectively. As the ship moves, successive bands of sea floor are insonified, and in this way an acoustic map of the sea floor is recorded.

A few of the important technical features of the GLORIA system are provided here. For more detailed information and specifications, the reader is referred to Somers and others (1978). The sidescan vehicle, or "fish", is 8 m long, weighs 2.25 tons in air, and is almost neutrally buoyant. The sonar arrays consist of a total of 120 transducers, 30 to a row, 60 to each side. The vehicle is towed about 400 m behind the ship with no active depth control, but at the normal survey speed of 8 knots (kts), or 15 km/hr, the vehicle depth is about 50 m (fig. 4). The operating frequency of the GLORIA system is about 6.5 kiloHertz (kHz), with the port array at 6.8 kHz and the starboard array at 6.2 kHz to eliminate cross-talk between the two sides. Each array is 5.3 m long by 40 centimeters (cm) high, a configuration that gives a horizontal acoustic beam 2.7° wide and a vertical beam of 35°. The beam width is specified between half-power points, and considerable energy actually radiates outside these limits. The arrays are designed to confine the energy as nearly as possible to the plane perpendicular to the track and to fill the quadrant from nadir (the point on the sea floor directly beneath the towed vehicle) up to near horizontal.

The maximum swath width largely depends on the prevailing acoustic propagation conditions of the water column. For GLORIA the swath width can be as great as 30 km on each side of the track. Under normal conditions, however, it is usually somewhat less. If acoustic conditions are unfavorable and the water depth is less than about 1,500 m, then the range may be less than 10 km on each side of the track. In the Gulf of Mexico during August through October, the pronounced thermocline reflected the far-range, low-incident-angle sound waves, restricting the swath width. The maximum range for the data reported in this atlas is 15 km to either side (30 km total swath). In the shallow water of the continental slope the maximum range obtained was considerably less.

The acoustic energy reflected from the sea floor is recorded in digital format on magnetic tape. Each pixel (digital picture element) of the image has a size, measured along the track, that is proportional to the range and that increases to hundreds of meters at extreme range because the sound beam diverges at 2.7°. The recording system was designed so that one complete scan is subdivided into 1,000 pixels. The cross-range pixel size represents about 50 m, which is smaller than the along-track pixel size; thus features in the raw data are elongated parallel to the track, particularly at extreme range.

Other Geophysical Data

Collected simultaneously with the sidescan-sonar data was a suite of geophysical data, which can be used to aid in the geologic interpretation of the sidescan imagery. Seismic-reflection profile data were collected along the ship's track by means of three systems: a 10-kHz echo sounder, a 3.5-kHz high-resolution subbottom profiler, and an airgun system. The airgun system consisted of a 160-cubic-inch airgun (80 cubic inch in the eastern Gulf on Leg 3) fired every 8 to 10 s using air compressed to 1,500 pounds per square inch (psi); and, as a receiver, a two-channel hydrophone with 48 elements in each of two active sections. Each type of data was recorded on analog recorders.

A proton-precession magnetometer was towed to collect total magnetic field values of the Earth along the ship's track during the 1985 survey.

ATLAS FORMAT AND KINDS OF DATA PRESENTED

This atlas is composed of three data sections. The first section presents the sonar-imagery mosaics of the EEZ sea floor, along with generalized geologic interpretations and bathymetry. Following the mosaics is a section providing seismic-reflection data collected during the surveys. The third section presents data on bathymetry and residual magnetic anomalies throughout the 1985 survey area.

Map Projection and Scale

The sidescan-sonar imagery is displayed on 16 sheets, which cover the northern half of the Gulf of Mexico. Each sheet covers two degrees of latitude from top to bottom and two degrees of longitude from side to side, except for five sheets near the edges of the survey, which cover only one degree or one-and-one-half degrees of latitude or longitude. An Albers Equal-Area projection was used for the sheets of imagery data and their companion overlays of bathymetry and geologic interpretation. The standard parallels used were 29.5° and 45.5° N. An Albers projection has some shape distortion with increasing distance from the standard parallels. Maximum distortion in the Gulf of Mexico is in the southernmost sheets and is 1.5 percent in both the east-west and north-south directions. The imagery sheets are printed at a scale of 1:500,000. At this scale one centimeter of distance on the sheet represents 5 km on the Earth's surface or 1 inch equals approximately 7 nautical miles. The Albers projection was selected for the imagery data display to be compatible with the USGS Continental Margin Map Series (fig. 2). This map series is a compilation of offshore geologic data into a digital data base (Escowitz, 1985).

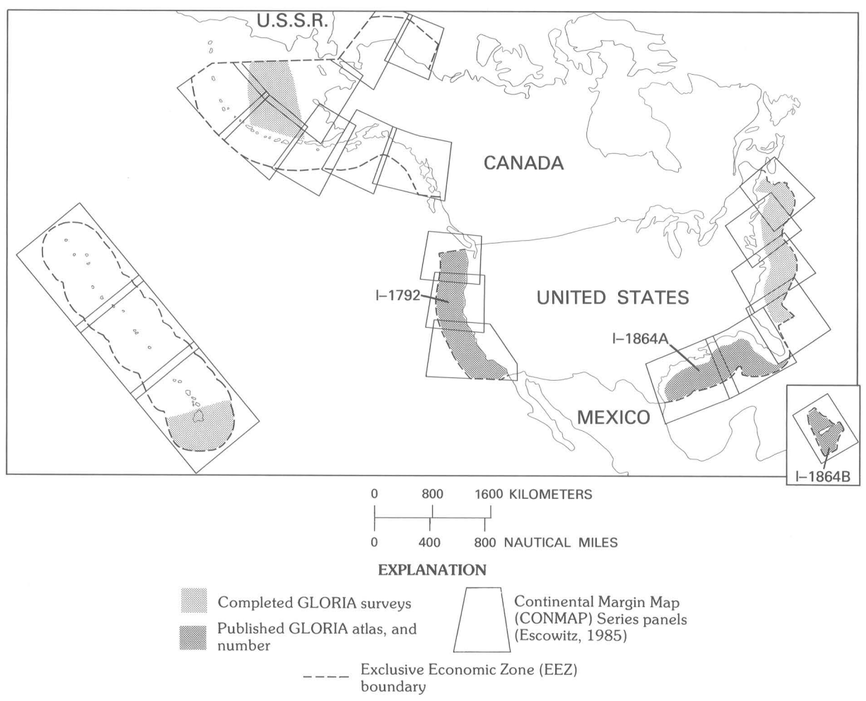

Figure 2—Status of the GLORIA mapping program.

Sonar-Imagery Mosaics

The sidescan-sonar data were mosaicked to produce 16 sheets, which provide continuous imagery of the sea floor of the EEZ in the Gulf of Mexico (p. A10 and A11). Each of the imagery sheets has a complementary facing page showing the imagery screened (subdued) under an overlay of generalized geologic interpretation and bathymetric contour data. Each of the sheets is composed of data segments approximately 6 hr in length that were image processed by computer, then mosaicked end-to-end along the ship's track, producing swaths. Adjacent swaths were stenciled together also by computer, resulting in a digital 2° by 2° (or smaller) sheet. A regular pattern of bands is visible on the imagery and represents the location of the ship's track. Because major spatial corrections are necessary in the area directly beneath the sidescan vehicle, individual pixels from this zone are enlarged, thus creating the pattern that shows the ship's path. Being able to identify the location of the ship's track is important in interpreting features, especially shadows. Identification of the ship's track also allows correlation of profile data (for example, seismic reflection and magnetic anomaly) with the imagery.

Each mosaic sheet is a halftone black and white print of the acoustic reflectivity of the sea floor. White represents the strongest acoustic reflectivity and black represents the weakest acoustic return. The darkness or lightness of a feature or an area on the mosaics, therefore, is a function of how much sound is reflected from the sea floor. Reflectivity, in turn, is controlled by the relief of the sea floor (height and gradient), by the microtopography and roughness of the sea floor (for example, sediment waves, and pressure features on submarine landslide deposits), and by the physical properties of the sea floor (such as sediment type, compaction, and induration). When viewed from the trackline, positive-relief features such as domes and escarpments (Sigsbee or Florida Escarpments) usually appear as a bright zone when facing the slope, whereas when looking down the slope, dark zones (shadows) result (fig. 5). Negative-relief features, such as canyons

or basins, usually appear as a dark zone (the near wall is shadowed) followed by a bright zone (the far wall is facing the sonar beam). Not all bright regions are related to topographic relief; many are caused by sedimentation patterns. Dark regions also have a variety of causes, of which shadows and certain sediment facies are the most common. Contained within the sidescan imagery is a wealth of information on both the geology of the sea floor and the processes by which sediment is deposited.

Bathymetry

The bathymetric contours are printed in blue directly onto each imagery sheet along with the geologic interpretation. Geographic names, also printed in blue, correspond to features identified on the airgun records in the seismic section of the atlas and are approved names from the Gazetteer of Undersea Features (Defense Mapping Agency, 1981). The bathymetric contours are in meters, with a 250-m or 500-m contour interval, except for a 100-m interval in areas where the water depth exceeds 3,000 m. The bathymetry was digitized from the National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (NOS) Bathymetric Map Series of 1:250,000 and 1:1,000,000 scale (see references). The quality and accuracy of the bathymetric data vary from sheet to sheet, and under no circumstances should the bathymetric maps be used for navigation. The continental slope seaward of Texas and Louisiana has a very complex topography resulting from salt deformation. In this area the bathymetry may not be a good representation of the topography and may not align with the imagery. The bathymetry should be used as a guide for interpretation and not as a precise rendition of the topography.

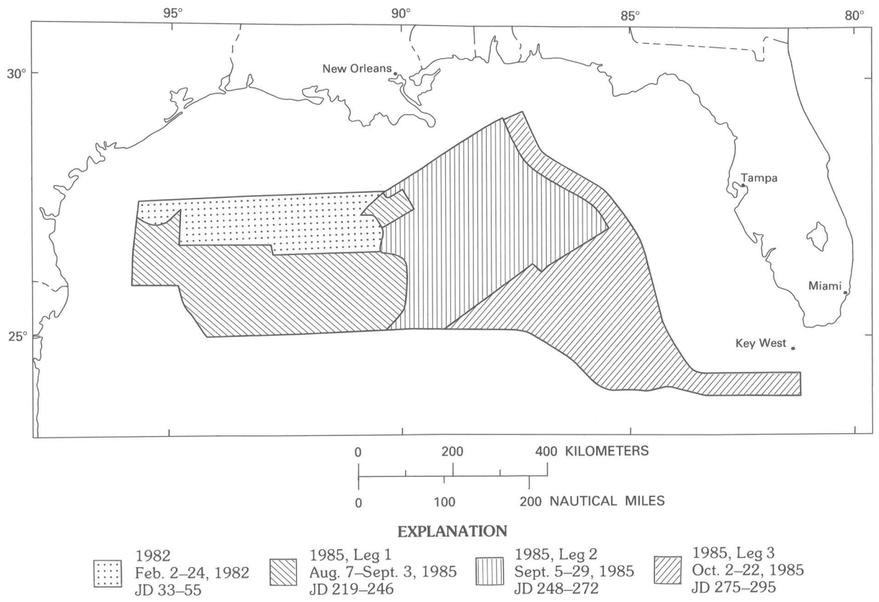

Figure 3—Limits of the 1982 survey and of Legs 1, 2, and 3 of the 1985 survey. JD, Julian day.

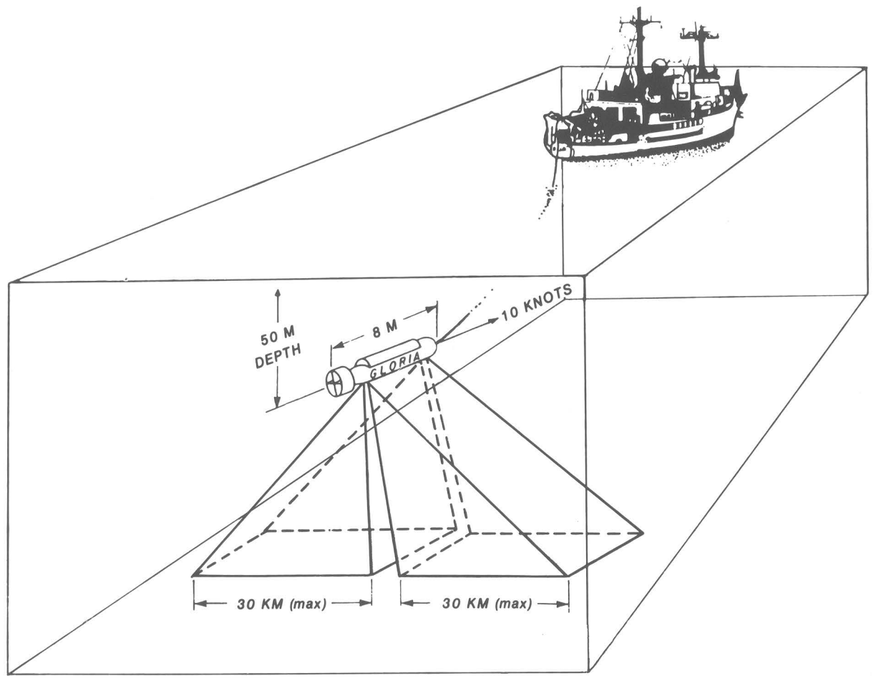

Figure 4—The GLORIA sidescan vehicle, or "fish," being towed behind the ship. The vehicle can map a swath of sea floor up to 60 km wide.

Seismic-Reflection Profile Data

Three seismic-reflection profile systems were used: a 10-kHz echo sounder, a 3.5-kHz high-resolution subbottom profiler, and an airgun system. Depth values were digitized from the 10-kHz echo sounder every 6 minutes (min) along with intermediate peak, trough, and inflection-point values. These values, in meters, were corrected for sound velocity and merged with the navigation data. The bathymetry values were used in the image processing to remove the water column for the sonographs. They are shown as profiles plotted along the ship's track at the beginning of the seismic-reflection profile section of the atlas (p. A46 and A47) as a key to aid in correlating the seismic-reflection profile data with the imagery. The bathymetry data are also shown in the magnetics section of the atlas for comparison with the magnetic anomaly data.

The 3.5-kHz data provide high-resolution, shallow-penetration seismic-reflection information that was used to help interpret the sidescan-sonar data. Examples of the 3.5-kHz data are shown to clarify features that are identified as part of the geologic interpretation of the mosaics.

The airgun data were recorded on analog recorders at different sweep rates (2 and 4 s in 1982 and 5, 8, and 2 or 10 s in 1985). The data were filtered between 20 and 200 Hz. Shown in the seismic-reflection profile section are photographs of the analog records recorded at a sweep rate of 4 s for the 1982 survey and 5 s for the 1985 survey. The photographs are printed, however, so that the vertical depth scale is consistent throughout the section. The vertical scale is annotated in two-way traveltime, in seconds. As an approximation, each second of two-way traveltime equals 750 m of depth (assuming a sound velocity in sea water of 1500 m/s). Within the sediments, the velocity of sound may be less, but generally it is greater, which means that each second within the sediments represents more than 750 m (for example, 800 to 900 m).

The Julian day and time are annotated along the profiles, as are course and speed changes. The 1982 survey was conducted during Julian days 33 to 55, and the 1985 survey from Julian day 219 to 295. The data are broken into segments to draw attention to major course changes, in order to facilitate correlation with the track map at the beginning of the seismic-profile section and with the imagery sheets. Occasional gaps occur in the records as a result of repairs being made to the airgun system; such gaps are identified with the words "No data". In some cases there is an actual gap in the data coverage, and in other cases the vessel turned off the track course for repairs but returned to allow complete coverage. By checking times on the records against the ship's tracks, one can determine if a real data gap exists. Handwritten annotations, visible on some of the records, are the shipboard remarks for post-cruise analysis.

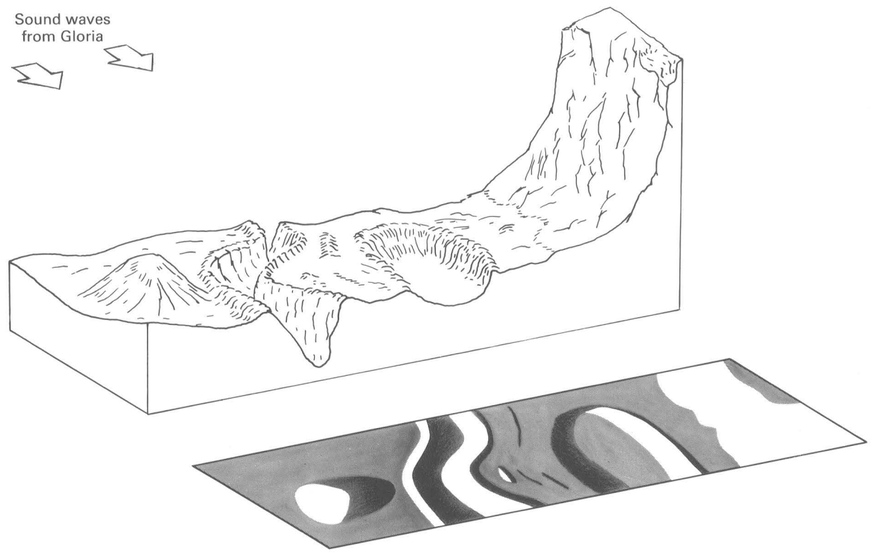

Figure 5—Block diagram showing a composite of sea-floor features typically observed in the Gulf of Mexico, and sketch of this morphology as it appears on a sidescan-sonar image.

Magnetic-Anomaly Data

Total Earth's magnetic field values were obtained along the ship's track. No magnetic field data were collected during the 1982 survey. Magnetic field data were collected continuously during the 1985 survey beginning on Julian day 224. Only minor gaps occur in the data; they were caused by system malfunction and when the system was secured in preparation for port stops. Total magnetic field values were logged by computer and merged with the navigation and bathymetry information. Residual magnetic anomaly values were calculated by subtracting the International Geomagnetic Reference Field updated to 1985 (IAGA, Division 1, Working Group I, 1986) from the total Earth's magnetic field values measured. These residual anomaly values are displayed in the magnetic anomaly profile section of the atlas as continuous profiles plotted with bathymetric data for each Julian day. The anomaly data are plotted in gammas (one gamma represents one nanotesla) against time, and are shown as profiles plotted along the ship's track at the beginning of the magnetic-anomaly section of the atlas (p. A82 and A83). The residual magnetic anomalies are subdued in the Gulf of Mexico except for several hundred-gamma anomalies near the Florida Escarpment in the eastern Gulf.

DIGITAL PROCESSING TECHNIQUES

Introduction

The imagery in this atlas is made from computer-processed, digitally collected sidescan sonographs. In order to process the digital sonar data, computer software had to be designed that would correct for both geometric and radiometric distortions that exist in the original "raw" data. This section describes the techniques developed by the USGS to correct and enhance GLORIA digital sonar images. A more detailed explanation of the digital processing is given by Chavez (1986).

Sonographs are a record of the acoustic backscattering properties of the sea floor; those from GLORIA represent the backscatter of the sea floor produced by the 6.5-kHz frequency. The strength of the acoustic backscatter is a convolution of several functions, the four major ones being: (1) the slope angle of a feature relative to the incident sonar signal (topographic characteristics); (2) the sea-floor roughness factor, the minimum being 4 cm of relief for the GLORIA system (determined by the wavelength of the sonar and the grazing angle of the sonar ray to the sea floor; Sabins, 1978); (3) the variation in physical properties of the upper few tens of centimeters of the sea floor; and (4) the water column—the distance of the vehicle above the sea floor—which attenuates the strength of the sonar signal as well as produces background noise. The backscatter was recorded as a digital number (DN) with a range of 0 to 255 discrete values (8-bit data generated from a pulse of sound every 30 s to give a maximum range of 22.5 km on each side of the ship's track). The reflected sound waves were recorded on a time basis so that the data are in a slant-range rather than a ground-range (true geographic) geometry. Also, the variations in the ship's speed generated variations in the size of the footprint (the area on the sea floor) of each pixel in the along-track direction. These distortions, as well as others discussed below, were corrected so that the sonograph images represent orthorectified and true plan views (assuming a flat sea floor) of acoustic backscatter patterns on the sea floor.

Geometric Corrections

The major sources of geometric distortions in the sidescan-sonar data are: (1) water-depth offset; (2) slant-range geometry; (3) aspect- or anamorphic-ratio distortion; and (4) changes in the ship's speed. Each of these major distortions was eliminated from the data presented in this atlas. Below is a brief explanation of the procedures used to correct for these geometric distortions.

The GLORIA system starts recording data as soon as the transmitted acoustical wave is terminated, and therefore the original images include pixels to both sides of the nadir (the projection directly beneath the ship) that contain water-column data. The number of these pixels varies along the trackline as a function of the water depth directly beneath the ship. The processing software merges the navigational and bathymetric data, recorded every four sonar scan lines, with the image data. Included as part of the header information for each pixel in the across-track direction is the water depth directly beneath the ship. The water-depth offset can be calculated in pixels to predict the location on each side to which the nadir pixel was mapped.

The slant-range distortion is a consequence of the range to features being measured relative to the vehicle, not to the projected location of the trackline on the sea floor below the vehicle. In trigonometric terms, GLORIA measures the length of the hypotenuse of a triangle (the distance a feature is from the vehicle). From the bathymetric data the vertical side of the triangle is known, and, therefore, the horizontal side of the triangle can be determined to properly locate pixels in the across-track direction. Thus, for example, in the raw data the point on the sea floor directly below the trackline—the nadir—is plotted the distance the vehicle is above the sea floor away from the nadir line on both the port and starboard sides. The water-depth and slant-range corrections remove the water column, thus drawing the nadir into the zero range (the point directly beneath the ship); and in the same way they properly locate other features in the across-track direction.

The third major geometric distortion present in GLORIA images is the aspect ratio, or anamorphic ratio, that exists between the along- and across-track directions. The sampling interval in the across-track direction for the 30-s pulse-repetition rate generates pixels with an approximate resolution of 45 m. The computer program that corrects for the water-depth and slant-range distortions generates 50-m-resolution pixels in the across-track direction. However, the resolution in the along-track direction is dependent not only on the 30-s pulse-repetition rate but also on the ship's speed. The average resolution in the along-track direction is approximately 125 m at a speed of 8 kts (15 km/hr), which produces images with an aspect-ratio distortion of about 2.5. This generates a raw image that is distorted or stretched by a factor of about 2.5 in the along-track direction. The fourth, and related, source of geometric distortion is introduced by any change that occurs in the ship's speed while it is collecting the image data. The ship's speed is influenced mainly by the direction and strength of current and wind relative to the ship's course and by whether the ship is heading in a straight line or is in a turn. During the surveys the speeds varied from about 7 to 10 kts (13 to 18 km/hr), which caused the pixel resolution in the along-track direction to vary from approximately 110 to 140 m. This introduced an "accordion" effect into the geometry of the image in the along-track direction (Chavez, 1986).

The aspect-ratio distortions discussed above were removed by using the latitude and longitude values extracted from the header of each record to compute the distance traveled by the ship every 30 min (unless a turn is detected, in which case the program used a 10-min interval). Given the distance traveled and the desired pixel size, the number of pixels required for the particular 30-min segment was calculated. To simultaneously correct for the aspect-ratio distortion, a 50-m-resolution pixel size was generated on the output image in the along-track direction. This pixel size was selected so that information in the across-track direction would not have to be omitted. This procedure corrects the image data for aspect-ratio distortions and for any distortion introduced by changes in the ship's speed.

Radiometric Corrections

Radiometric corrections, the second major category of processing steps, change the DN value of a pixel rather than its spatial location, as is the case with geometric corrections. Four different corrections were used for the GLORIA data in this atlas: (l) a shading correction to correct for the attenuation of the sonar energy in water as a function of range; (2) a power correction for very-near-nadir data because of slow buildup; (3) a speckle-noise correction; and (4) removal of striping noise. The value of making these corrections is that, in the case of noise, the corrections remove artifacts associated with the data acquisition, and in the case of attenuation, they normalize all data so that pixel values from the across-track direction can be compared directly with each other.

The loss of power due to attenuation and the power buildup problems were both corrected by using a two-pass algorithm. During the first pass through the data, the average DN value was computed for each column of pixels of the digital image in the along-track direction. These values were then normalized by the average of all the column averages (the overall average of the image) to generate correction coefficients for each column. The correction coefficients were then applied to each pixel during the second pass through the data. The coefficients are nonlinear and are a function of range, so they effectively removed attenuation in the across-track direction. This technique has the characteristics of a spatial filter that removes large horizontal low-frequency patterns that are present because of the radiometric problems introduced by the imaging system (Chavez, 1986). By normalizing to the average of the image rather than to a set DN value, backscatter comparisons could be made between different areas or different images. The correction also allowed areas within the image with lower or higher backscatter characteristics to be properly identified and mapped. This was not possible before the correction because the DN values were strongly modified as a function of their range position. Profiles of different areas in the across-track direction could then be used for backscatter comparison.

Speckle noise was removed by applying a small smoothing filter (2 samples by 2 lines) to the entire image. This approach was found best with GLORIA data, because in addition to removing speckle noise, it helped smooth the blocky appearance that the image otherwise would have had—caused by the stretching (by a factor of 2.5) in the along-track direction by pixel duplication—that was introduced when correcting for the aspect-ratio distortion.

Another radiometric or noise problem commonly present in data collected by scanning devices is striping in the scan direction. A combination of high- and low-pass spatial filtering was used to remove the striping. Two separate images were generated from the input data; one composed of the high-frequency components minus the noise frequency, and the other composed of the low-frequency components minus the noise. The two resultant images were then combined to produce an image similar to the original but without the noise (Chavez and Soderblom, 1974). The filter shapes used to remove the striping noise from the GLORIA data were a 1-line by 71-sample high-pass filter and a 9-line by 71-sample low-pass filter (except for the 1982 data, for which a 21-line by 71-sample low-pass filter was used).

Digital Mosaicking

After the sidescan-sonar data underwent the initial processing to correct them geometrically and radiometrically, they were ready for the digital mosaicking steps that result in the 2° × 2° (or smaller) imagery sheets shown in the sonar mosaic section of the atlas. The initially processed segments of data, approximately 6 hr in length, were spliced end-to-end to make a continuous line segment for portions of the tracklines where the ship's heading remained generally constant. The segments were tone matched by adjusting the contrast stretch of each to minimize the seam where they were joined.

Navigational information (latitude and longitude) was determined along the center line of the continuous segment of data at the start, end, and two intermediate points. These four control points, with additional pairs of points for each located along the edges of the image, were used to position the continuous line segment within the imagery sheet. After the map projection and latitude and longitude boundaries for the sheet were selected, a transformation file was created to position the 12 control points and then the complete image within the sheet.

The next step was to stencil adjacent line segments together, providing a continuous mosaic covering the imagery sheet. Interactively a line was drawn on a video display outlining the portion of each image to be retained. This line was smoothed and then converted from vector to raster format. The rasterized mask was superimposed on the sidescan image and all pixels outside the area of the mask were converted to zero values, thereby retaining only that portion of the image desired. After this process of stenciling, each line segment was mosaicked to adjacent segments, sequentially building the composite map. In this way a digital file for each of the imagery sheets was created with the desired map projection. The scale of the sheets was determined by output of film negatives from the Scitex scanner.

GEOLOGIC INTERPRETATION

Background

The GLORIA sidescan-sonar images provide a unique view of the sea floor in the deep water of the Gulf of Mexico. A better understanding of the morphology, surficial geology, and sedimentary processes of the continental slope and rise in the Gulf of Mexico is important for evaluating and developing energy and mineral resources, and for siting sea-floor structures. The GLORIA data provide information on depositional environments and geologic processes that is important in developing depositional models useful as analogs in understanding the rock record.

The Gulf of Mexico, a small ocean basin, is geologically diverse. The EEZ in the Gulf of Mexico can be divided into three major sedimentary provinces: a salt deformation province in the western section, the Mississippi Canyon and Fan system in the central section, and a carbonate province in the eastern section, which is separated from the terrigenous Mississippi Fan by the Florida Escarpment.

Western Gulf of Mexico

The most striking feature on the imagery in the western Gulf is the Sigsbee Escarpment, which marks the seaward edge of the salt deformation province. The 3,000-m contour roughly outlines the base of this escarpment (fig. 6). Vertical relief on the escarpment is approximately 500 m, and piles of debris are visible on the sonographs along its base, suggesting that sediment is transported down the escarpment. Seaward of the escarpment, patches of highly reflective (bright) sea floor with numerous lineations are interpreted as bedform fields formed by the reworking of debris from the escarpment. Seismic-reflection profiles across the escarpment suggest that a wedge of salt is overriding sediments that were deposited in the deep waters of the Gulf (Amery, 1969).

Landward of the escarpment, the continental slope has a very complex morphology, formed in response to intrusion by the salt. The continental shelf in the Gulf of Mexico prograded seaward during the Tertiary as a series of depocenters migrated eastward from the Rio Grande River area of Texas to the presently active Mississippi River area in the north-central Gulf (Humphris, 1984). Loading of these Tertiary sediments onto an underlying salt layer of Jurassic age has resulted in diapiric intrusion by the salt. Diapirs have created numerous domes and isolated basins on the slope that have significantly influenced the paths of submarine canyons crossing the continental slope. Two remnant pathways appear to be traceable on the GLORIA imagery from the upper slope, tying into the two major reentrants in the Sigsbee Escarpment. The reentrant near long. 92° W. has a leveed channel emanating from it and meandering seaward (to the southeast) for approximately 160 km to the edge of the survey area. Identifying salt domes and basins on the slope based on imagery alone is difficult. In some cases the salt domes are highly reflective, because of the inclination of the flanks or the microtopography on the crests, whereas in other instances basin floors are reflective, possibly because of differences in sediment texture. An integration of bathymetric, seismic-reflection profile, and imagery data is necessary for a detailed interpretation of the sea-floor morphology.

The migrating depocenters in the Gulf have consisted of a series of deltas, some of them located near the edge of the continental shelf (Suter and Berryhill, 1985). On these deltas, as on the modern Mississippi River Delta, mass wasting resulted in slumps and slides, and was an important process in distributing sediments seaward. One such Pleistocene-age shelf-edge delta is located in the northwestern corner of the Gulf in the East Breaks area. Lehner (1969) described a major submarine slide that originated from the edge of this delta. The extent of the slide and the influence that salt diapirs had on its path are both revealed on the GLORIA images. The brightness of the backscatter from the surface of the slide is related to microtopography having relief of approximately 10 m (fig.7) (McGregor and Twichell, 1985). The continental slope seaward of the Rio Grande River has also undergone extensive mass wasting, as indicated by highly reflective sea floor classified as irregular sea floor (ISF) in the interpretation. Part of the Rio Grande Fan also has high surface reflectivity. The 3.5-kHz profiles (fig. 8) show that this region is characterized by a hummocky sea

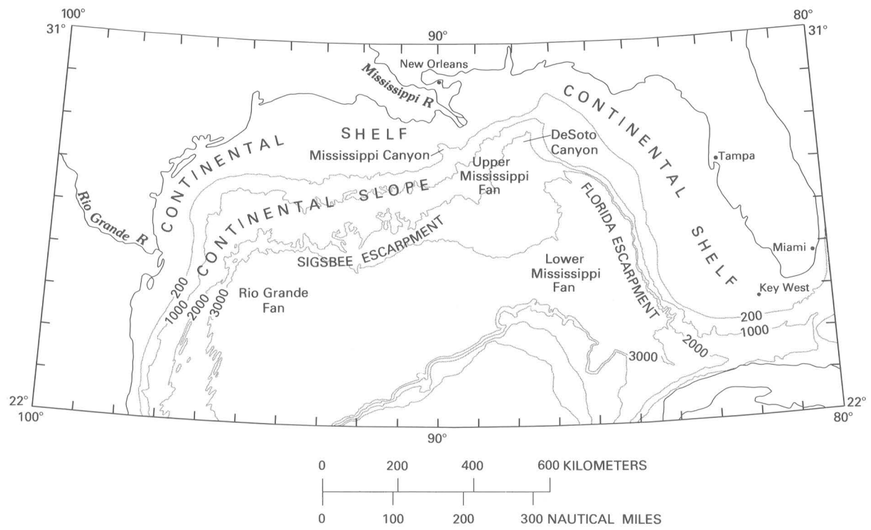

Figure 6—Generalized bathymetry and subsea features of the Gulf of Mexico. Bathymetric contours in meters.

floor. Regions mapped as being hummocky sea floor have been interpreted not only from the imagery but also from the 3.5-kHz data, with characteristics of irregular surface relief similar to that shown in figure 8.

Central Gulf of Mexico

The Mississippi Canyon and Fan system is the dominant morphologic feature in the central Gulf. The Sigsbee Escarpment cannot be identified because it is buried by sediments from the Mississippi Canyon. Diapirs influence the location of the Mississippi Canyon on the continental slope and are present on the slope northeast of the Mississippi Canyon over to De Soto Canyon. On the imagery they have high backscatter in comparison to the surrounding sea floor, which is very dark. The 3.5-kHz subbottom data show this dark area to be well laminated; it is characterized as such in the explanation for the geologic interpretation of the sonar-imagery mosaics (p. A8, fig. 13).

The Mississippi Canyon shows as a highly reflective region on the imagery because it is filled with debris-flow deposits. The seismic-reflection profile records show this canyon fill to be composed of acoustically transparent units. Where the flows have spilled over the canyon walls at meanders, the deposits have an arcuate pattern on the imagery. As the filled Mississippi Canyon is traced seaward onto the middle part of the Mississippi Fan, a meandering channel becomes apparent. Adjacent to this channel on the eastern fan the imagery shows a highly reflective region marked by very intricate flow patterns. This region is interpreted to be debris-flow deposits emanating from the Mississippi Canyon and covering most of the fan. On the 3.5-kHz subbottom data across most of these deposits, there is no subbottom penetration (fig. 9). Walker and Massingill (1970) identified submarine slump features on the mid-fan based on seismic-reflection profile data. Prior to collection of the GLORIA data, the immense area covered by material emplaced by mass-wasting processes was not imagined. The mid-fan channel is overrun and buried by these debris-flow deposits. The channel appears different acoustically upstream of the blockage because sediments have filled it. Downstream, the channel floor is not obvious. The surface of the fan to the west of the channel has a different acoustic character than to the east. It is also covered by a series of debris flows, some of which can be seen to originate from the bank overflow features on the upper fan. South of the channel on the mid-fan are pronounced south-trending lineations that are associated with erosional processes on this part of the fan. Some areas of the fan are characterized as having an irregular surface, which may represent partly buried material related to older mass-wasting events.

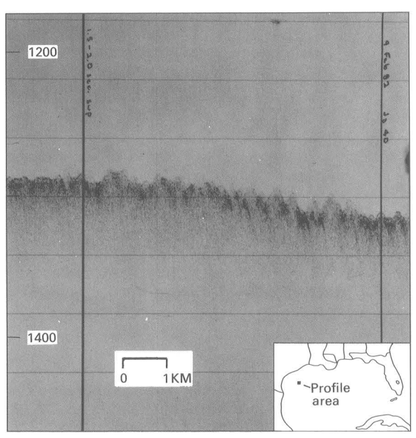

Figure 7—A 10-kHz high-resolution seismic-reflection profile across East Breaks submarine slide in the northwestern Gulf. Profile shows irregular surface of slide, which contributes to its high reflectivity on the GLORIA mosaic. Vertical scale shows depth below sea level, in meters.

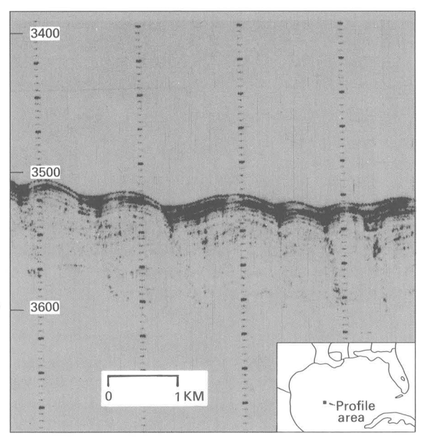

Figure 8—A 3.5-kHz high-resolution seismic-reflection profile showing sea-floor characteristics described as hummocky. Vertical scale shows depth below sea level, in meters.

Eastern Gulf of Mexico

In the northeastern Gulf, a highly reflective area on the imagery marks submarine debris-flow deposits in the De Soto Canyon area. A meandering channel shown as a bright sinuous line on the images emerges from the deposits and trends southward, parallel to the Florida Escarpment. Another, less reflective, channel (perhaps abandoned) lies closer to the base of the escarpment, and a tongue of the debris-flow deposits from De Soto Canyon extends into this channel. The bright meandering channel is part of an elevated channel and levee system (levee ridge). The highly reflective debris-flow deposits from the Mississippi Canyon area are dammed by this elevated channel until the flow eventually overtops the levee and buries the channel. The southern extent of this channel and its deposits is masked by the debris-flow deposits.

The dominant feature in the eastern Gulf is the Florida Escarpment, which has a gradient of as much as 40° and relief ranging from 1,000 m in the north near De Soto Canyon to 2,500 m west of the Florida Keys. The escarpment consists of Lower Cretaceous to Miocene carbonates and is part of a reef that extends north from Mexico through Texas and Louisiana, southeast from Mississippi, around Florida and the Bahamas (Bryant and others, 1969; Antoine and others, 1967), and north under the eastern U.S. Atlantic continental margin (Schlee and others, 1979).

On the basis of seismic-reflection profiles, the relief and morphology of the Florida Escarpment are attributed to the vertical growth of a reef on the gradually subsiding continental margin (Antoine and others, 1967; Corso and Buffler, 1985). Samples recently collected by dredging and by submersible dives indicate that only a fine-grained back-reef lagoonal facies is exposed on the escarpment (Freeman-Lynde, 1983). The GLORIA imagery shows that the erosional morphology varies along the escarpment. North of lat. 27° N. the escarpment is dissected by a series of closely spaced canyons with tributary gullies. South of lat. 27° N., large box canyons with nearly vertical headwalls have been cut as much as 15 km into the escarpment. Numerous scarps having up to 250 m of relief are present in the carbonate sediments above the escarpment. These scarps are the product of mass wasting of the carbonate sediments. Some of the scarps align with the canyons, suggesting that the canyons are conduits for mass-wasting products from the continental slope above. Massive slumps of the Tertiary sequence have resulted in the deposition of carbonate material in the deep water of the Gulf, interbedded with clastic material of the Mississippi Fan.

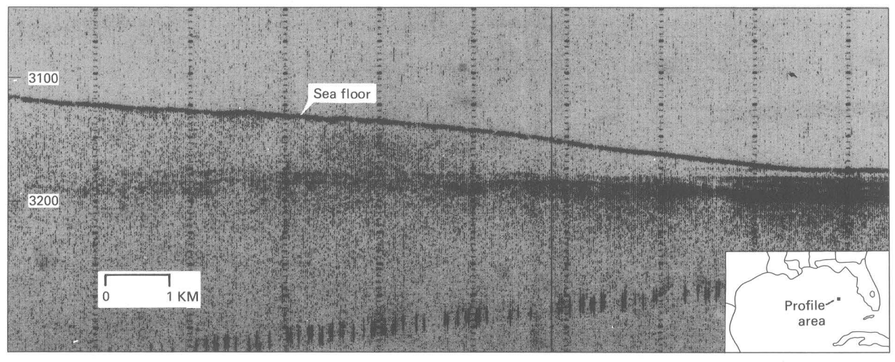

Figure 9—A 3.5-kHz high-resolution seismic-reflection profile of acoustically transparent debris-flow deposits burying stratified sediments. Vertical scale shows depth below sea level, in meters.

Summary

Mass wasting was found from the GLORIA survey to be much more extensive in the Gulf of Mexico than previously thought. The survey data revealed that movement of terrigenous sediments and both lithified and unconsolidated carbonates has occurred in a variety of styles and volumes. Mass-wasting processes have been a major contributor to the sediments in the deep water of the Gulf of Mexico. Four submarine channels can also be identified meandering across the floor of the Gulf, providing pathways for the transportation and distribution of sediments.

PARTICIPANTS IN THE GULF OF MEXICO SURVEYS

SCIENTIFIC PERSONNEL	1985 Leg 1	1985 Leg 2	1985 Leg 3	1982
Dr. Bonnie McGregor, USGS, co-chief scientist	X	X		
Mr. Guy Rothwell, IOS, co-chief scientist	X			
Mr. Neil Kenyon, IOS, co-chief scientist		X		X
Mr. David Twichell, USGS, co-chief scientist		X	X	X
Dr. Lindsay Parson, IOS, co-chief scientist			X	
Dr. Louis Garrison, USGS, co-chief scientist				X
Dr. Michael Somers, IOS, GLORIA engineer	X			X
Mr. Malcolm Harris, IOS, GLORIA engineer		X		
Mr. Derek Bishop, IOS, GLORIA engineer	X		X	
Mr. Jon Campbell, IOS, GLORIA engineer			X	X
Mr. Ross Walker, IOS, GLORIA engineer	X	X		
Mr. John Cherriman, IOS, GLORIA engineer			X	
Mr. Eric Darlington, IOS, GLORIA engineer		X		
Mr. Andrew Harris, IOS, GLORIA engineer			X	
Dr. Robert Mattick, USGS, geologist	X			
Dr. John Schlee, USGS, geologist		X		
Dr. Page Valentine, USGS, geologist			X	
Dr. William Sweet, MMS, geologist	X			
Mr. Dann Blackwood, USGS, photographer	X			X
Mr. Kim Benjamin, WHOI, engineer	X		X	
Mr. Quentin Huggett, IOS, geologist	X			
Mr. Christopher Jackson, RVS, shipboard computing	X			
Mr. Edward Cooper, RVS, shipboard computing	X			
Mr. Alan Gray, IOS, airgun technician	X			
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Mr. Robin Bonner, IOS, airgun technician			X	X
Mr. Collin Jacobs, IOS, geologist-photographer		X	X	
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Mr. Derek Lewis, RVS, shipboard computing			X	X
Mr. Steve Mateus, USGS, geologist			X	
Dr. Mahlon Ball, USGS, geologist				X
Dr. Edward Escowitz, USGS, geologist				X
Mr. Gareth Knight, RVS, shipboard computing				X
Ms. Kathryn Scanlon, USGS, geologist				X
Mr. Richard Sylwester, USGS, electronics technician				X
Mr. John West, USGS, airgun technician				X
Ms. Sarah Eisner, USGS, geologist				X
Mr. Steve Wolf, USGS, geologist				X

USGS, U.S. Geological Survey
IOS, Institute of Oceanographic Sciences (U.K.)
MMS, Minerals Management Service
WHOI, Woods Hole Oceanographic Institution
RVS, Research Vessel Services (U.K.)
LSU, Louisiana State University
SIO, Scripps Institution of Oceanography

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———1975b, East Breaks: Bathymetric Map NG 15–1, scale 1:250,000.

———1975c, Garden Banks: Bathymetric Map NG 15–2, scale 1:250,000.

———1975d, Green Canyon: Bathymetric Map NH 15–3, scale 1:250,000.

———1975e, Mississippi Canyon: Bathymetric Map NH 16–10, scale 1:250,000.

———1979a, De Soto Canyon: Bathymetric Map NH 16–11, scale 1:250,000.

———1979b, Howell Hook: Bathymetric Map NH 16–9, scale 1:250,000.

———1979c, The Elbow: Bathymetric Map NG 16–3, scale 1:250,000.

———1979d, Vernon Basin: Bathymetric Map NG 16–6, scale 1:250,000.

———1981, Alaminos Canyon: Bathymetric Map NG 15–4, scale 1:250,000.

———1982a, Atwater: Bathymetric Map NG 16–1, scale 1:250,000.

———1982b, Dry Tortugas: Bathymetric Map NG 17–10, scale 1:250,000.

———1982c, Lloyd: Bathymetric Map NG 16–2, scale 1:250,000.

———1982d, Rankin: Bathymetric Map NG 16–12, scale 1:250,000.

———1986a, Eastern Gulf of Mexico Regional Map [bathymetric] : scale 1:1 million.

———1986b, Western Gulf of Mexico Regional Map [bathymetric] : scale 1:1 million.

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It is recommended that reference to the atlas be made in the following form:
EEZ-SCAN 85 Scientific Staff, 1987, Atlas of the U.S. Exclusive Economic Zone, Gulf of Mexico: U.S. Geological Survey Miscellaneous Investigations Series I-1864-A, 104 p., scale 1:500,000.

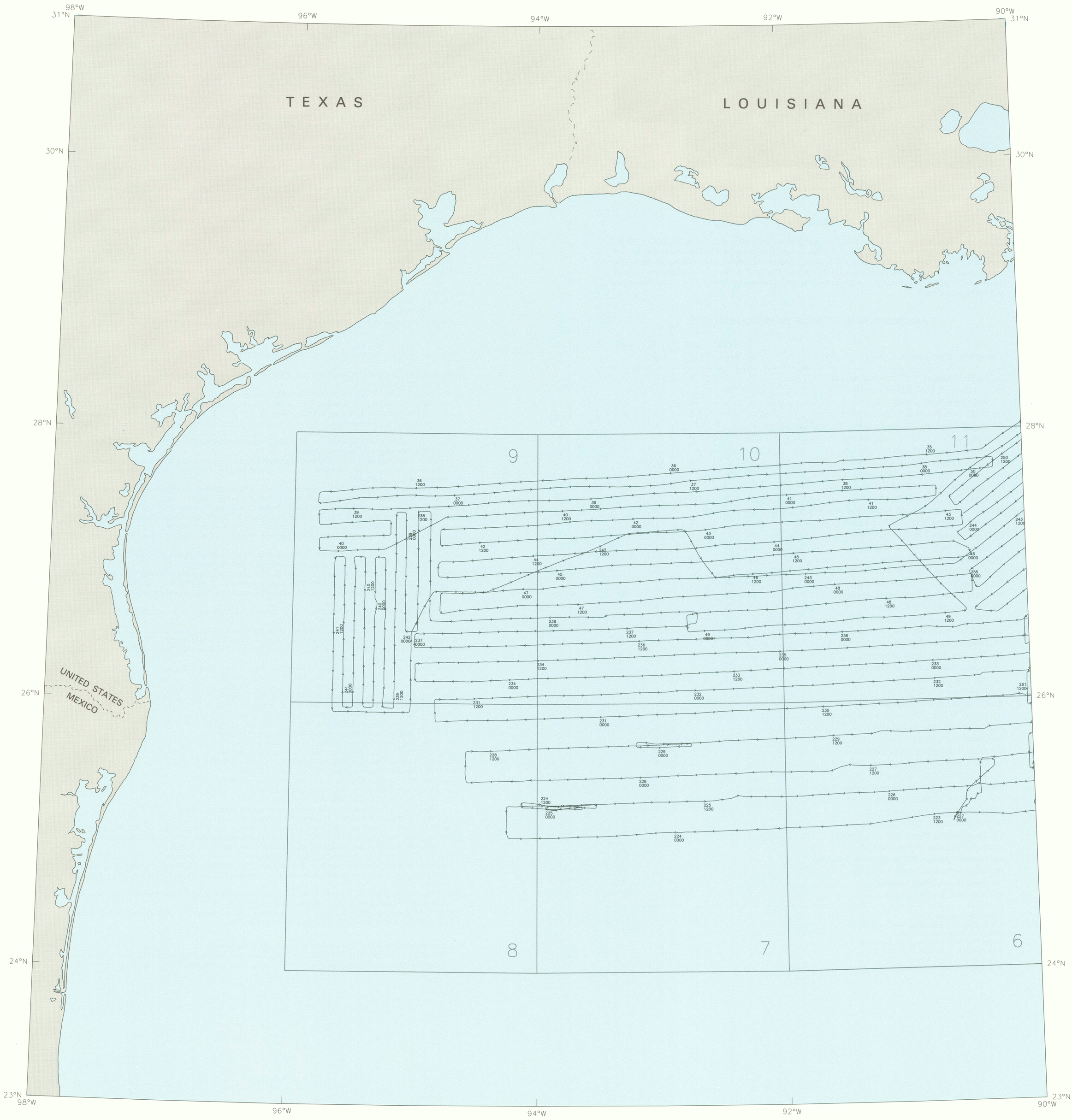


Figure 10—Tracklines of the 1982 and 1985 surveys in the western Gulf of Mexico. Julian day and time (Greenwich Mean Time) are annotated on the tracklines at 12-hour intervals, and every hour is marked by an arrowhead showing direction of travel. Outlines of imagery sheets 6–11 are also indicated.

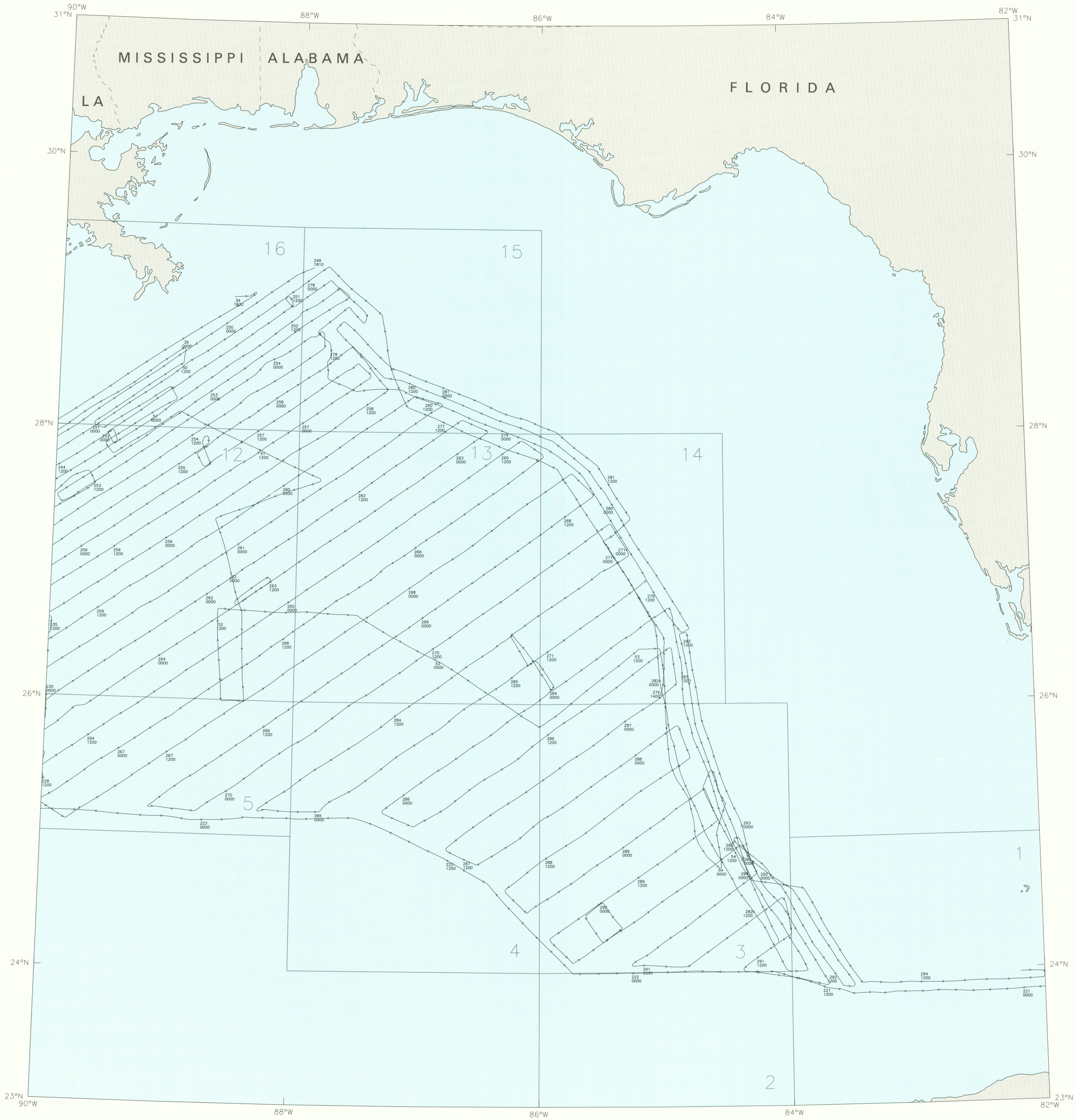
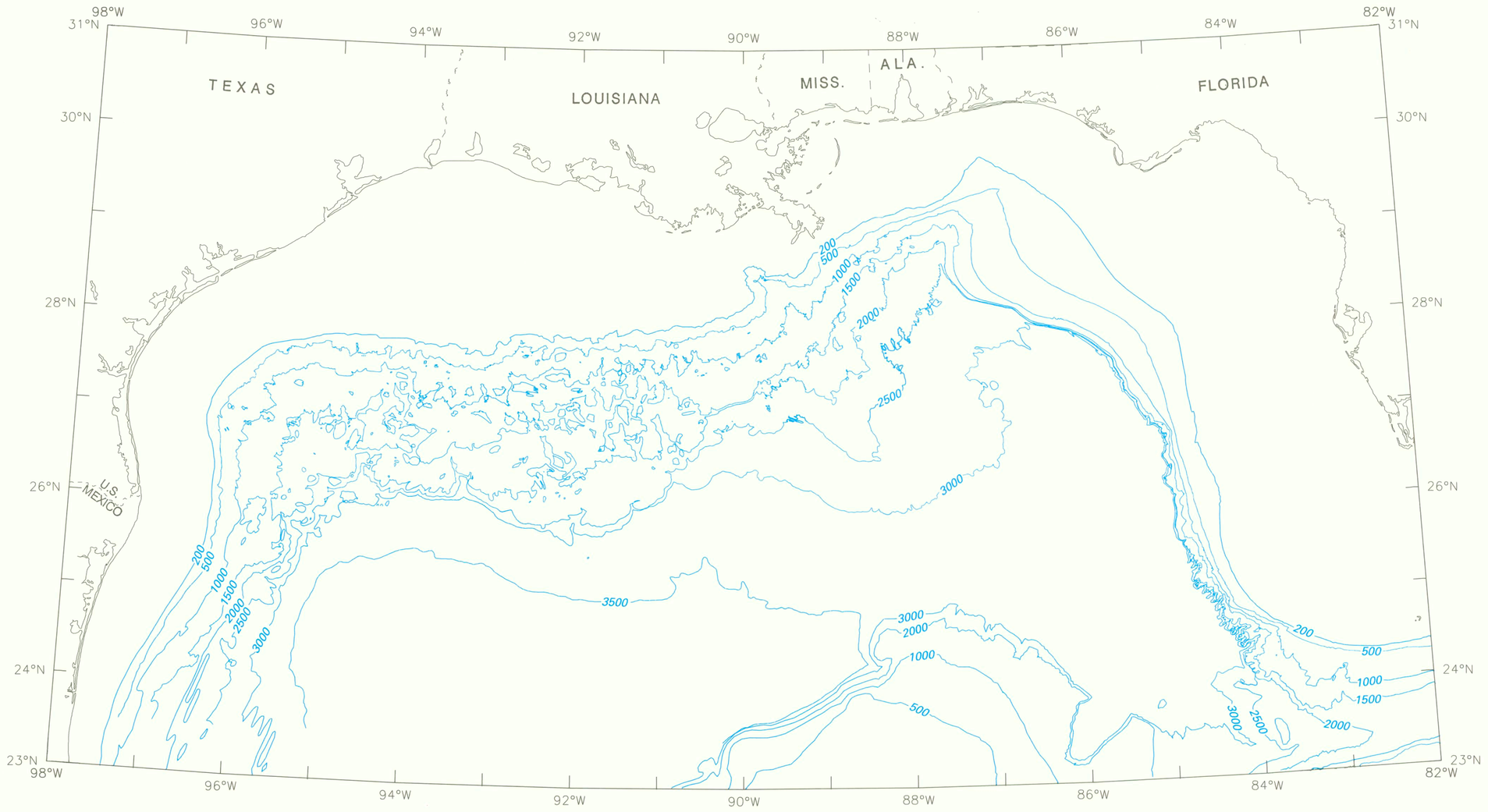


Figure 11—Tracklines of the 1982 and 1985 surveys in the eastern Gulf of Mexico. Julian day and time (Greenwich Mean Time) are annotated on the tracklines at 12-hour intervals, and every hour is marked by an arrowhead showing direction of travel. Outlines of imagery sheets 1–5 and 12–16 are also indicated.



SCALE 1:5 000 000

100 0 100 200 300 NAUTICAL MILES

100 0 100 200 300 400 500 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

Figure 12—Bathymetry of the northern half of the Gulf of Mexico, seaward of the continental shelf edge (200-m contour). Contour interval 500 m and 1,000 m. Bathymetry derived from National Ocean Service bathymetric maps (see reference list in text section).

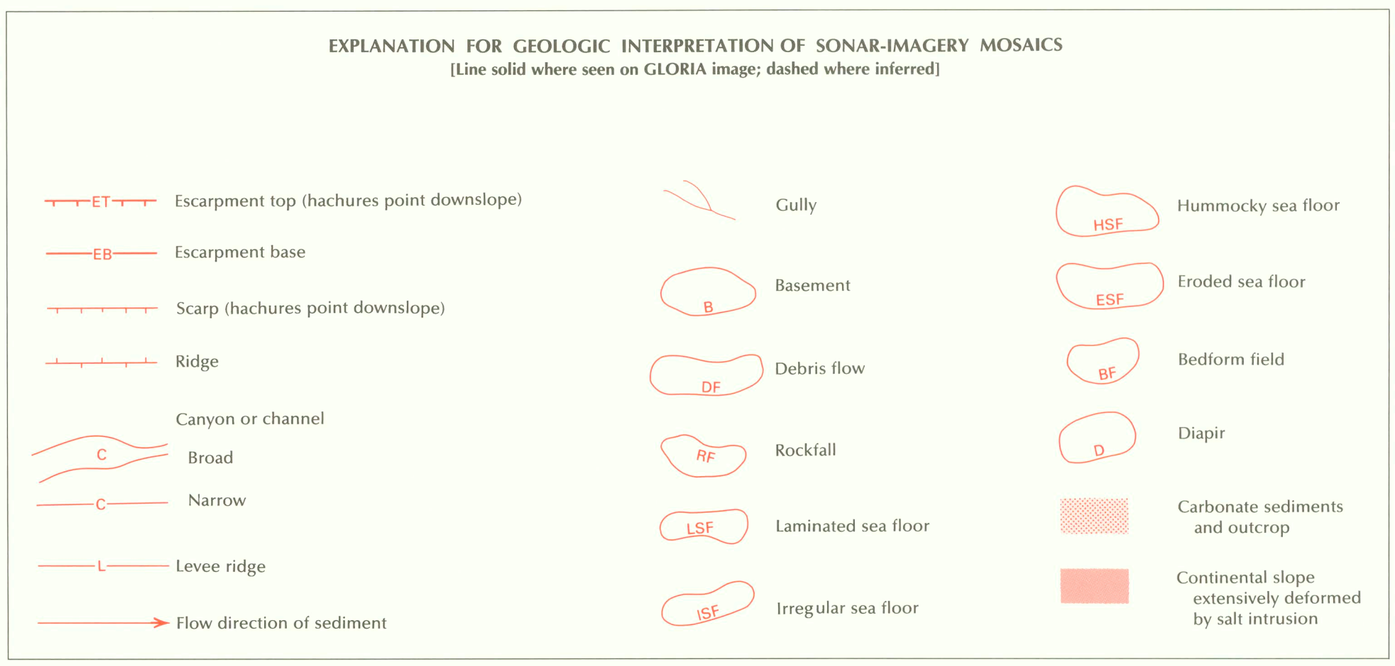


Figure 13—Explanation for geologic interpretation of sonar-imagery mosaics (sheets 1–16, p. A12–A43).

SONAR-IMAGERY MOSAICS WITH GEOLOGIC INTERPRETATIONS AND BATHYMETRY (SHEETS 1–16)

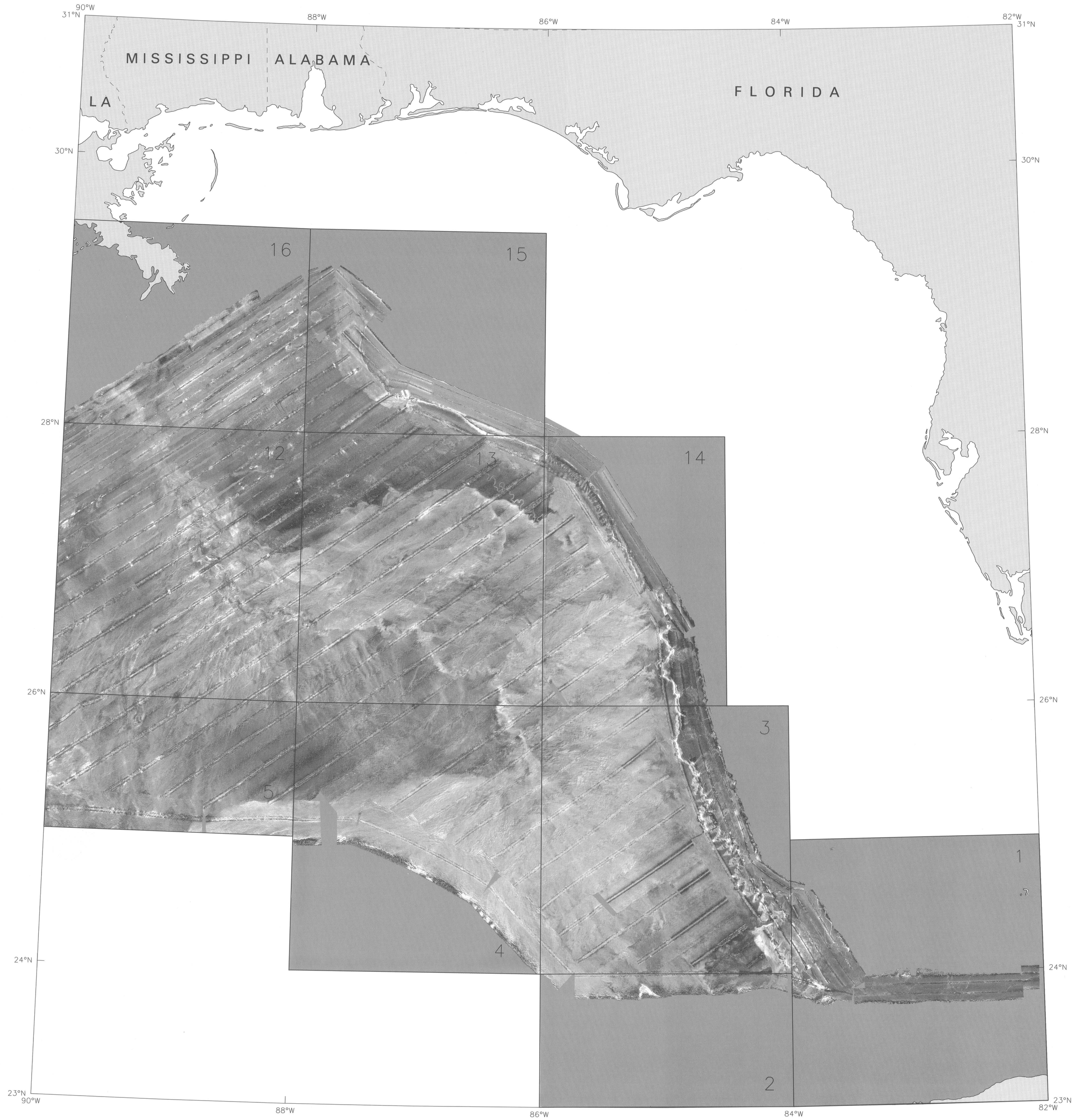
SCALE 1:2 000 000

50 0 50 100 150 NAUTICAL MILES

50 0 50 100 150 200 250 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

Mosaic of the sidescan-sonar imagery in the western Gulf of Mexico. Each pixel of data represents 200 m on the sea floor. Outlines of imagery sheets 6–11 are indicated.



SCALE 1:2 000 000

50 0 50 100 150 NAUTICAL MILES

50 0 50 100 150 200 250 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

Mosaic of the sidescan-sonar imagery in the eastern Gulf of Mexico. Each pixel of data represents 200 m on the sea floor. Outlines of imagery sheets 1–5 and 12–16 are indicated.

SONAR MOSAIC—SHEET 1

84°W
25°N
83°W
82°W
25°N
24°N
24°N
23°N
84°W
83°W
82°W
23°N

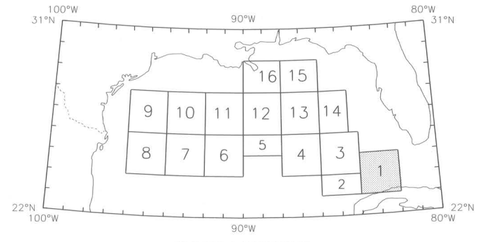
NO DATA

SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

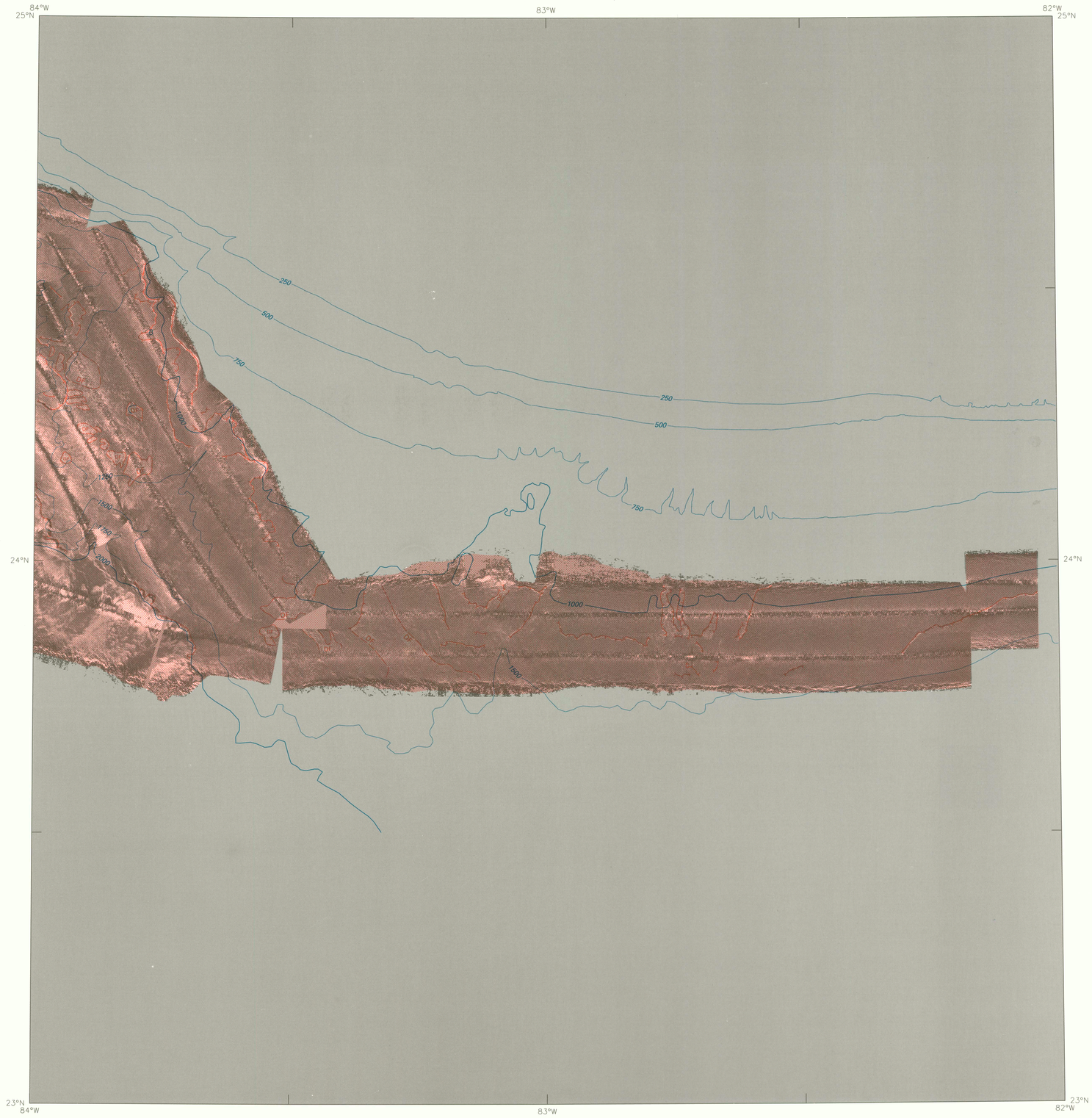
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

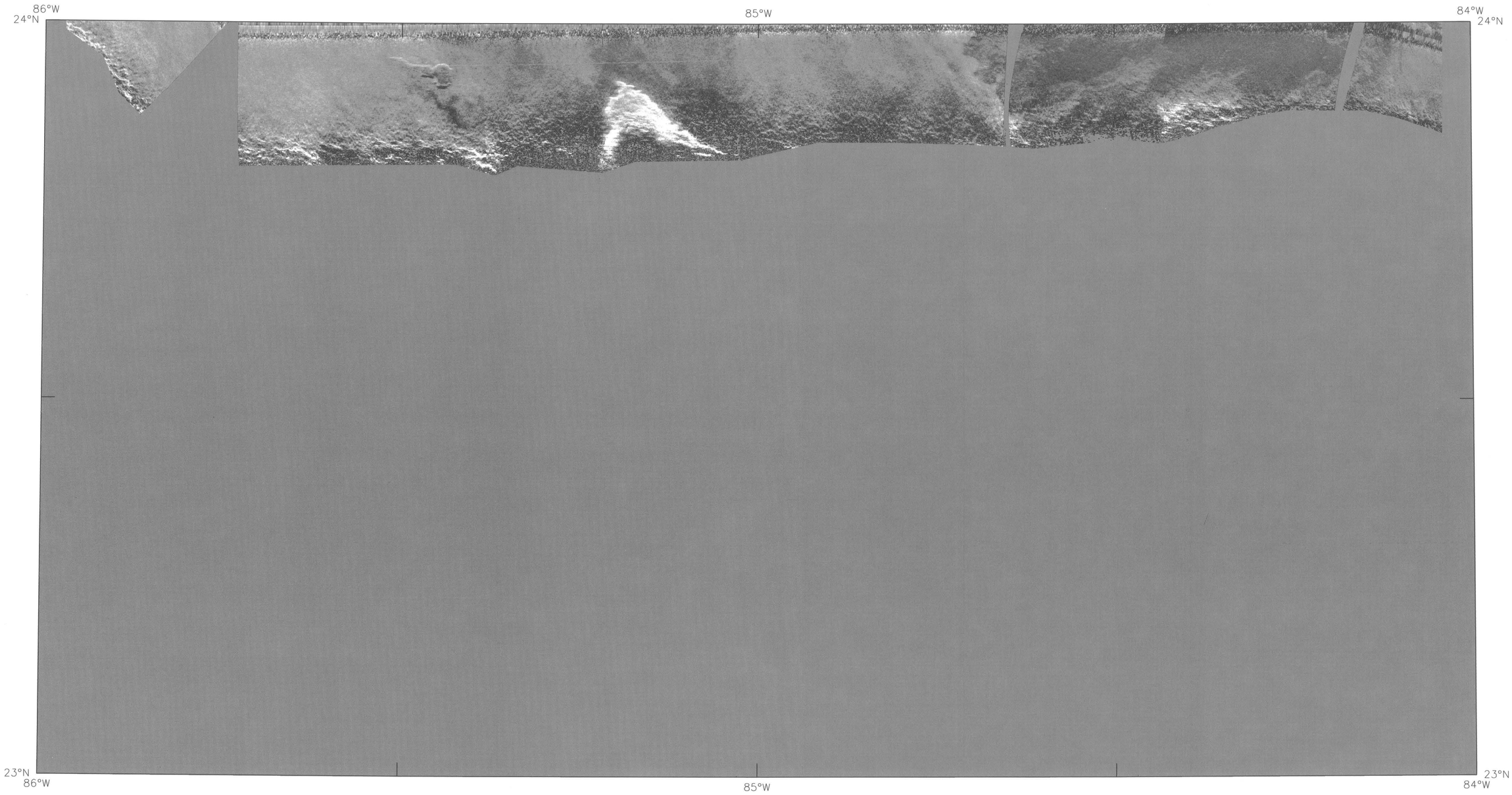


SHEET LOCATION

SONAR MOSAIC—SHEET 1
GEOLOGIC INTERPRETATION
BATHYMETRY



SONAR MOSAIC—SHEET 2



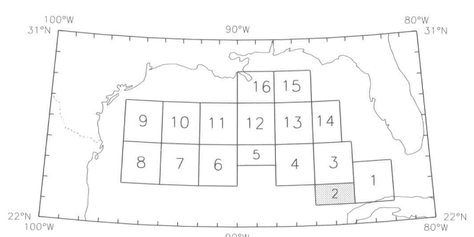
NO DATA

SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

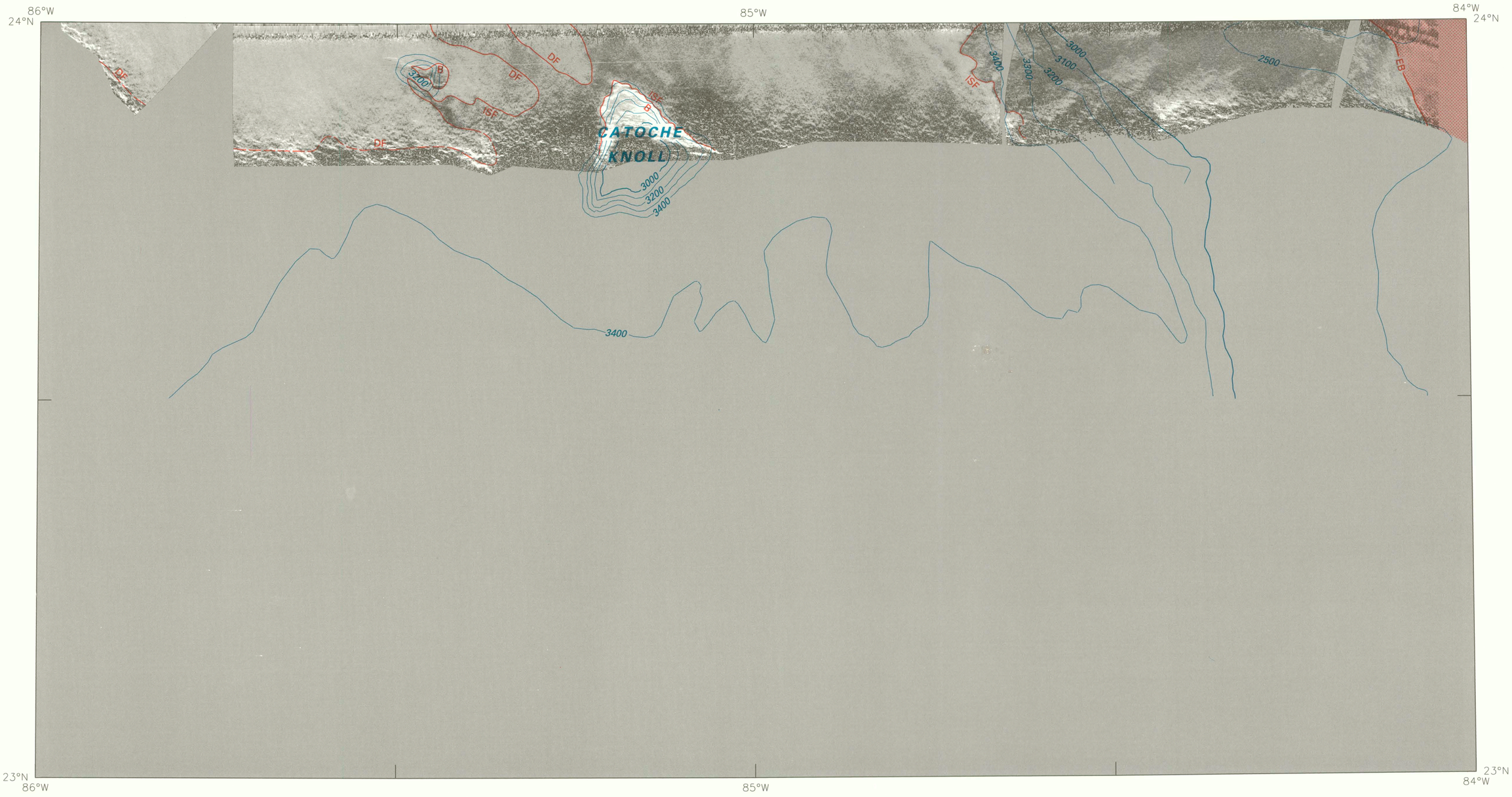
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 2
GEOLOGIC INTERPRETATION
BATHYMETRY



NO DATA

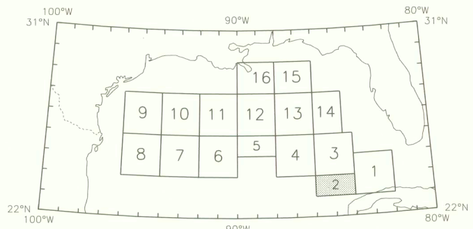
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 500 METERS
SUPPLEMENTED BY 100-METER INTERVAL,
3000 METERS TO MAXIMUM DEPTH



SHEET LOCATION

SONAR MOSAIC—SHEET 3

NO DATA

SCALE 1:500,000

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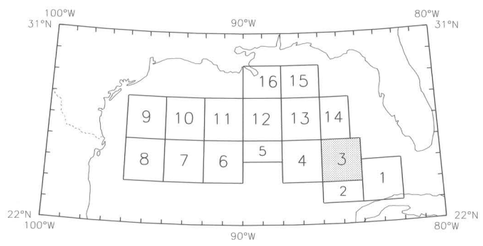
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 3
GEOLOGIC INTERPRETATION
BATHYMETRY

86°W 85°W 84°W
26°N 25°N 24°N

FLORIDA ESCARPMENT

NO DATA

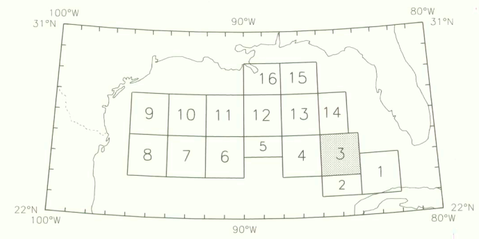
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 250 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 4

NO DATA

SCALE 1:500,000

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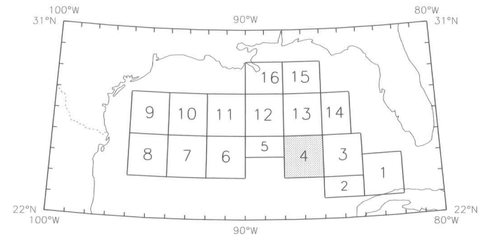
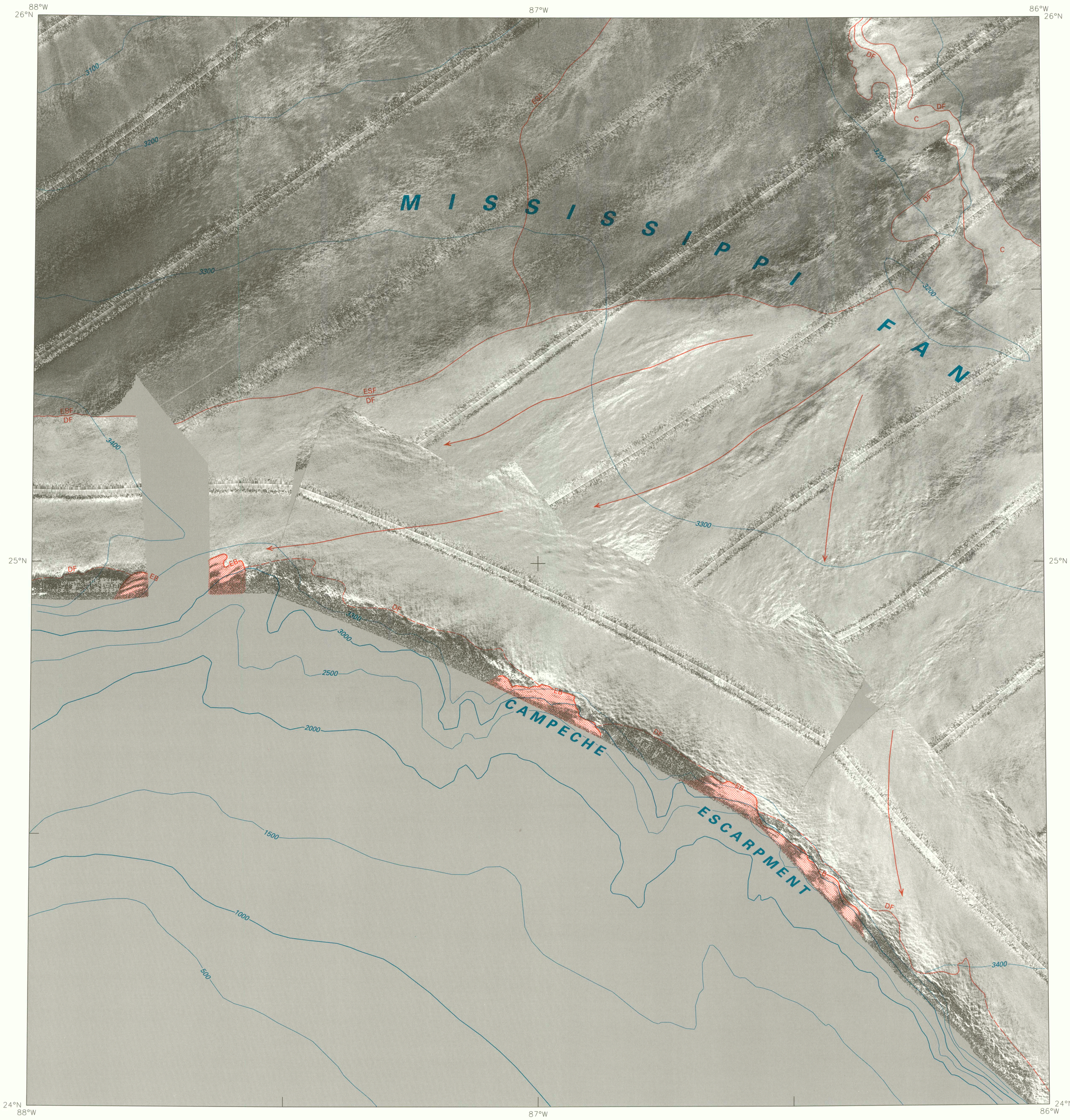
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 4
GEOLOGIC INTERPRETATION
BATHYMETRY



NO DATA

SCALE 1:500,000

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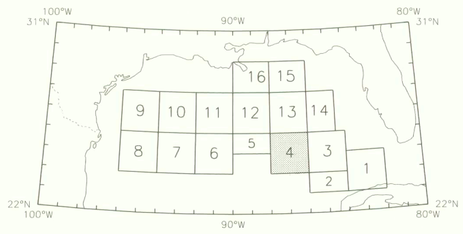
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 500 METERS
SUPPLEMENTED BY 100-METER INTERVAL



SHEET LOCATION

SONAR MOSAIC—SHEET 5

NO DATA

SCALE 1:500,000

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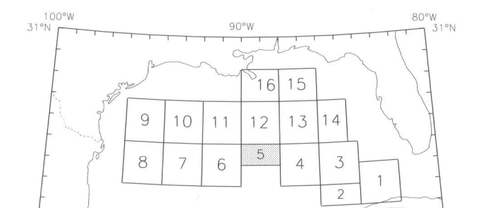
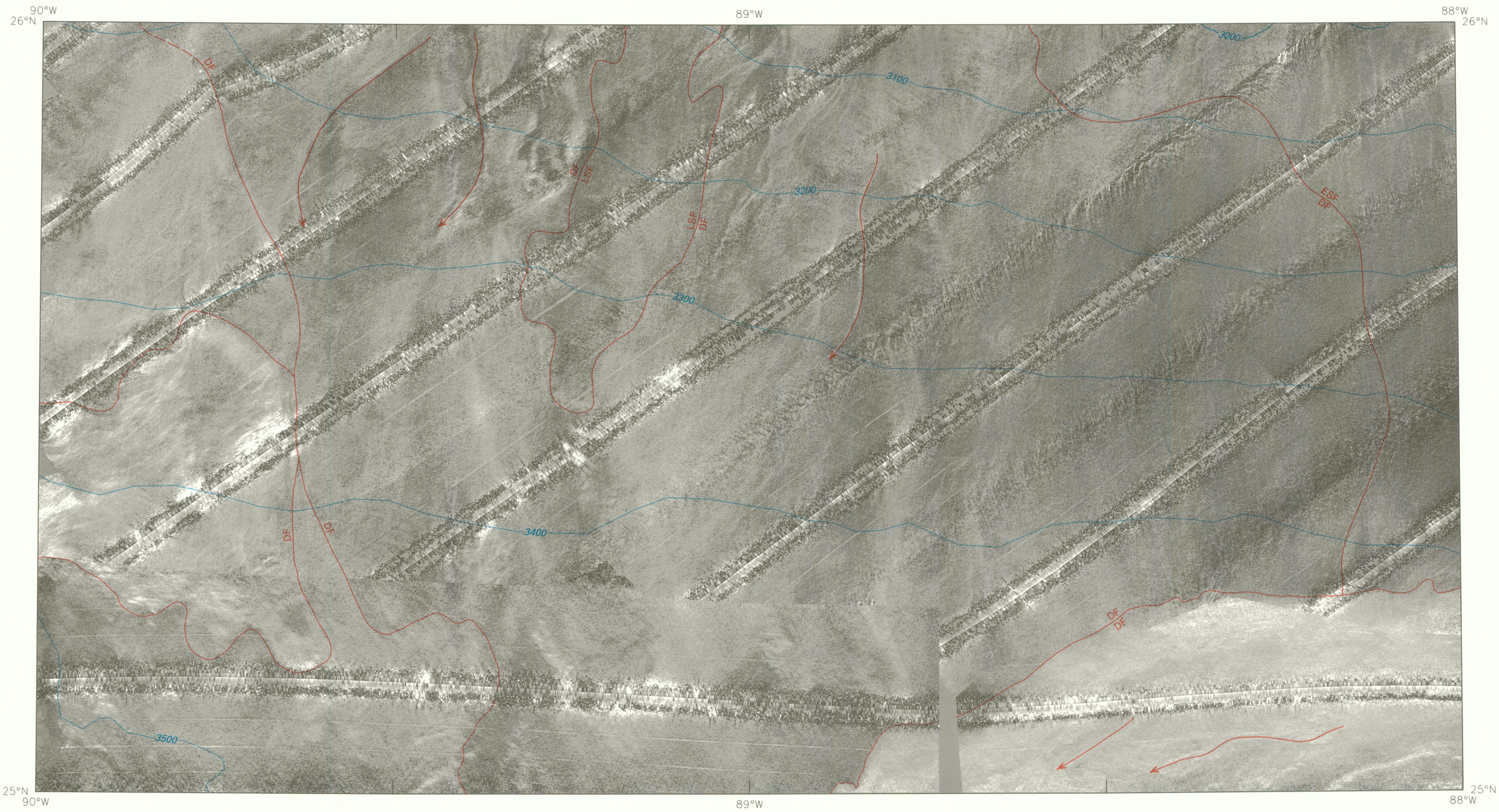
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 5
GEOLOGIC INTERPRETATION
BATHYMETRY



NO DATA

SCALE 1:500,000

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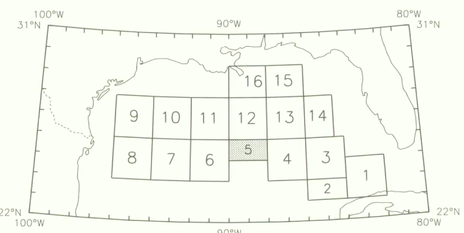
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 100 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 6

92°W
26°N
91°W
90°W
26°N
25°N
25°N
24°N
92°W
91°W
90°W
24°N

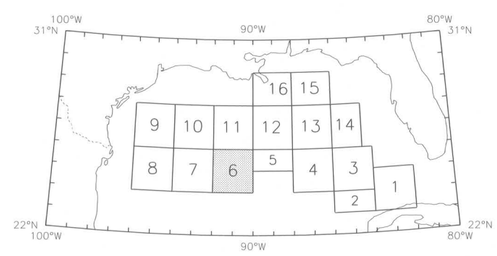
NO DATA

SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

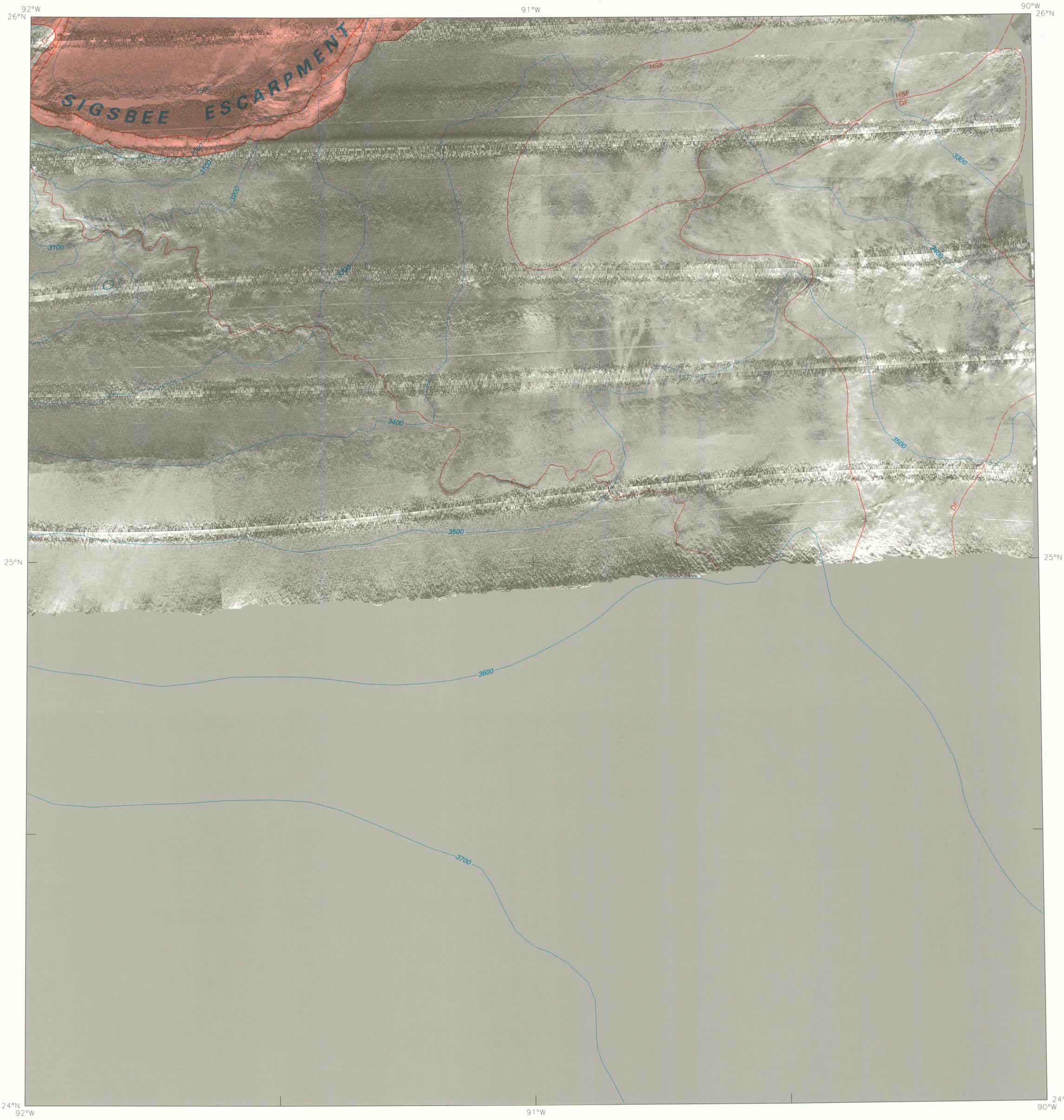
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 6
GEOLOGIC INTERPRETATION
BATHYMETRY



NO DATA

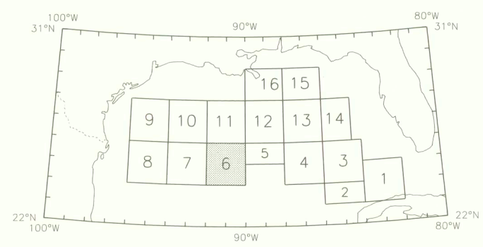
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

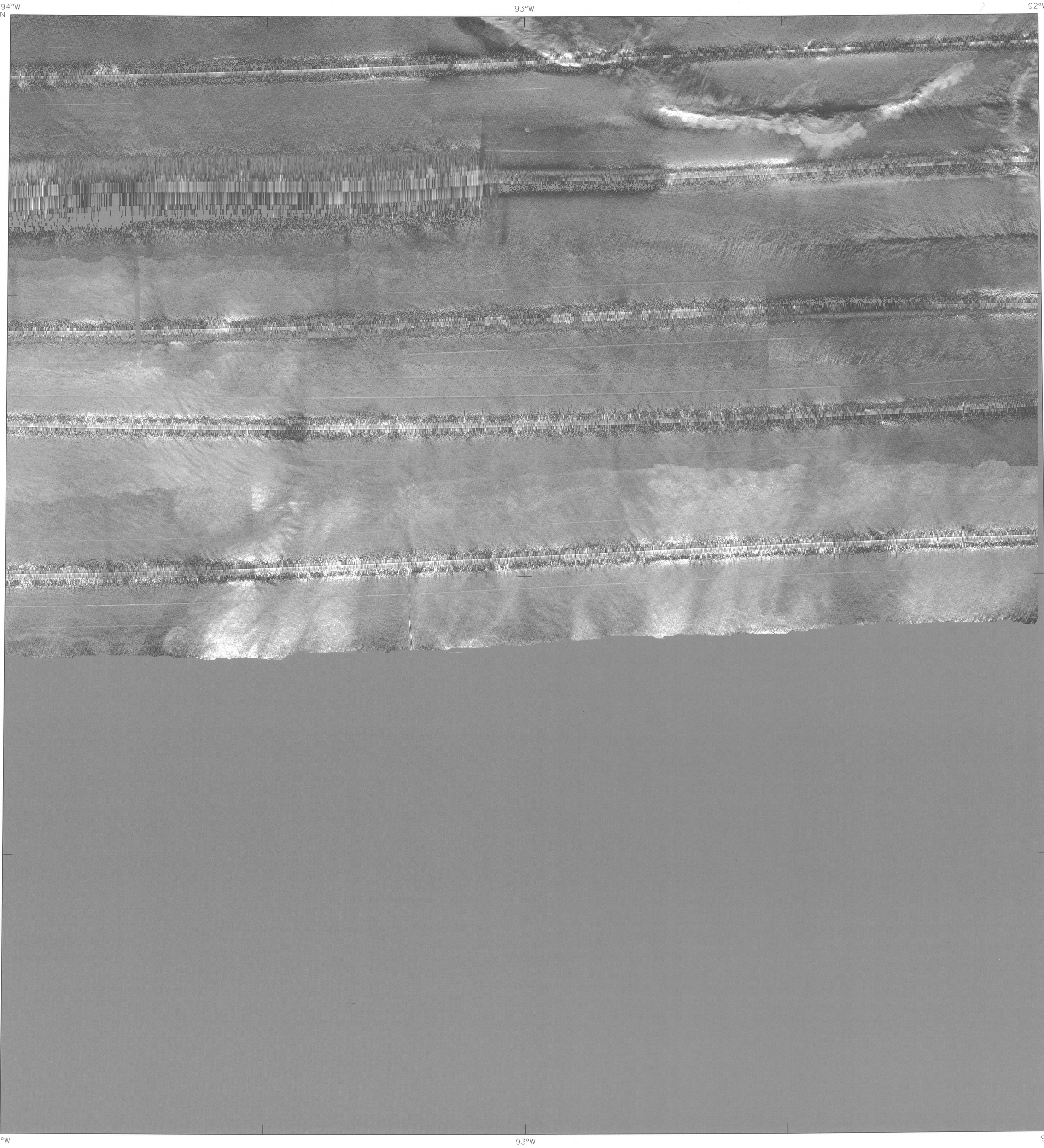
BATHYMETRIC CONTOUR INTERVAL 500 METERS
SUPPLEMENTED BY 100-METER INTERVAL,
3000 METERS TO MAXIMUM DEPTH



SHEET LOCATION

SONAR MOSAIC—SHEET 7

94°W 93°W 92°W
26°N 25°N 24°N



NO DATA

SCALE 1:500,000

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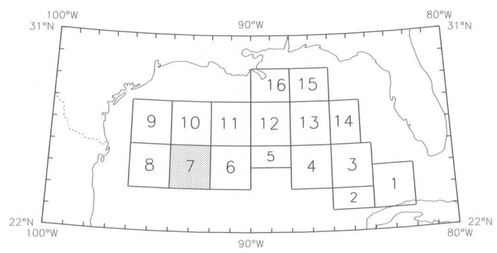
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 7
GEOLOGIC INTERPRETATION
BATHYMETRY

94°W
93°W
92°W
26°N
25°N
24°N

SIGSBEE ESCARPMENT

BF
HSF
LSF
C

2500
3000
3100
3200
3300
3400
3500
3600
3700

NO DATA

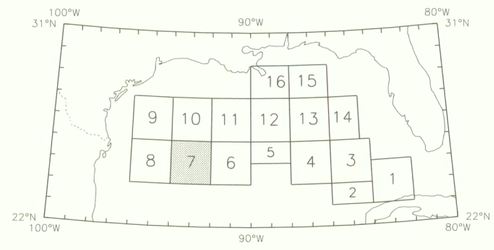
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 500 METERS
SUPPLEMENTED BY 100-METER INTERVAL,
3000 METERS TO MAXIMUM DEPTH



SHEET LOCATION

SONAR MOSAIC—SHEET 8

NO DATA

SCALE 1:500,000

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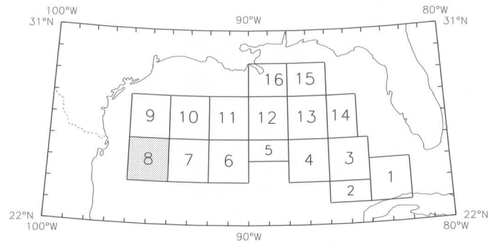
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 8
GEOLOGIC INTERPRETATION
BATHYMETRY

NO DATA

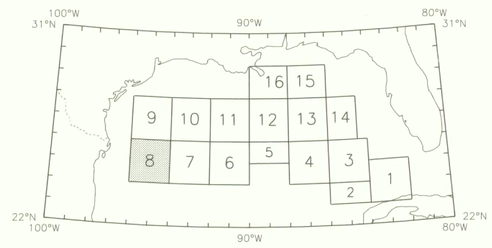
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

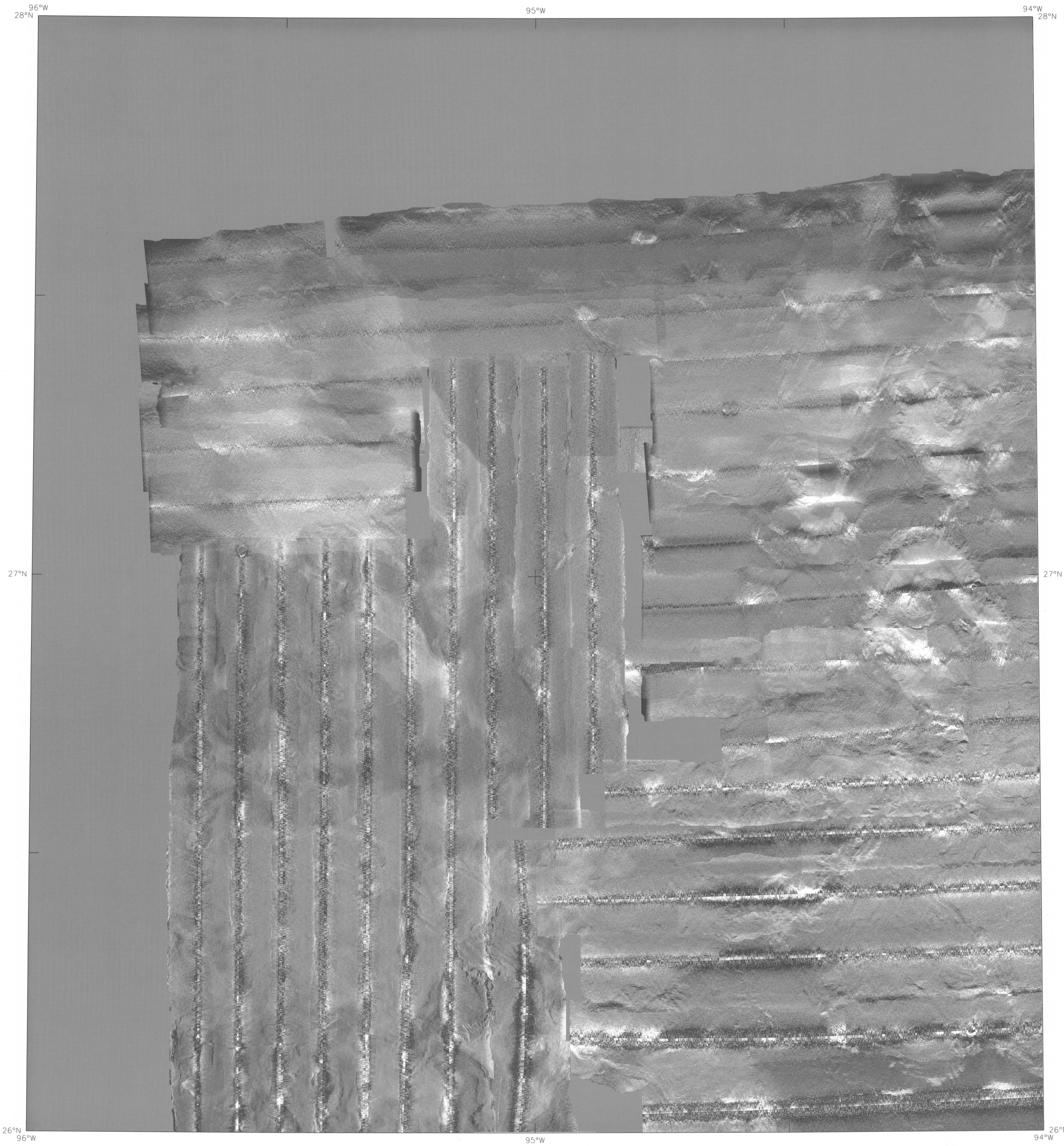
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 500 METERS
SUPPLEMENTED BY 100-METER INTERVAL,
3000 METERS TO MAXIMUM DEPTH



SHEET LOCATION

SONAR MOSAIC—SHEET 9



NO DATA

SCALE 1:500,000

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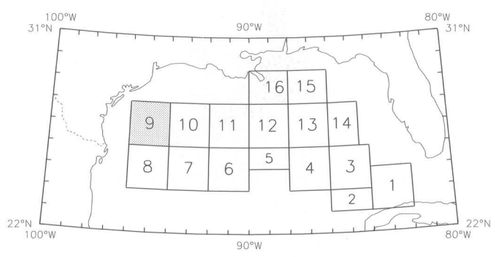
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 9
GEOLOGIC INTERPRETATION
BATHYMETRY

NO DATA

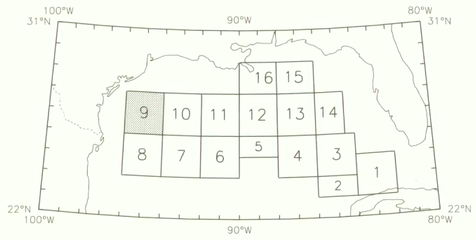
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 250 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 10

94°W 28°N
93°W
92°W 28°N
27°N
27°N
26°N 94°W
93°W
26°N 92°W

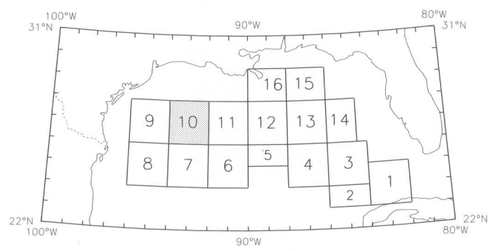
NO DATA

SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 10
GEOLOGIC INTERPRETATION
BATHYMETRY

94°W 93°W 92°W
28°N 27°N 26°N

SIGSBEE ESCARPMENT
KEATHLEY CANYON

C
ET
EB
DF
BF

NO DATA

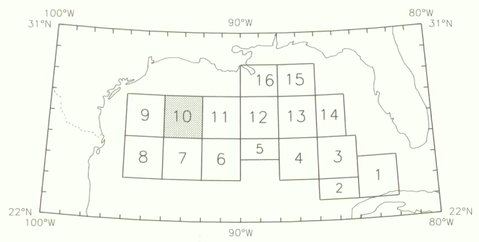
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 250 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 11

92°W 28°N — 91°W — 90°W 28°N

27°N — 27°N

26°N 92°W — 91°W — 26°N 90°W

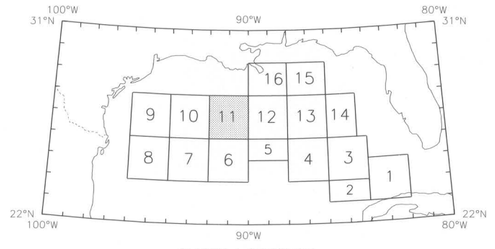
NO DATA

SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 11
GEOLOGIC INTERPRETATION
BATHYMETRY

92°W 91°W 90°W
28°N 27°N 26°N

ORCA BASIN

SIGSBEE ESCARPMENT

ET EB DF HSF

NO DATA

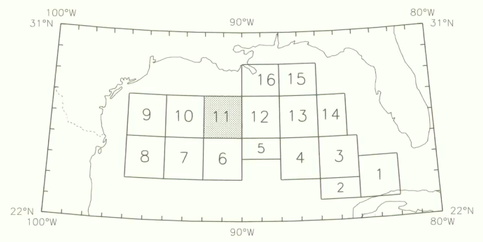
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

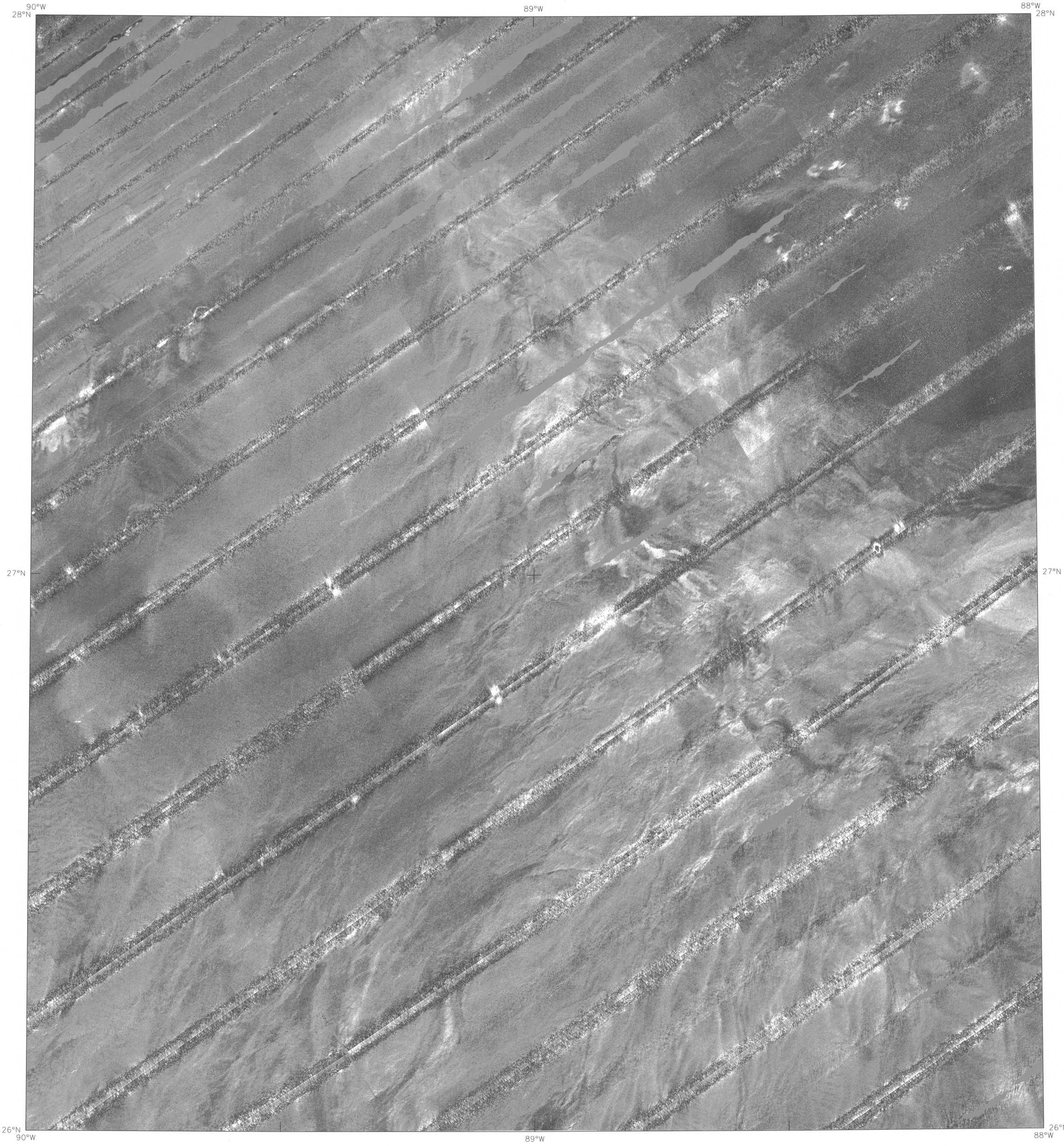
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 250 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 12



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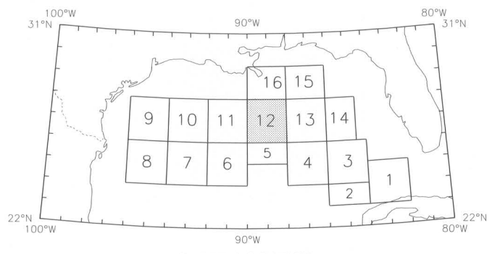
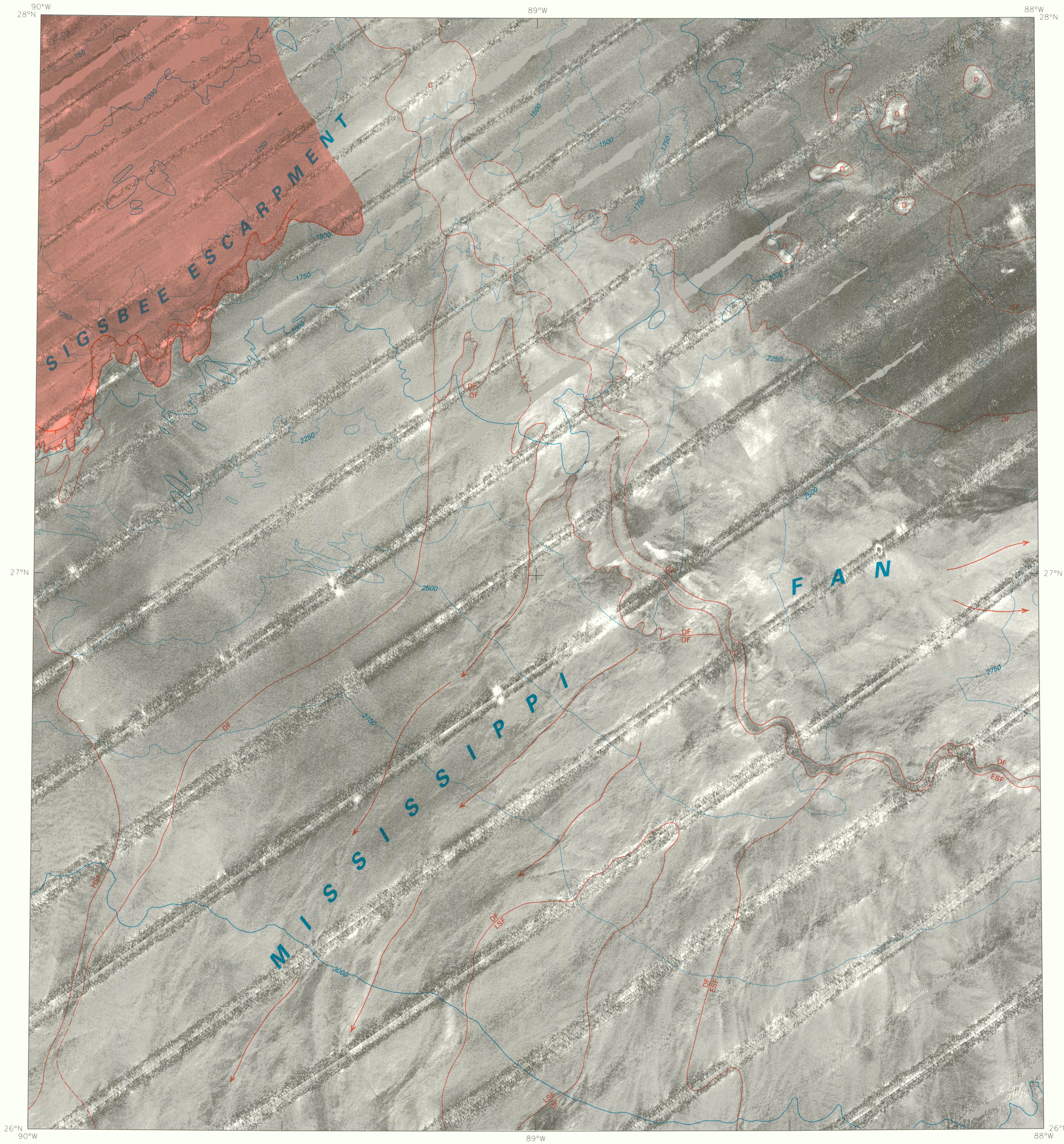
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 12
GEOLOGIC INTERPRETATION
BATHYMETRY



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SCALE 1:500,000

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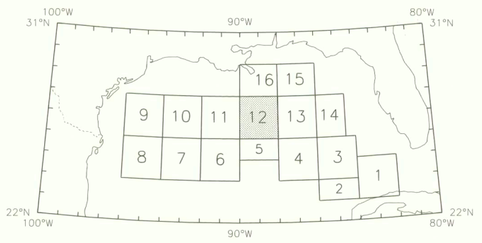
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 250 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 13

88°W 87°W 86°W
28°N 27°N 26°N

NO DATA

SCALE 1:500,000

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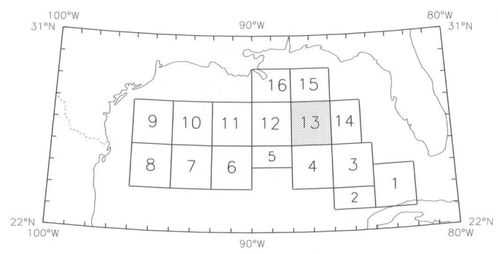
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 13
GEOLOGIC INTERPRETATION
BATHYMETRY

NO DATA

SCALE 1:500,000

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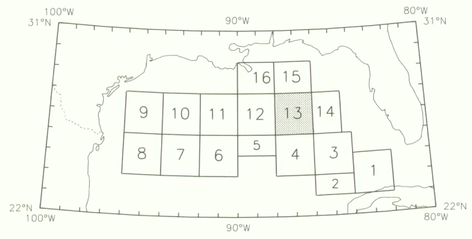
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 250 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 14

NO DATA

SCALE 1:500,000

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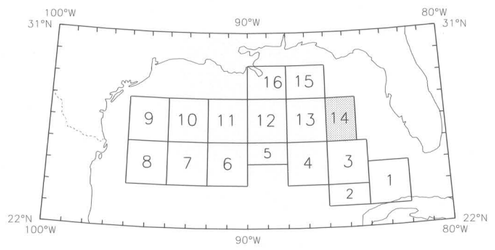
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 14
GEOLOGIC INTERPRETATION
BATHYMETRY

NO DATA

SCALE 1:500,000

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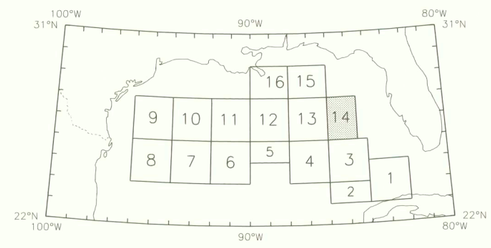
10 0 10 20 30 40 50 KILOMETERS

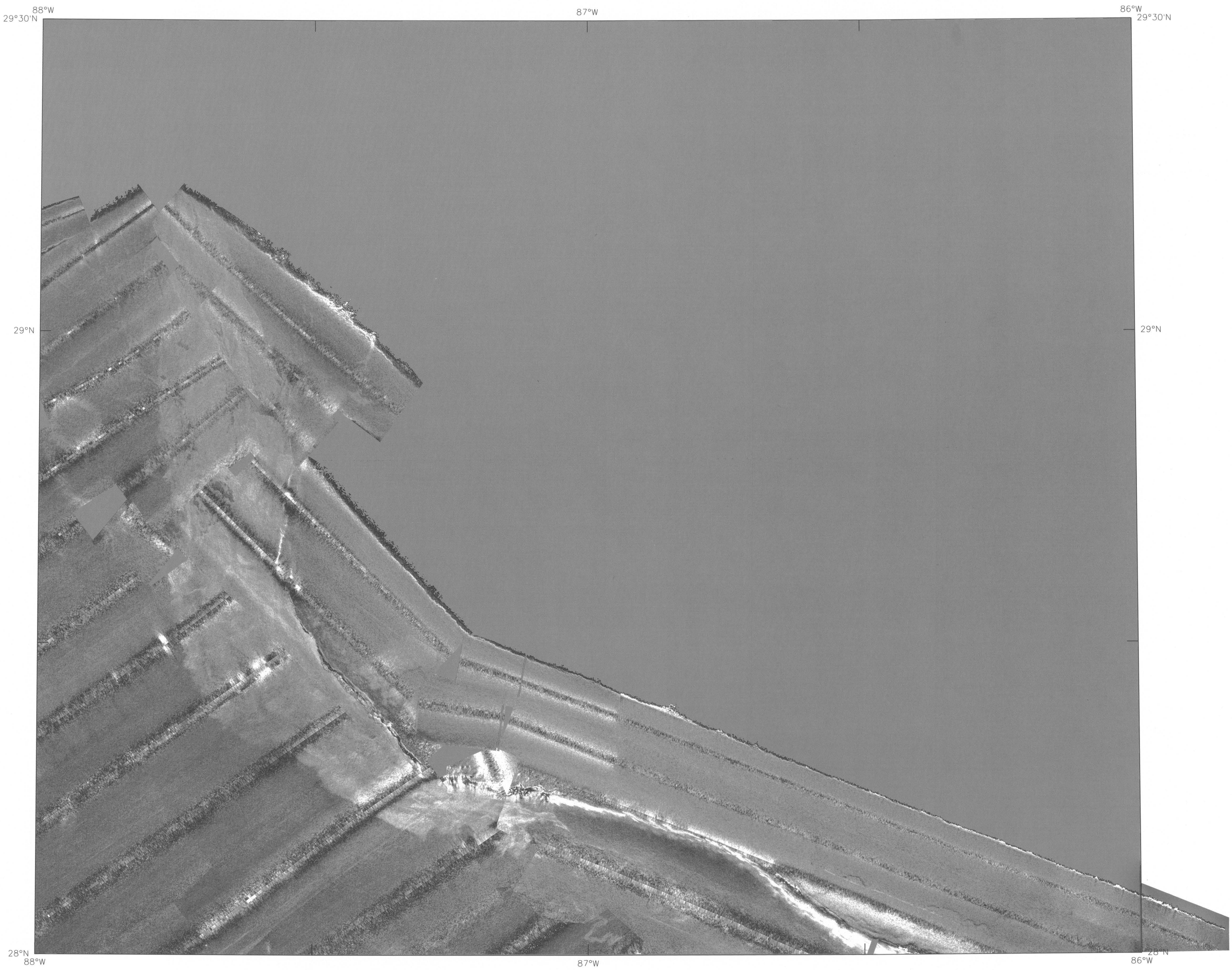
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 250 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 15



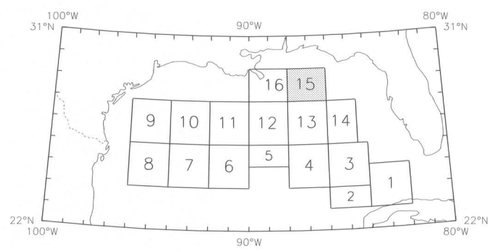
NO DATA

SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

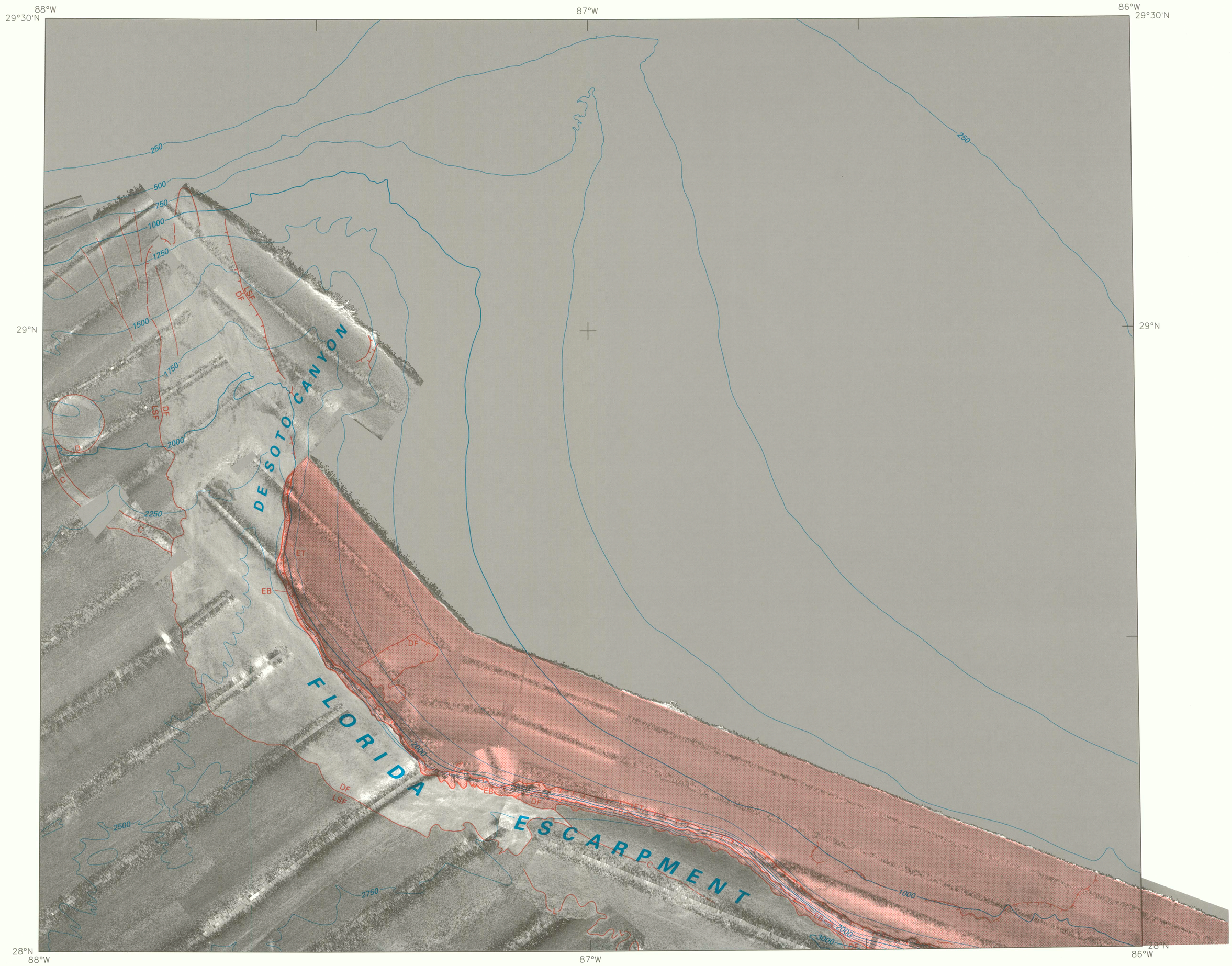
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 15
GEOLOGIC INTERPRETATION
BATHYMETRY



NO DATA

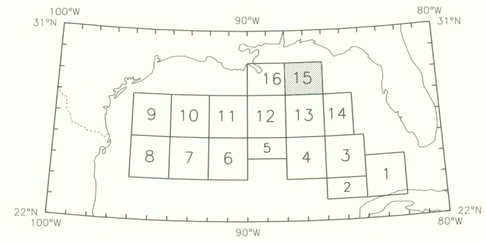
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

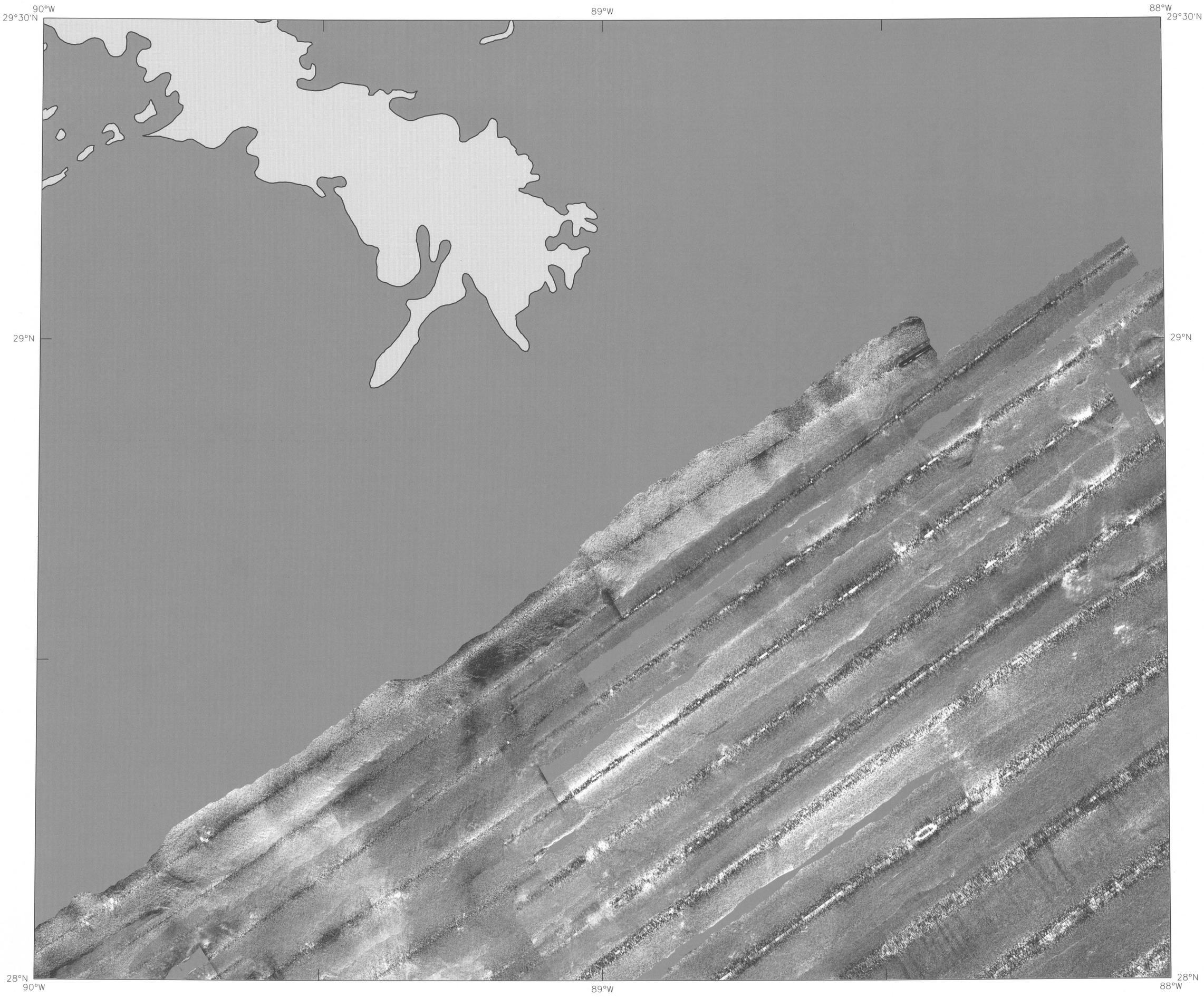
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 250 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 16



NO DATA

SCALE 1:500,000

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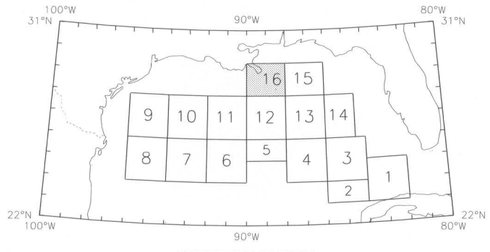
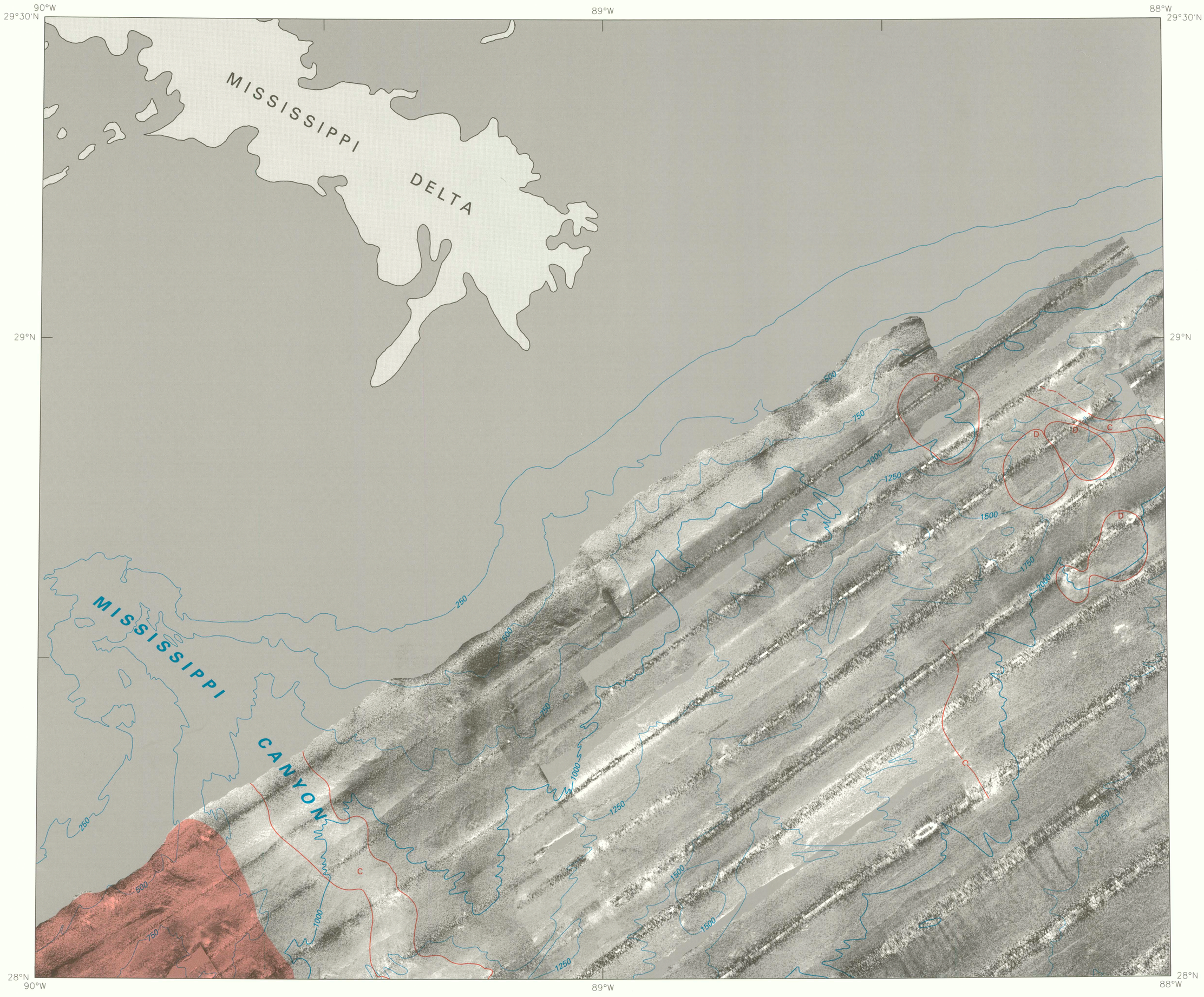
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 16
GEOLOGIC INTERPRETATION
BATHYMETRY



NO DATA

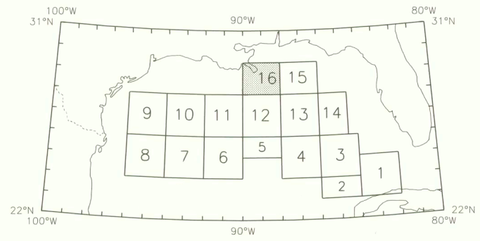
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 250 METERS



SHEET LOCATION

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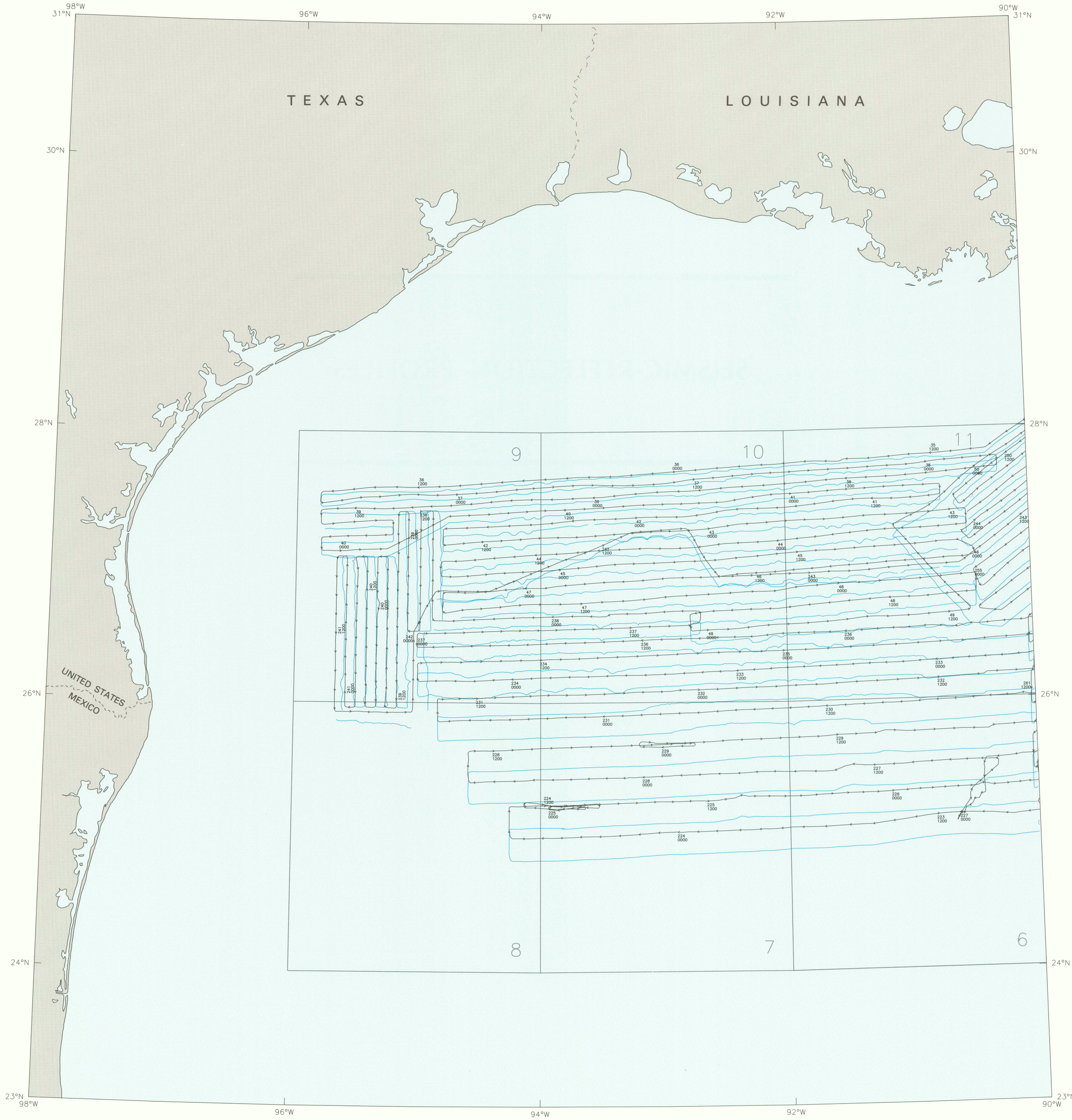
SEISMIC-REFLECTION PROFILES



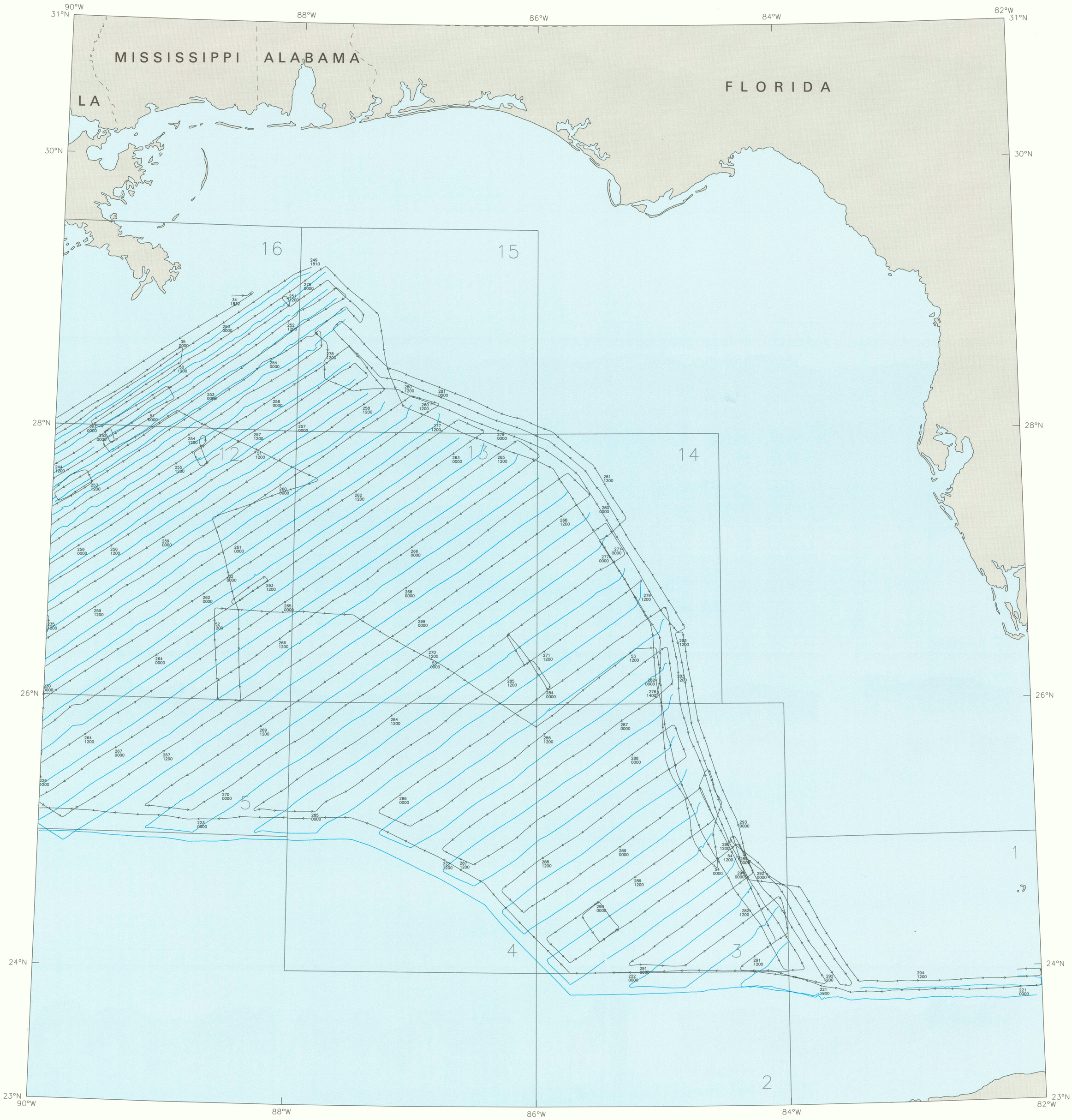
SCALE 1:2 000 000

50 0 50 100 150 NAUTICAL MILES

50 0 50 100 150 200 250 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

Map showing generalized bathymetric profiles (in blue) along tracklines in the western Gulf of Mexico. Sea-floor depth at any point along a trackline can be determined by measuring the distance from that point to the profile. Profiles are scaled so that a 1-cm offset from the trackline (sea level) represents a water depth of 4,000 m.



SCALE 1:2 000 000

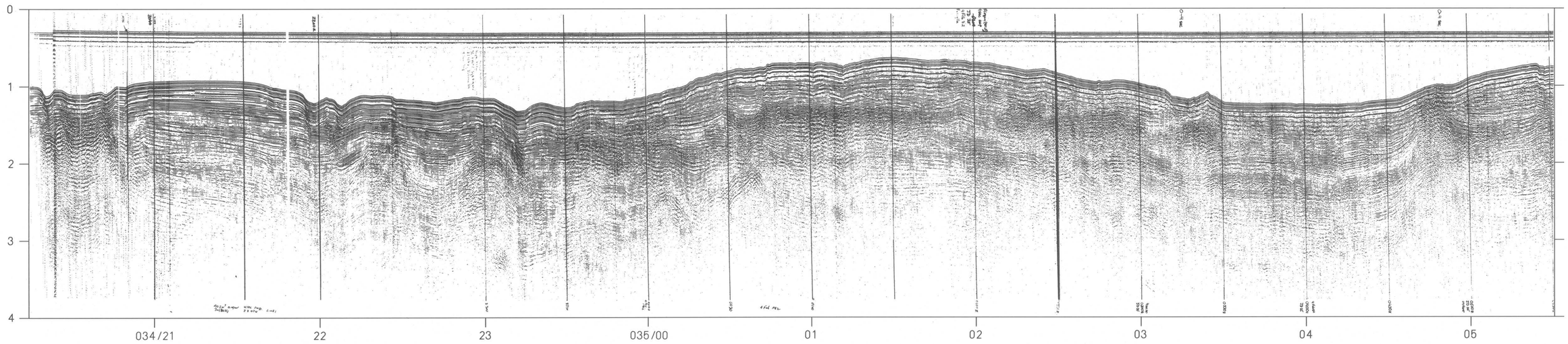
50 0 50 100 150 NAUTICAL MILES

50 0 50 100 150 200 250 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

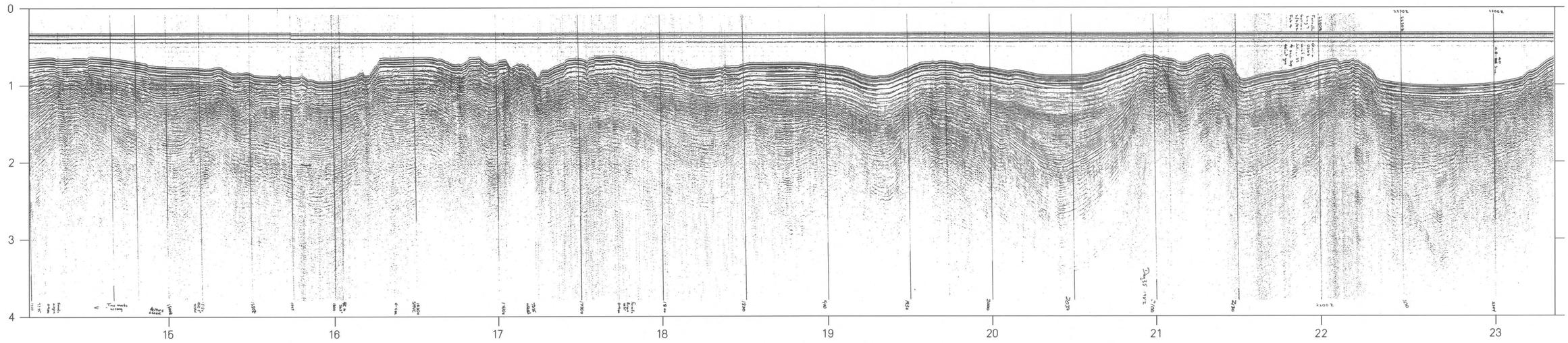
Map showing generalized bathymetric profiles (in blue) along tracklines in the eastern Gulf of Mexico. Sea-floor depth at any point along a trackline can be determined by measuring the distance from that point to the profile. Profiles are scaled so that a 1–cm offset from the trackline (sea level) represents a water depth of 4,000 m.

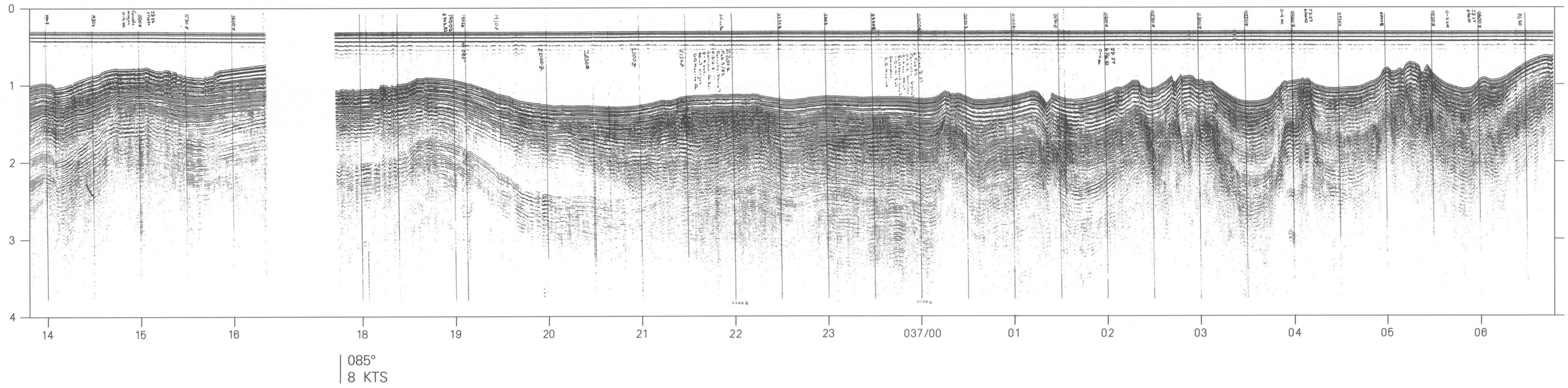
MISSISSIPPI CANYON



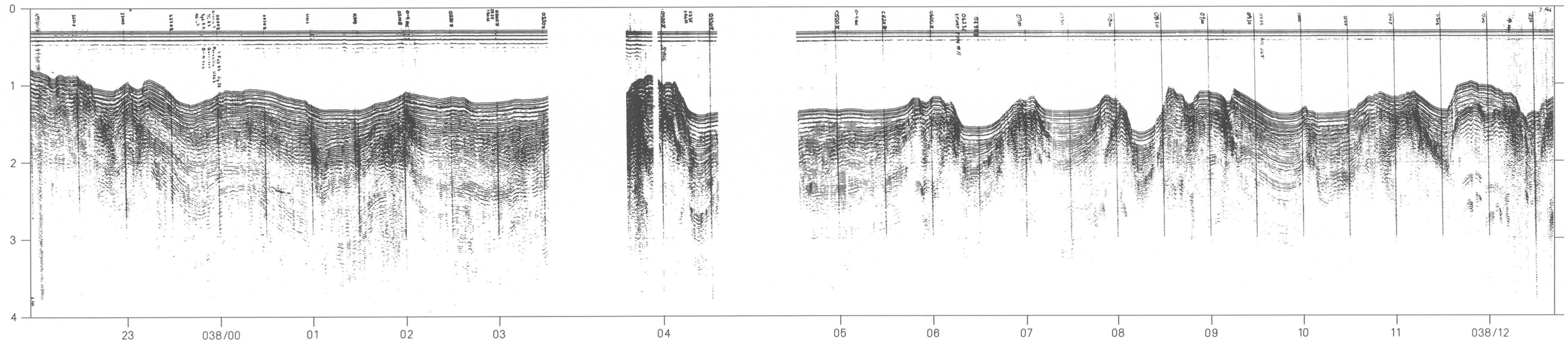
234°
8.4 KTS

TWO-WAY TRAVELTIME, IN SECONDS





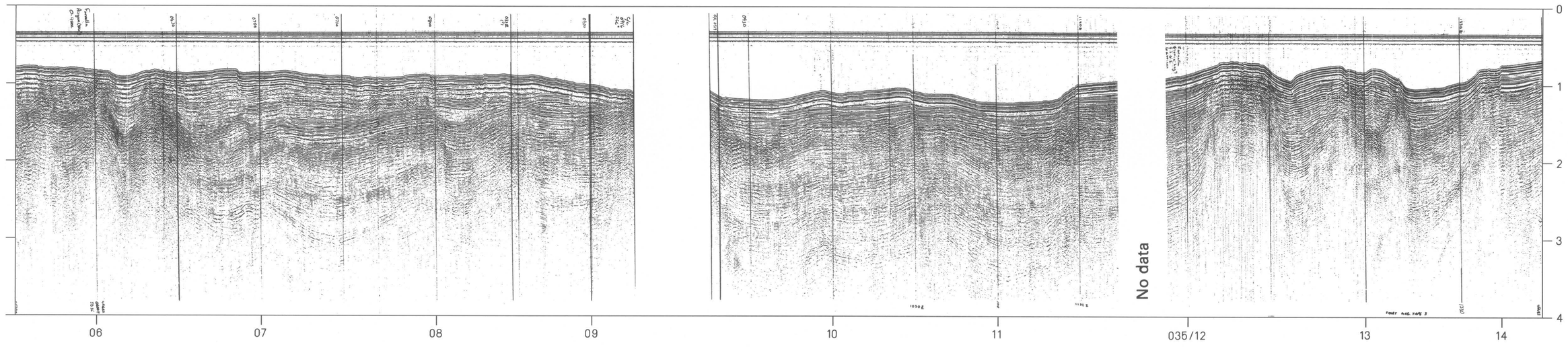
085°
8 KTS

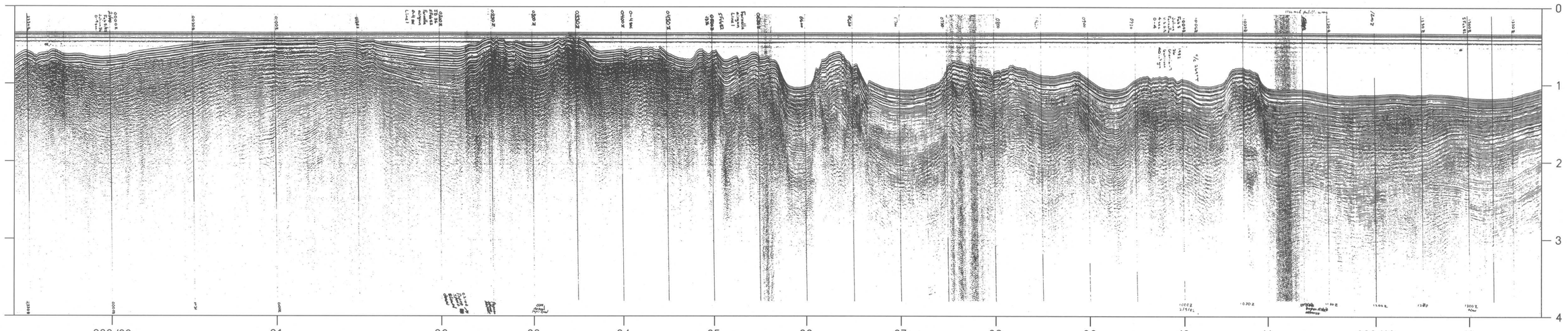


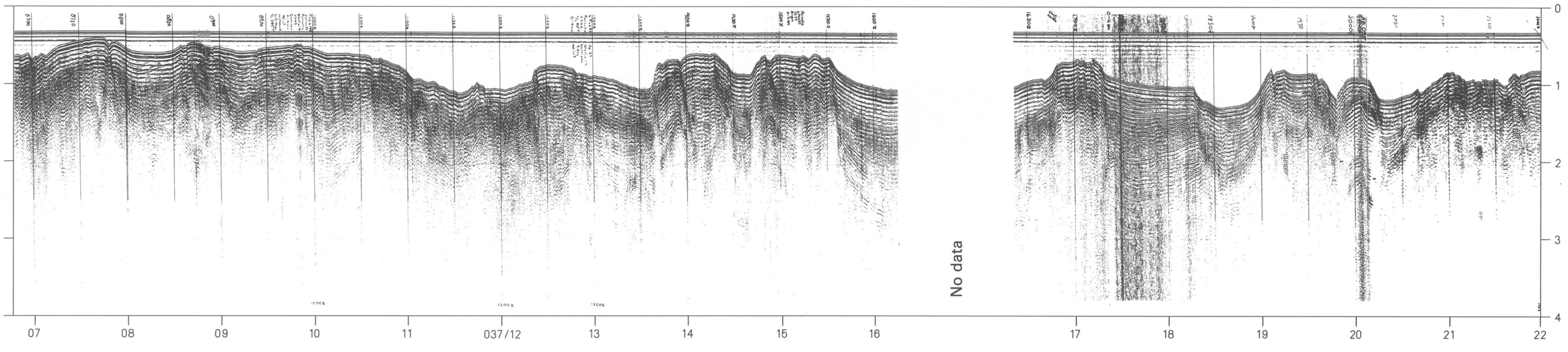
180°
8 KTS

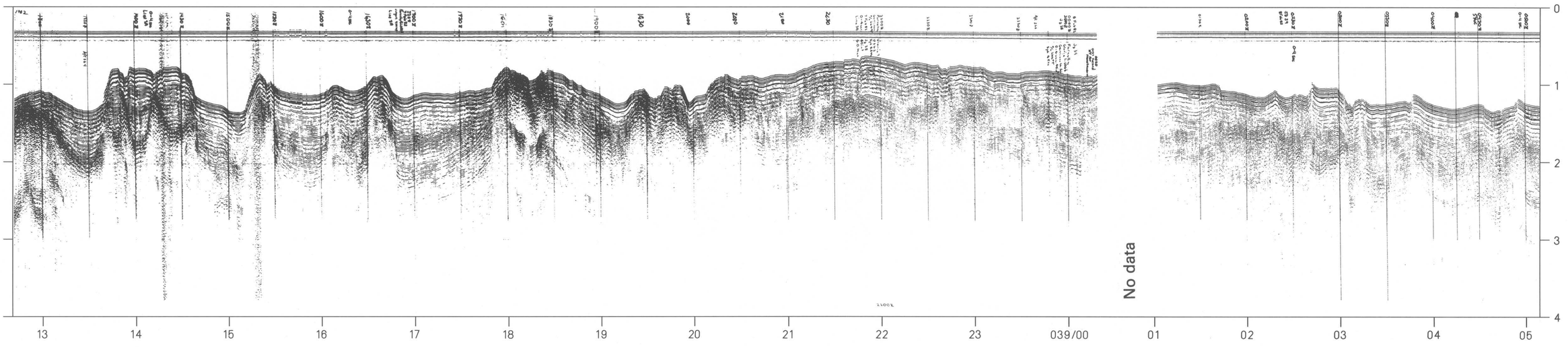
268°
8.8 KTS

HOURS





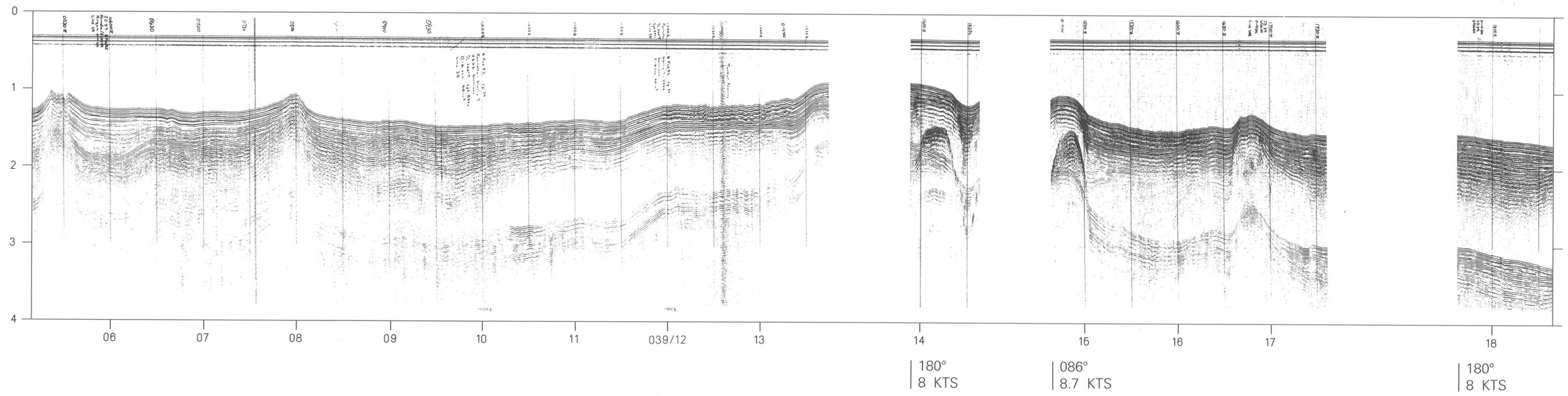


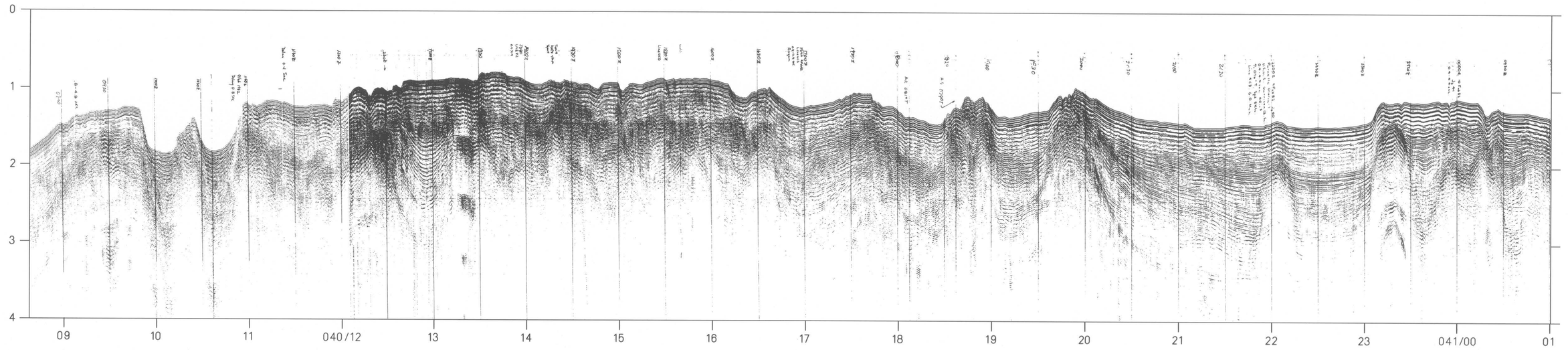


TWO-WAY TRAVELTIME, IN SECONDS

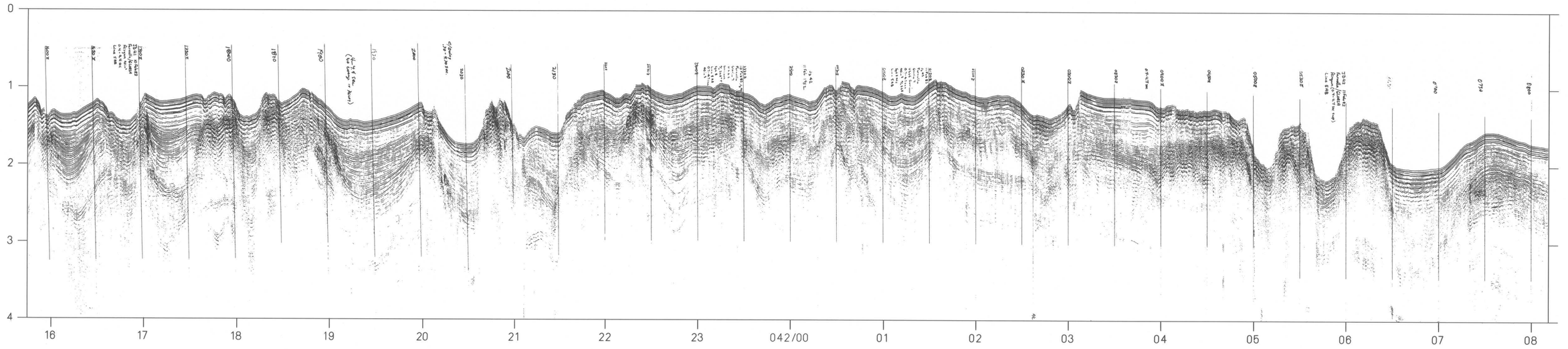
HOURS

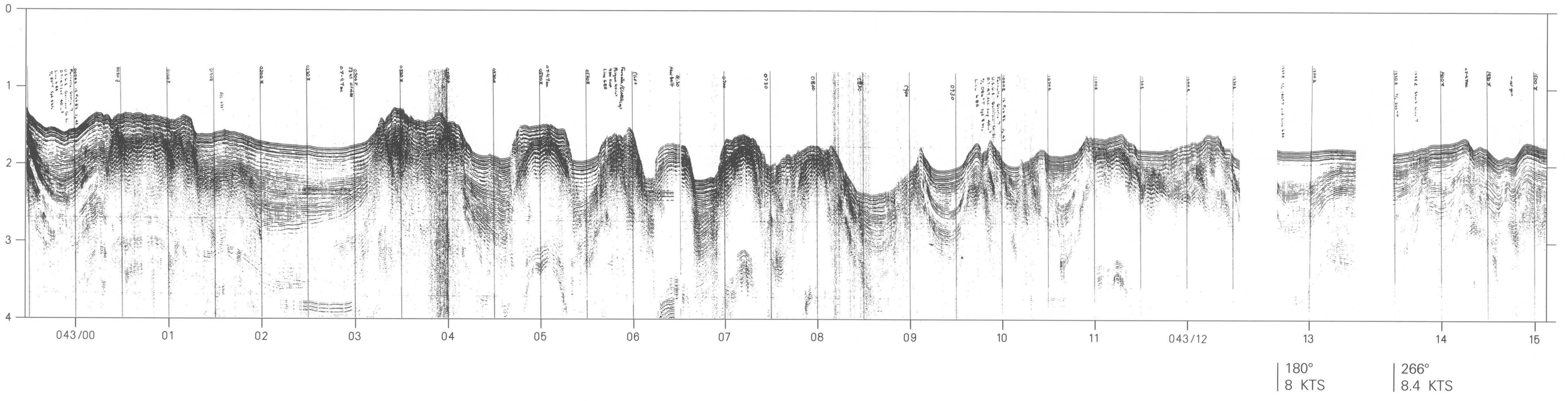
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY



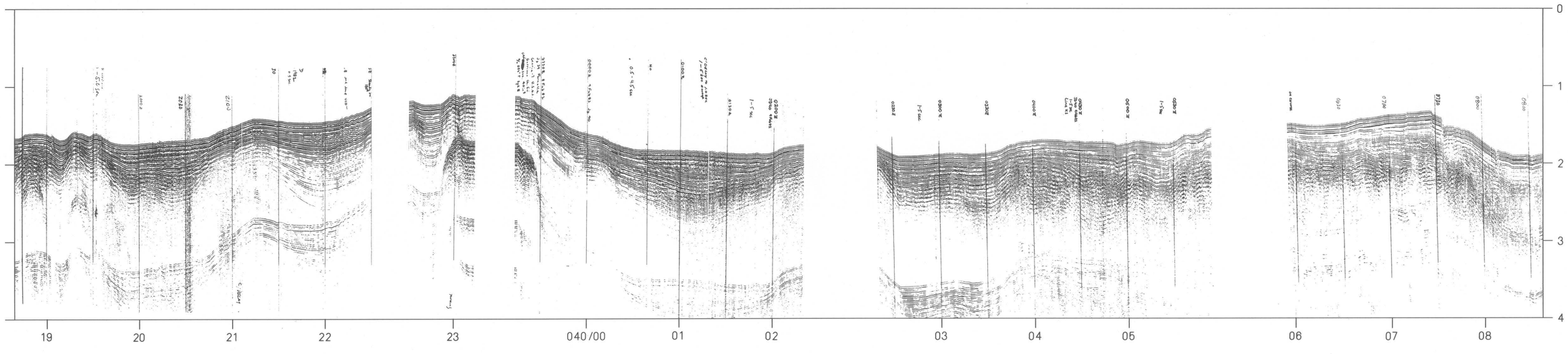


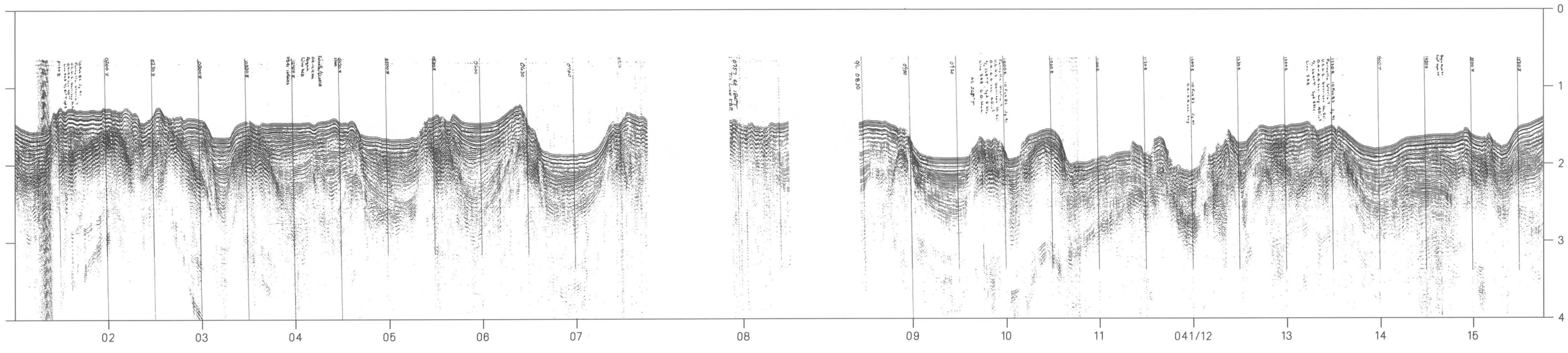
TWO-WAY TRAVELTIME, IN SECONDS

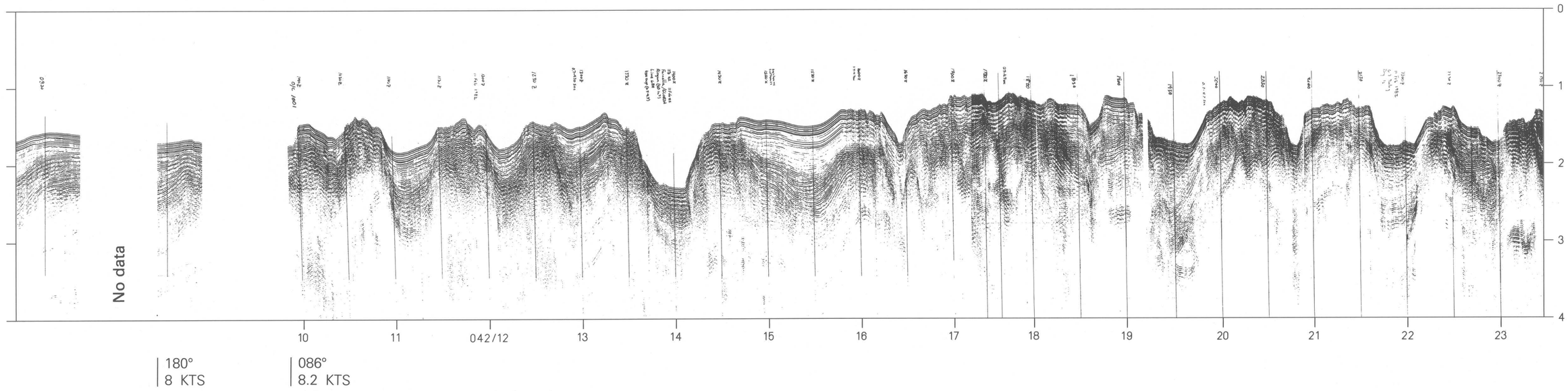


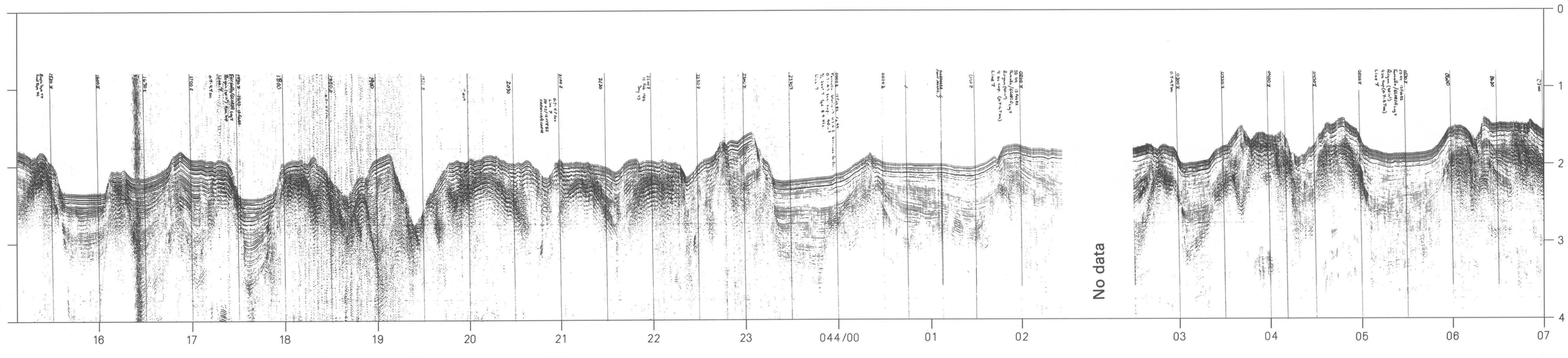


HOURS





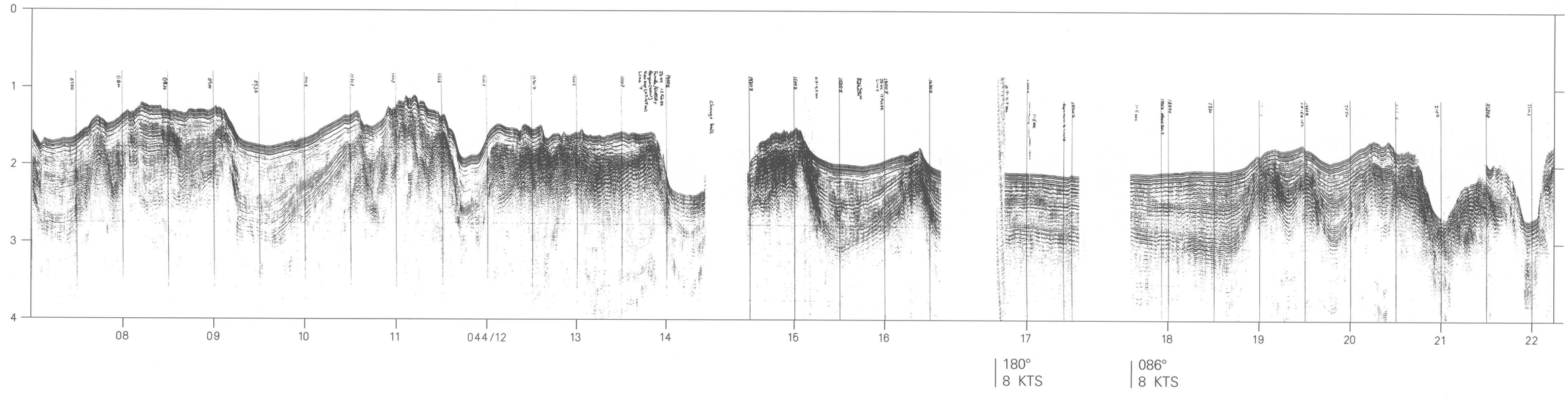




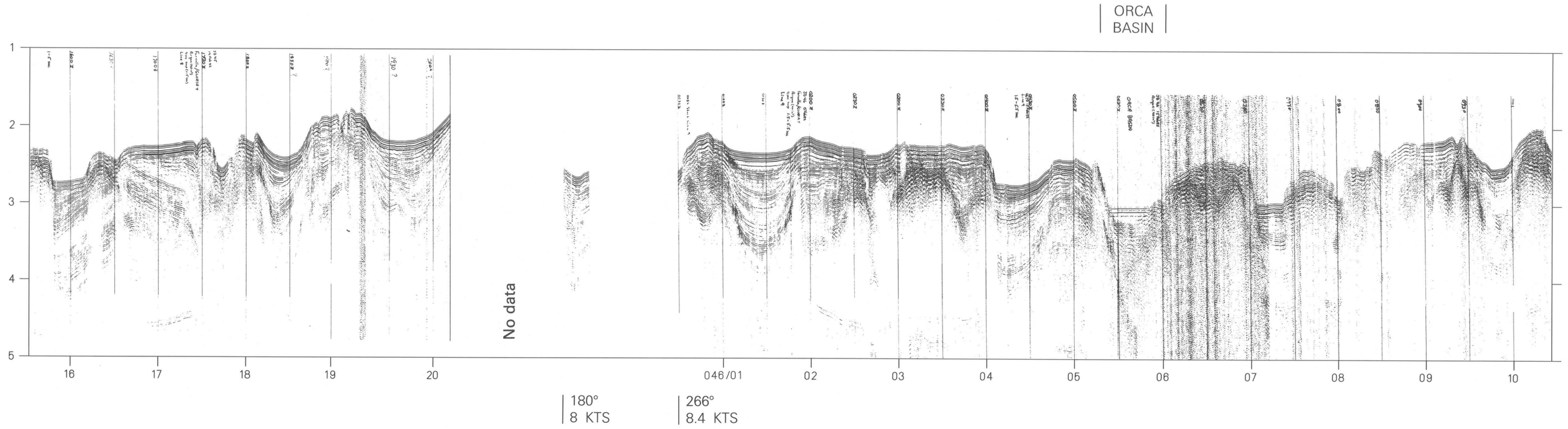
TWO-WAY TRAVELTIME, IN SECONDS

HOURS

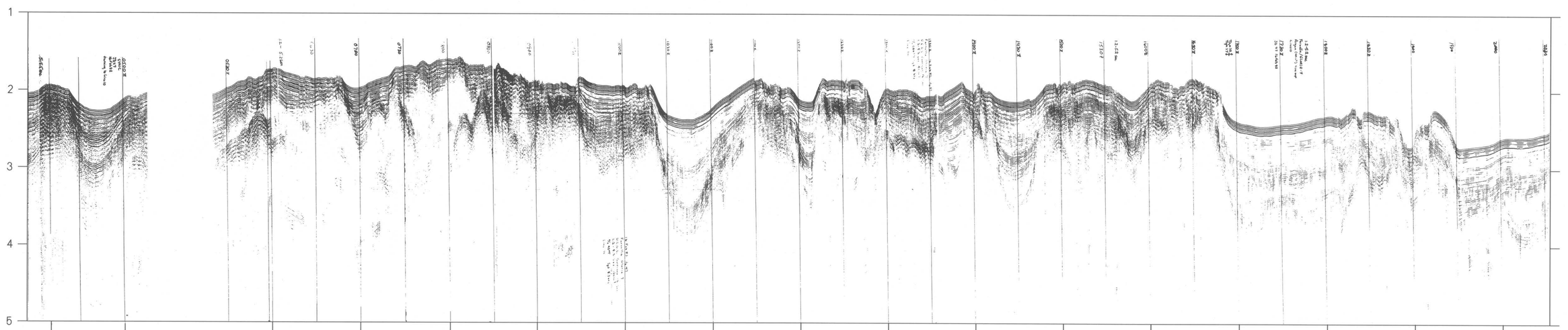
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

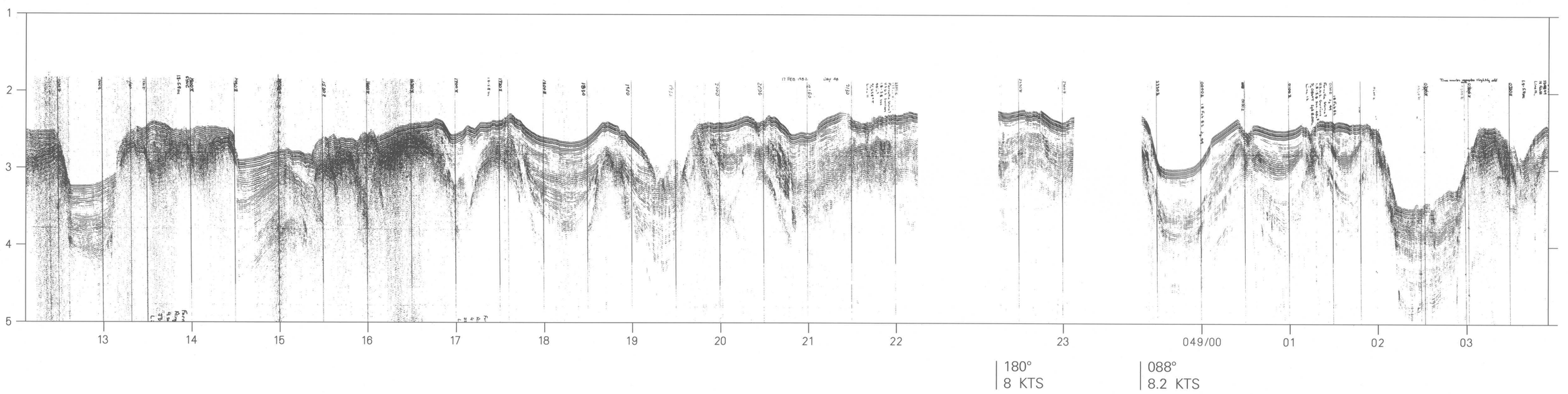


ORCA BASIN

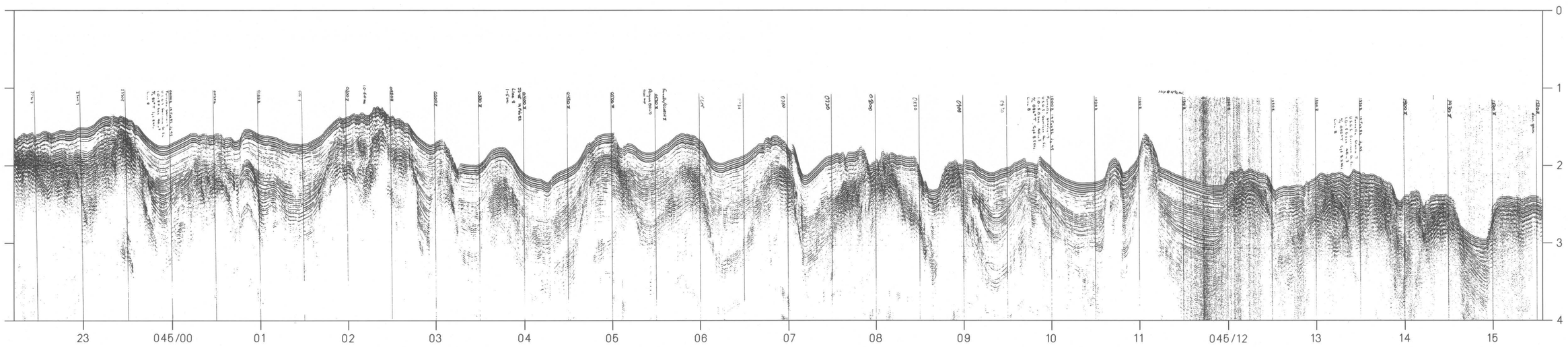


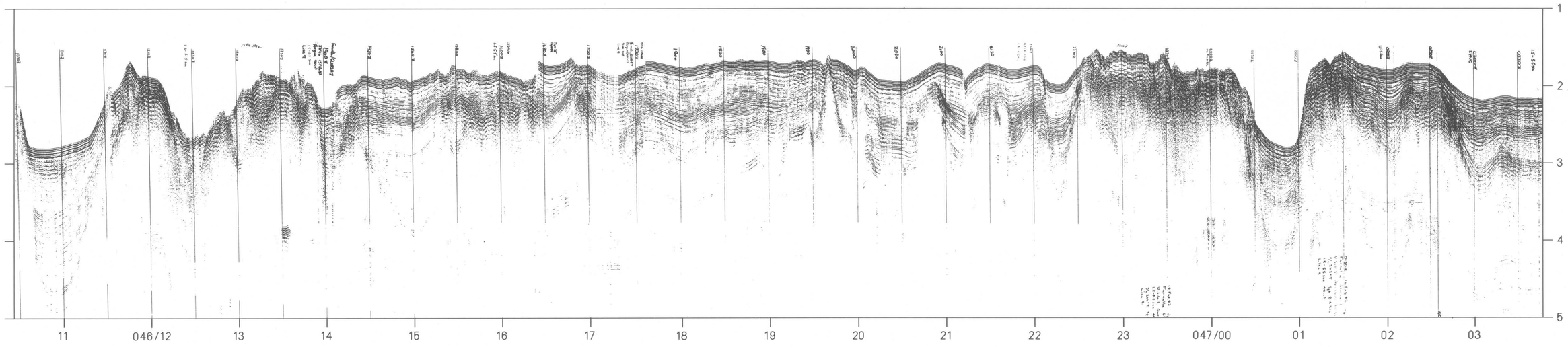
TWO-WAY TRAVELTIME, IN SECONDS

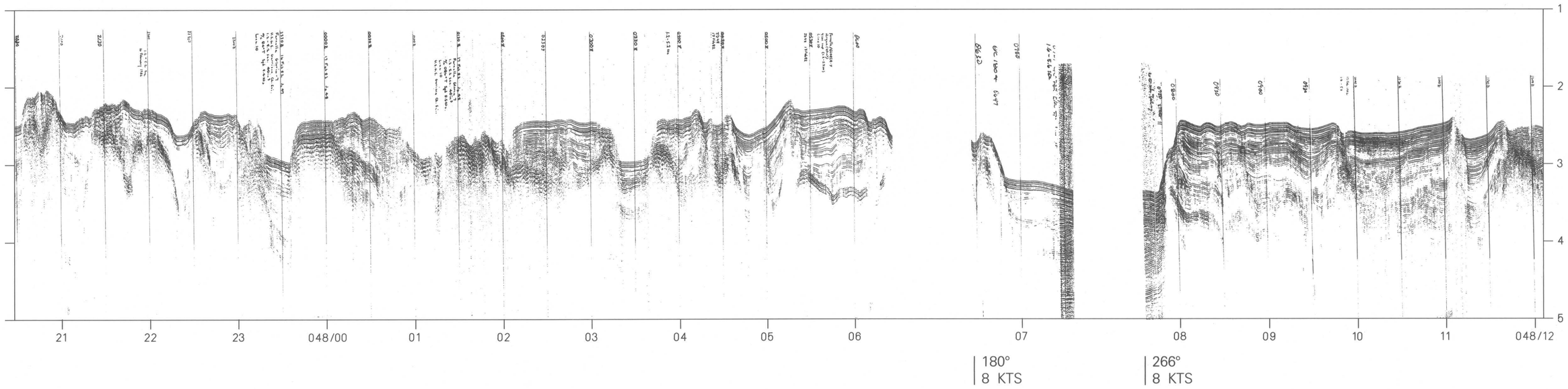


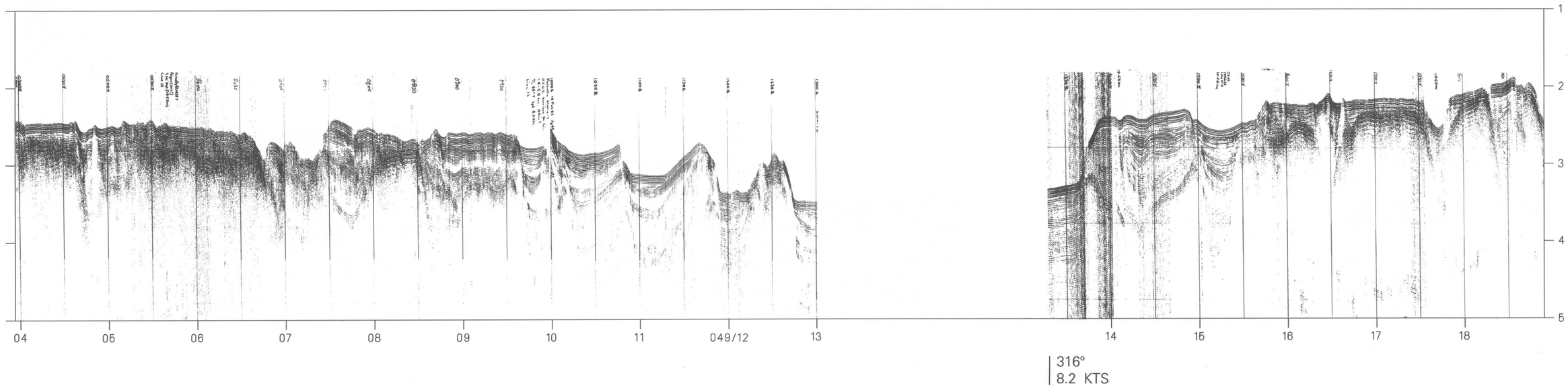


HOURS



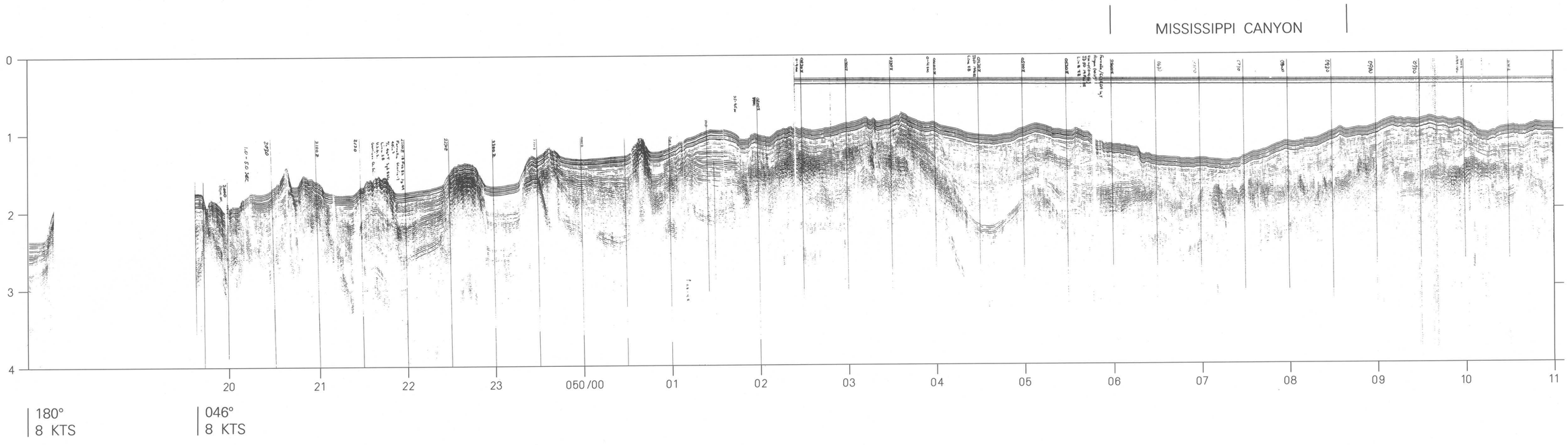






TWO-WAY TRAVELTIME, IN SECONDS

HOURS


MISSISSIPPI CANYON
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046°
8 KTS
MISSISSIPPI CANYON
MISSISSIPPI CANYON
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143°
8 KTS
046°
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112°
8 KTS
TWO-WAY TRAVELTIME, IN SECONDS
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090°
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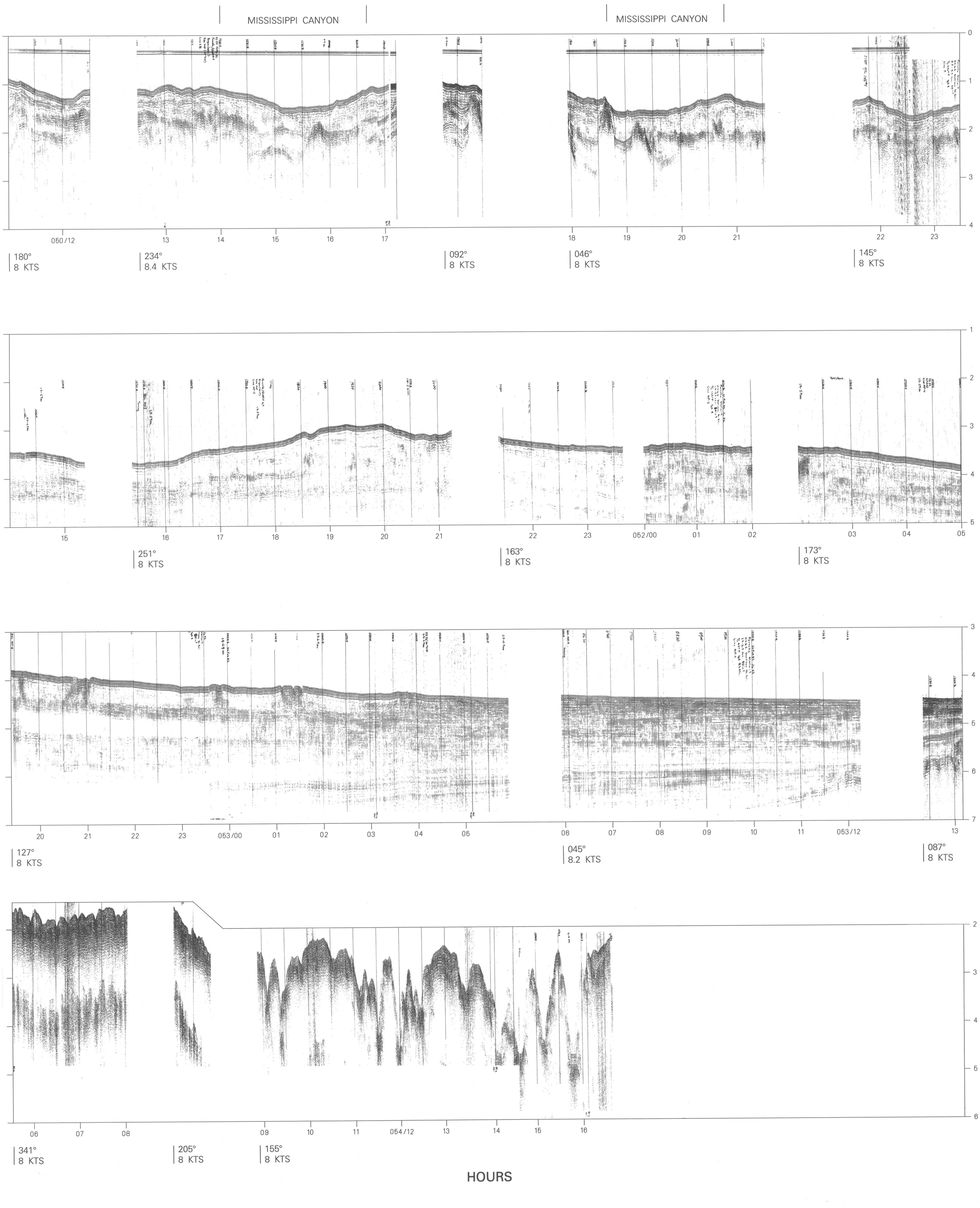
173°
8 KTS
158°
8 KTS
140°
168°
147°
129°
000°
8 KTS
014°
HOURS


MISSISSIPPI CANYON
MISSISSIPPI CANYON
050/12
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180°
8 KTS
234°
8.4 KTS
092°
8 KTS
046°
8 KTS
145°
8 KTS
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251°
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173°
8 KTS
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127°
8 KTS
045°
8.2 KTS
087°
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054/12
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341°
8 KTS
205°
8 KTS
155°
8 KTS
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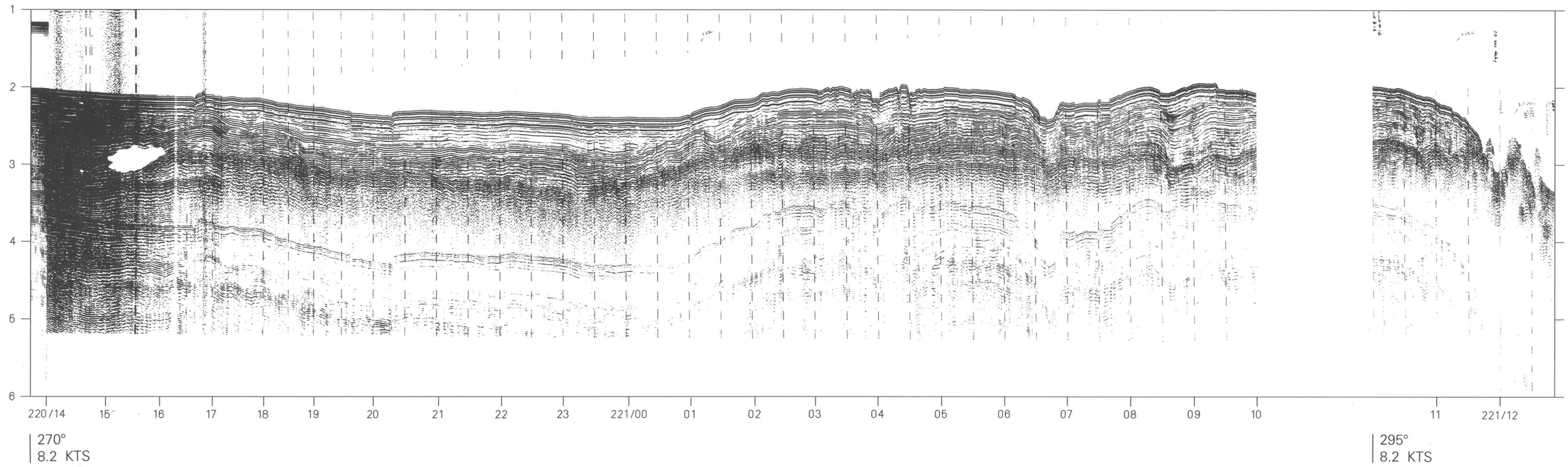
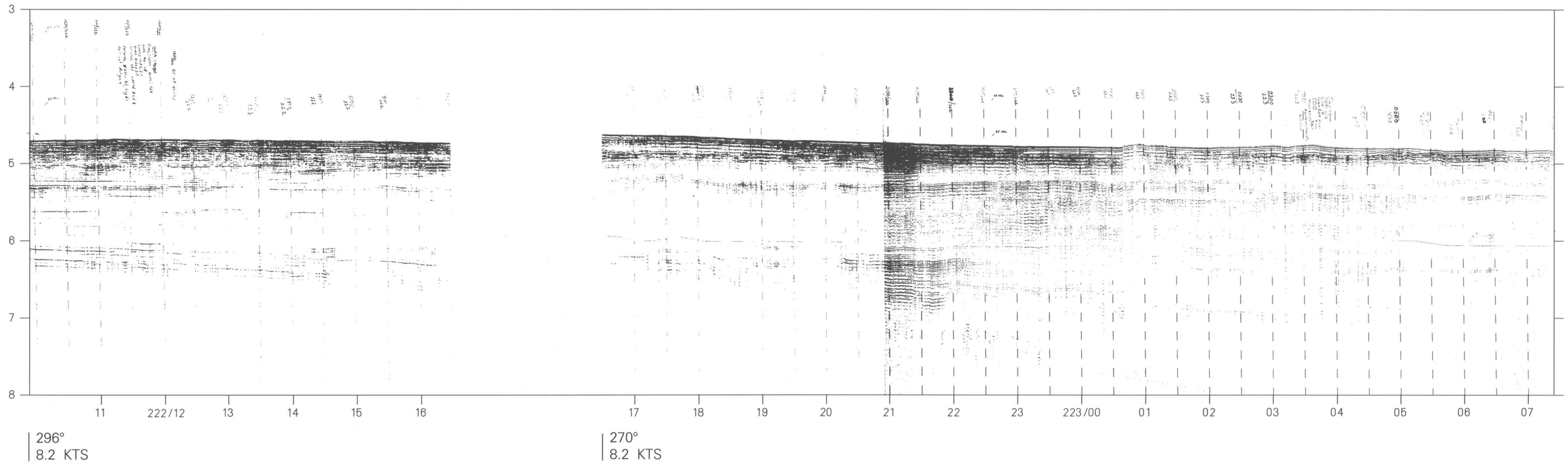
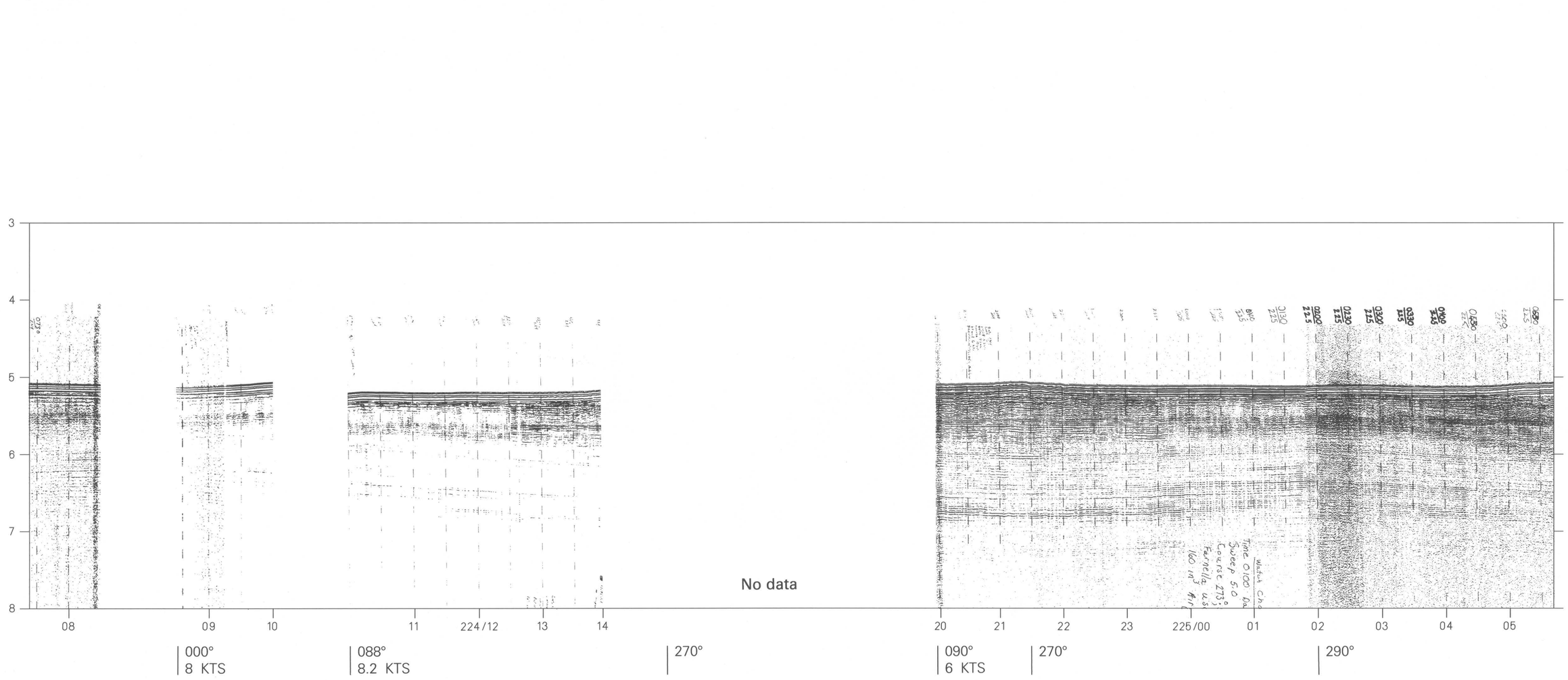
TWO-WAY TRAVELTIME, IN SECONDS
HOURS

DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

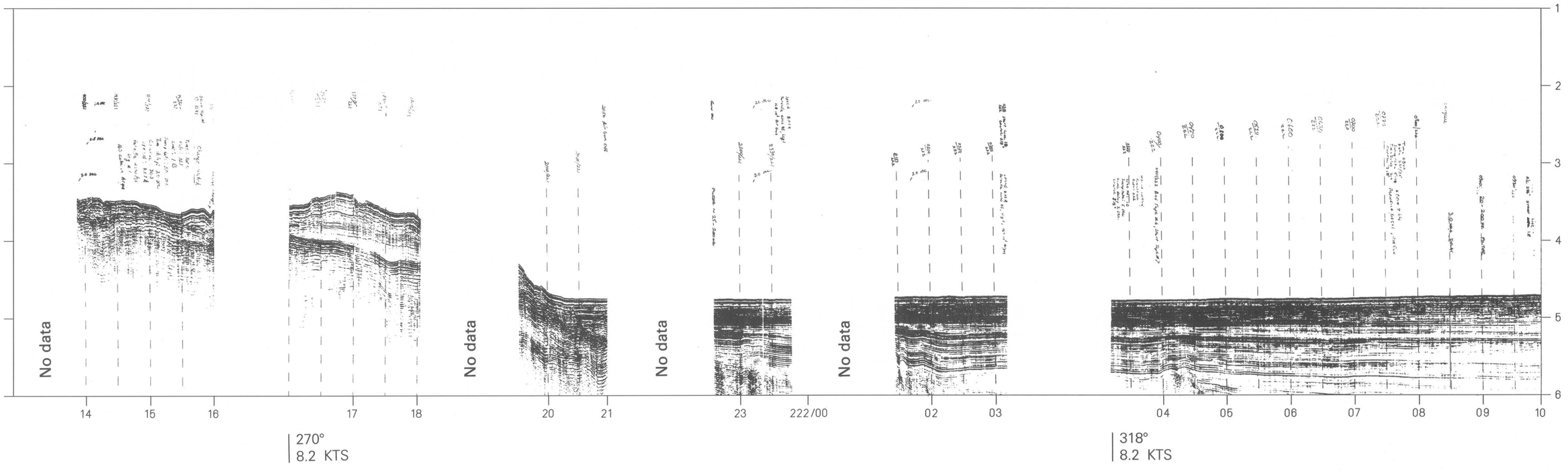


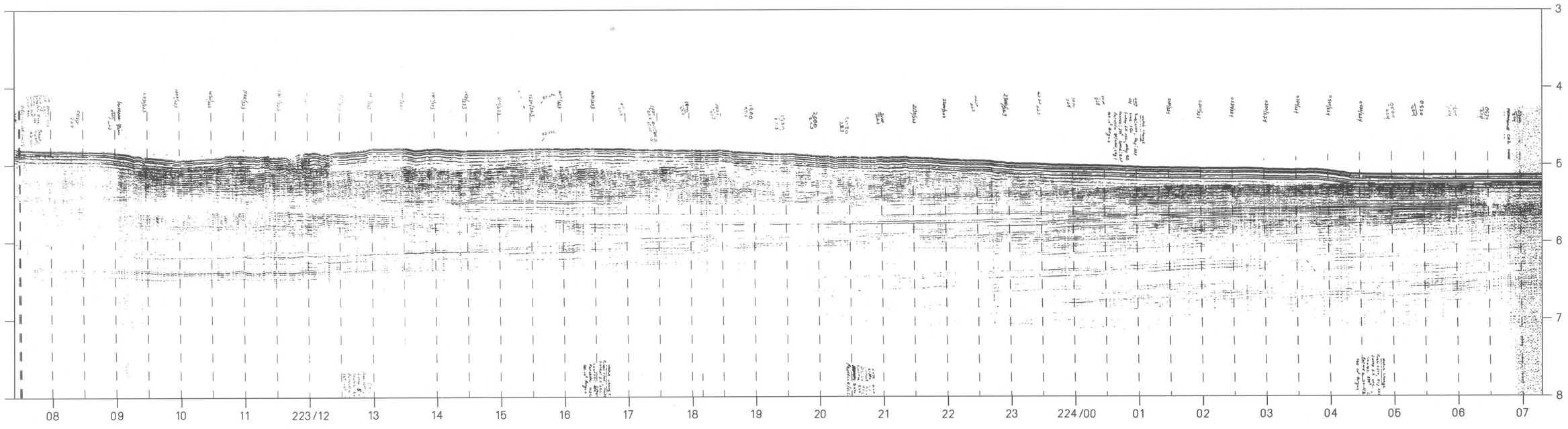
TWO-WAY TRAVELTIME, IN SECONDS



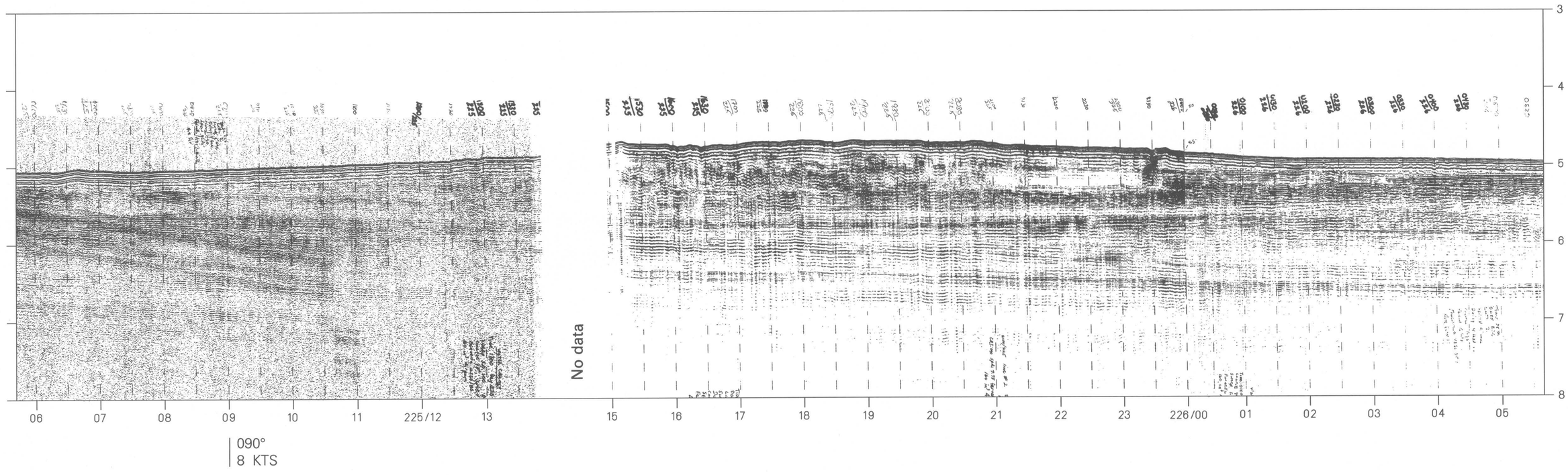


HOURS

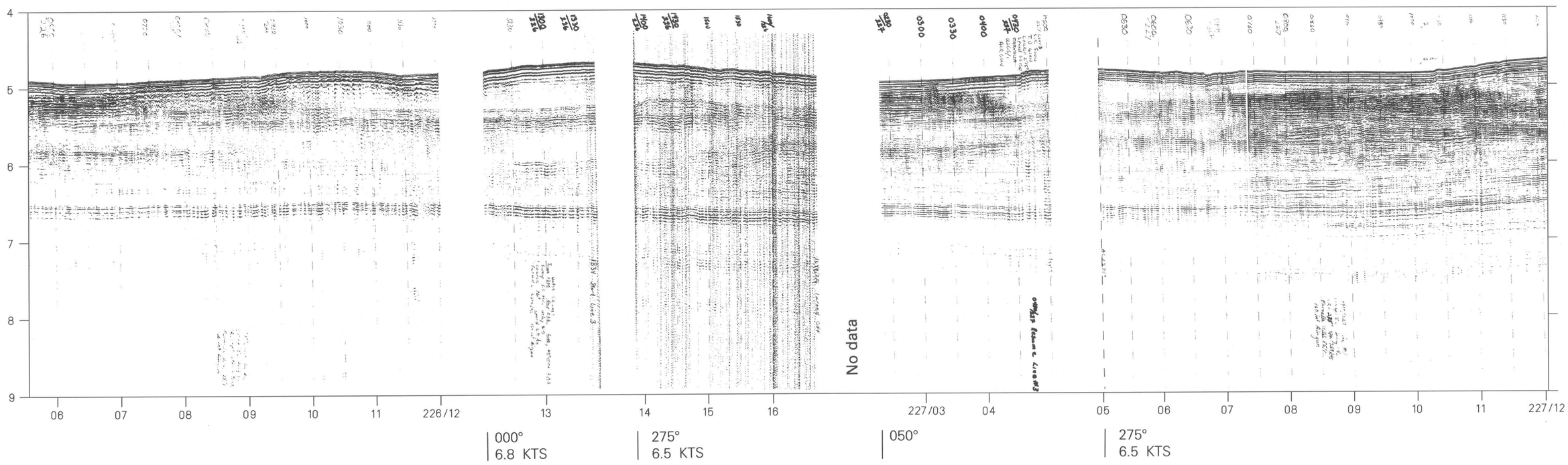




TWO-WAY TRAVELTIME, IN SECONDS



HOURS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226/12
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000°
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275°
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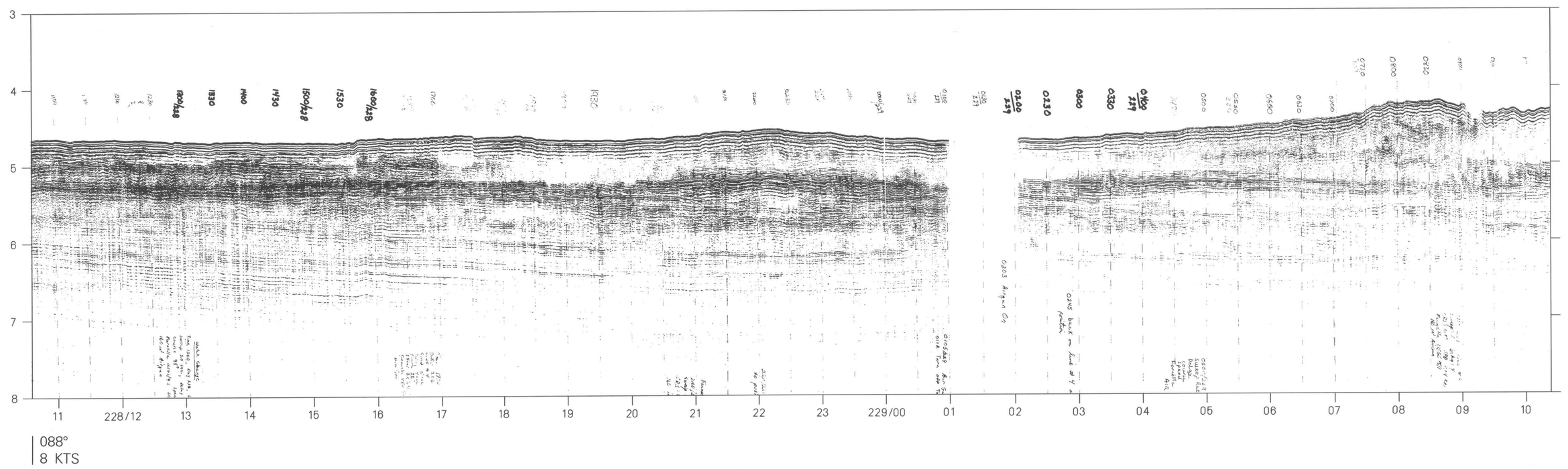
050°
275°
6.5 KTS


TWO-WAY TRAVELTIME, IN SECONDS
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228/12
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229/00
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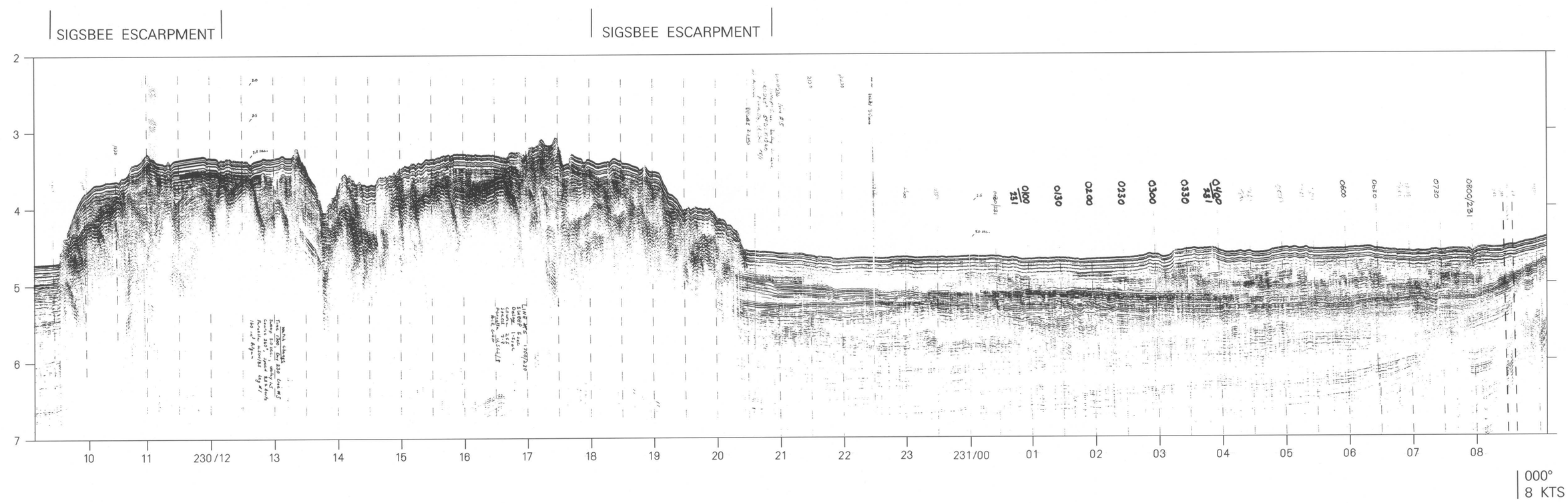
088°
8 KTS


SIGSBEE ESCARPMENT
SIGSBEE ESCARPMENT
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230/12
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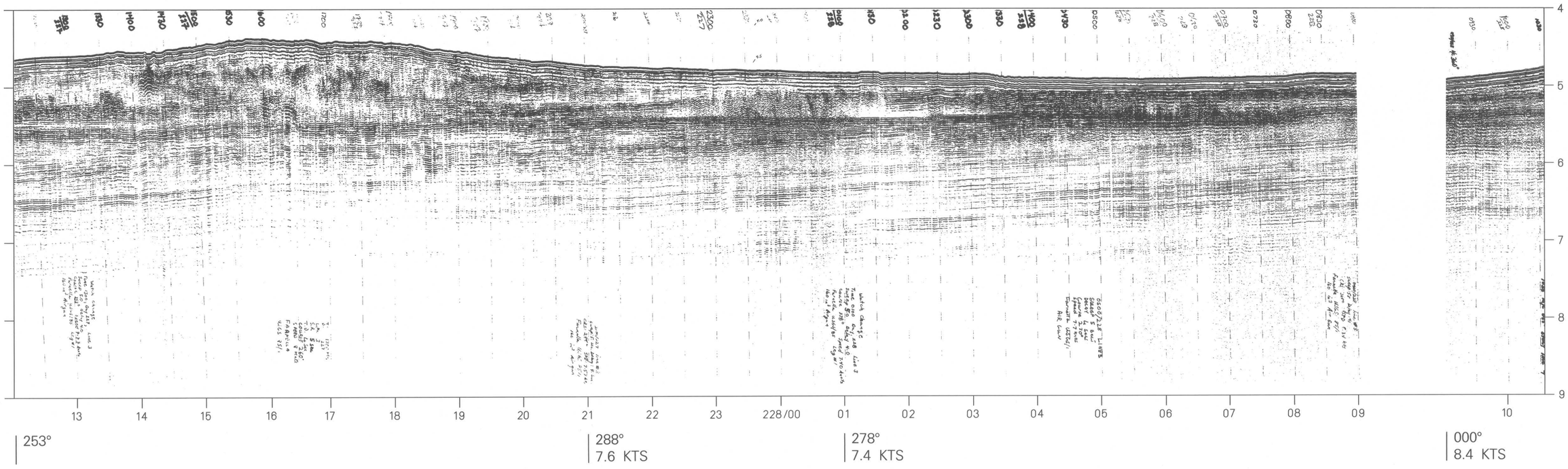
HOURS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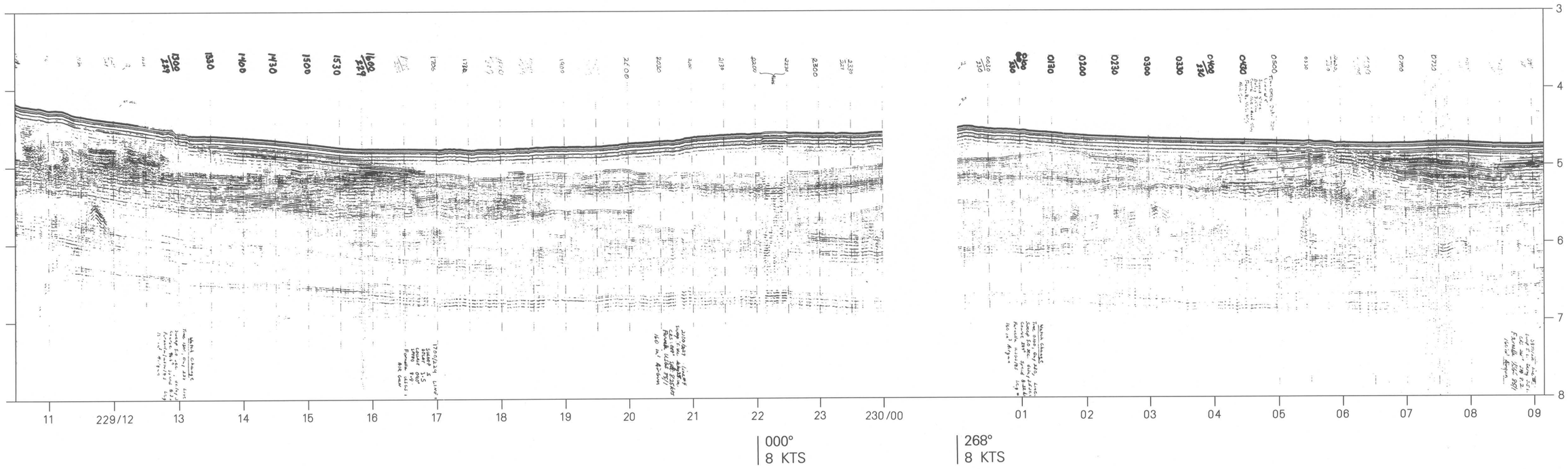
288°
7.6 KTS
278°
7.4 KTS
000°
8.4 KTS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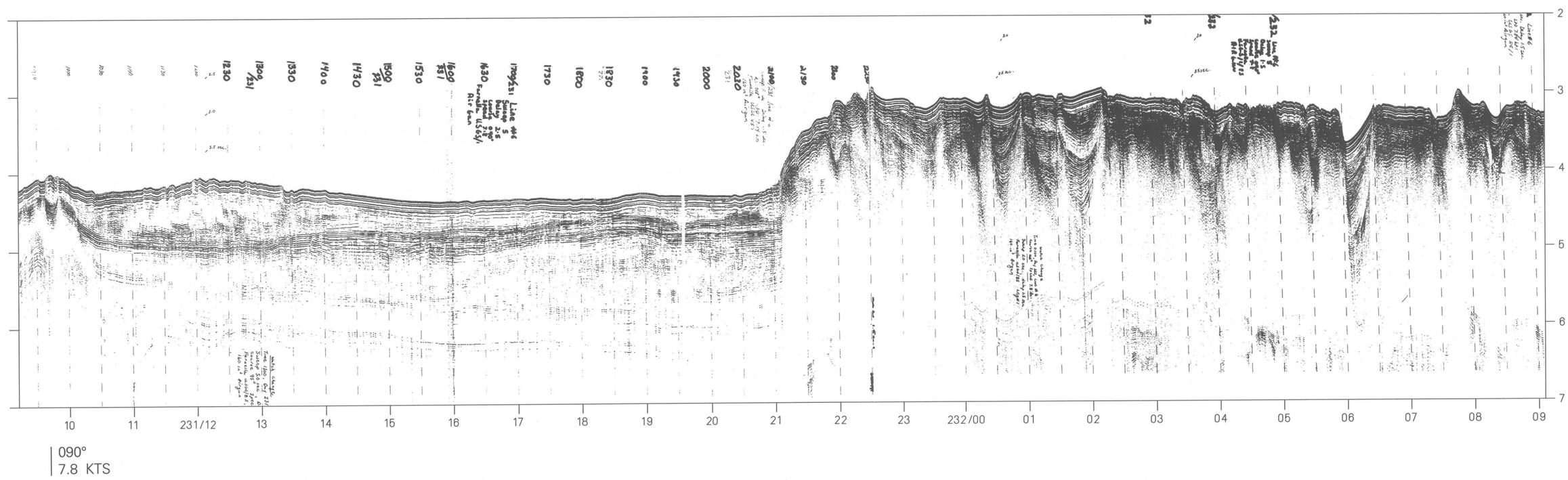
268°
8 KTS
TWO-WAY TRAVELTIME, IN SECONDS


SIGSBEE
ESCARPMENT
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232/00
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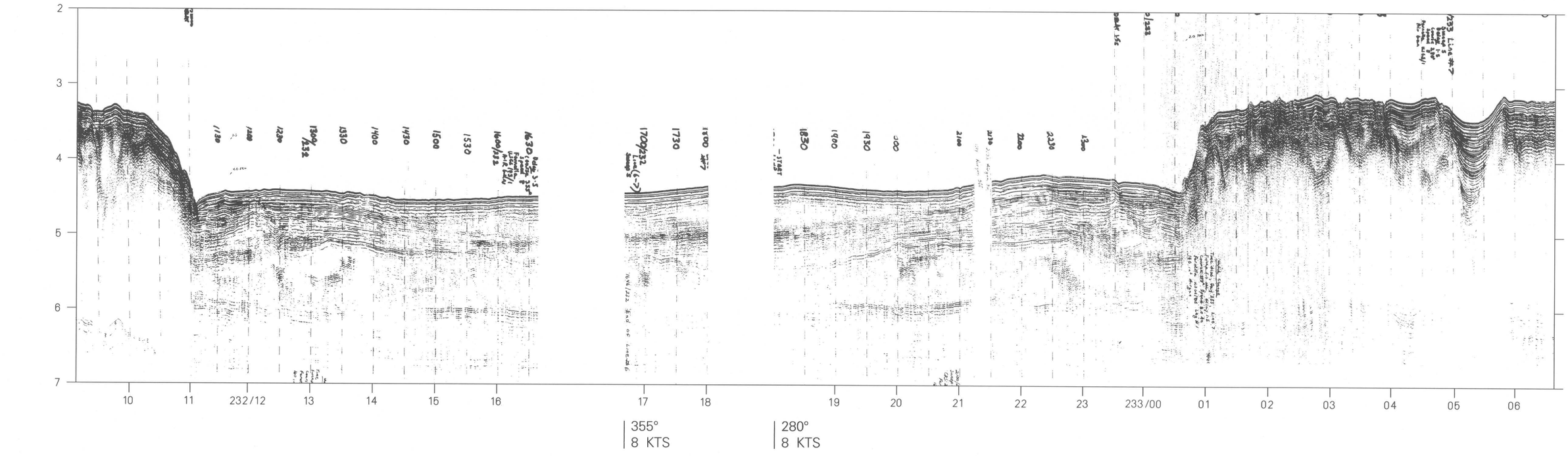
090°
7.8 KTS
HOURS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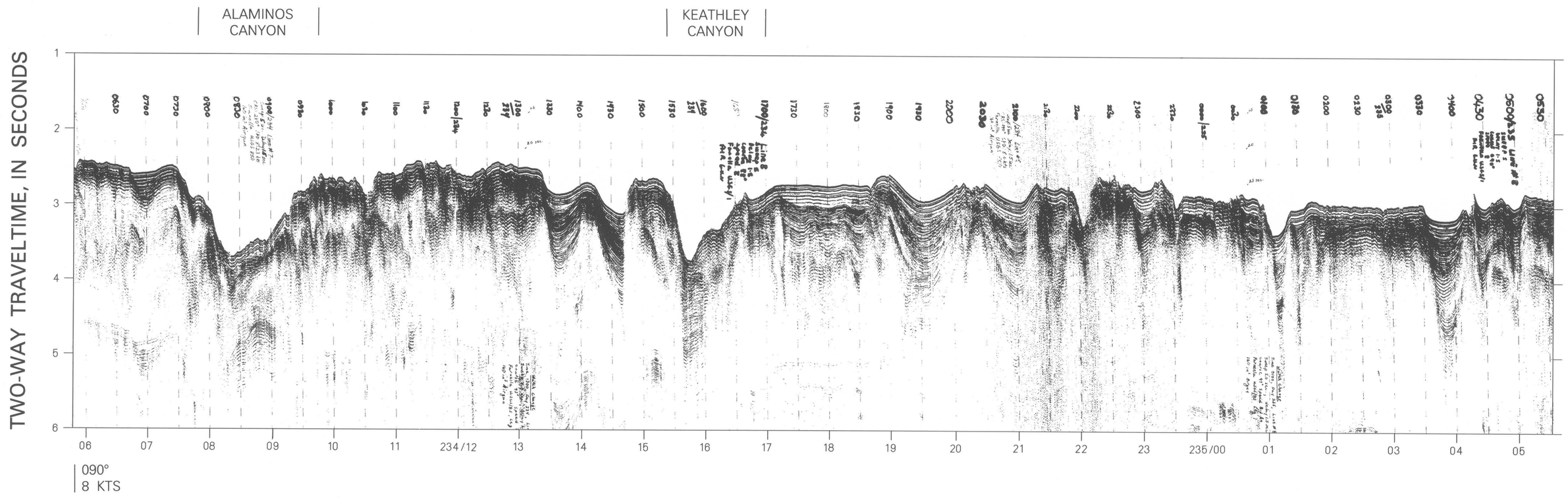
280°
8 KTS


ALAMINOS
CANYON
KEATHLEY
CANYON
TWO-WAY TRAVELTIME, IN SECONDS
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234/12
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235/00
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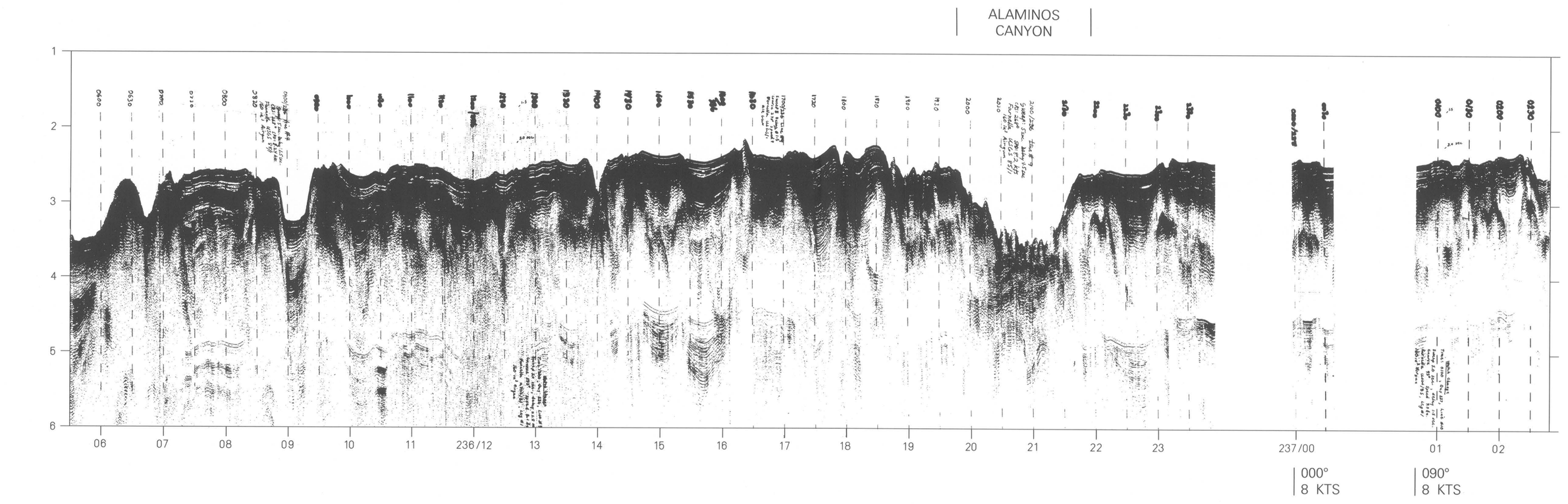
ALAMINOS
CANYON
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8 KTS
090°
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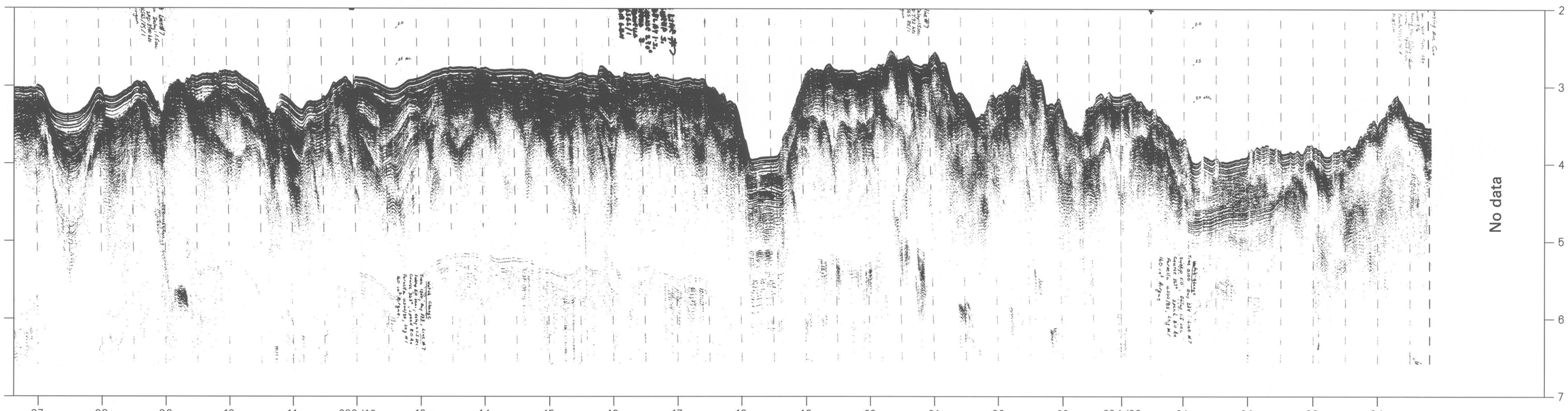
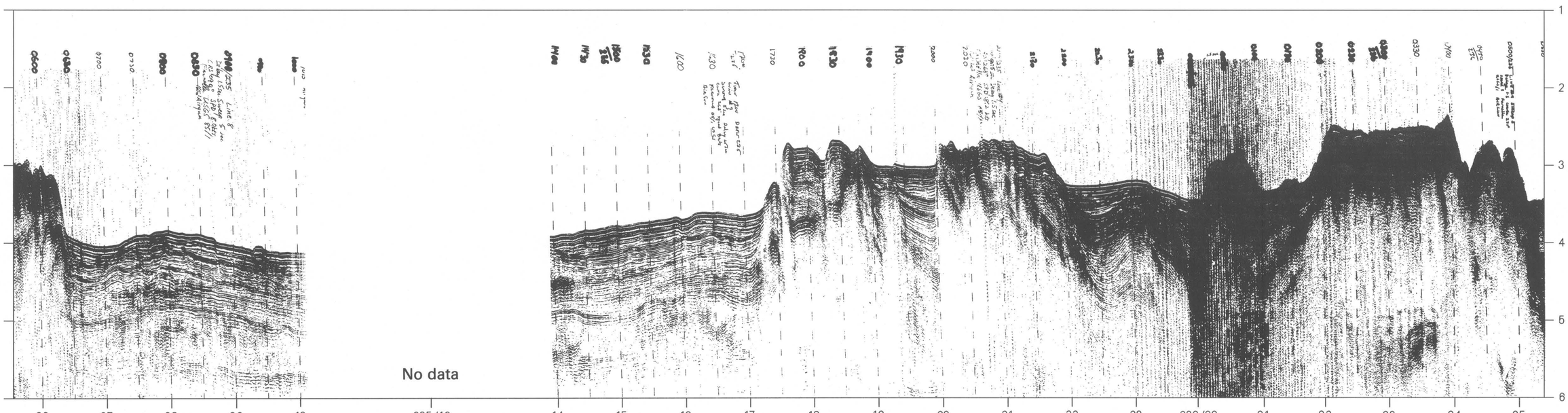
HOURS

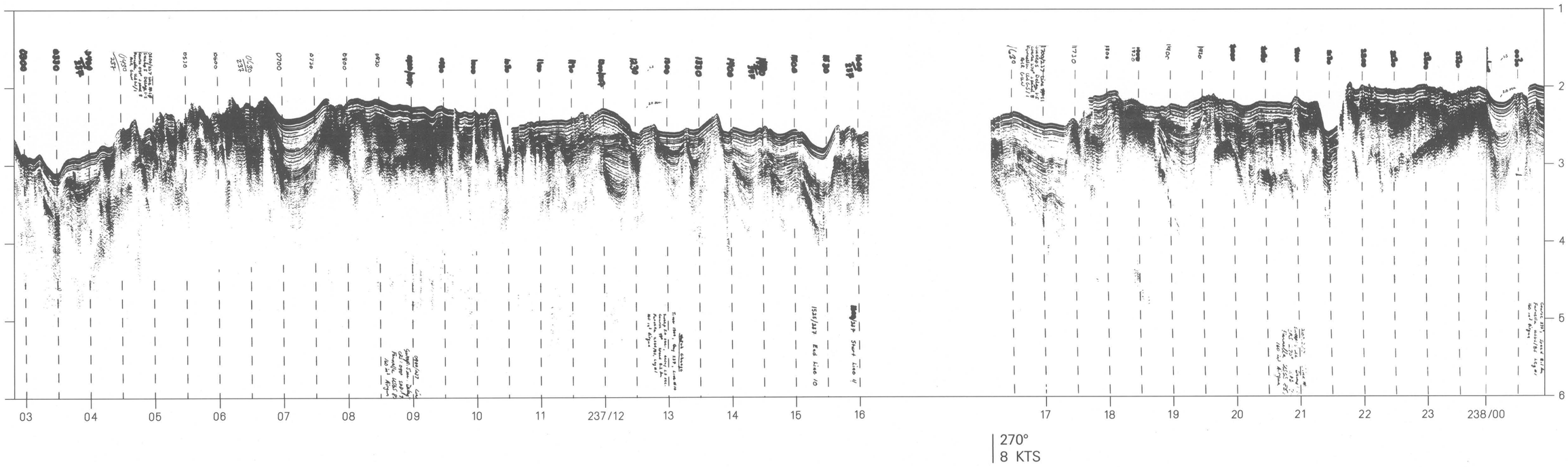
KEATHLEY CANYON

ALAMINOS CANYON



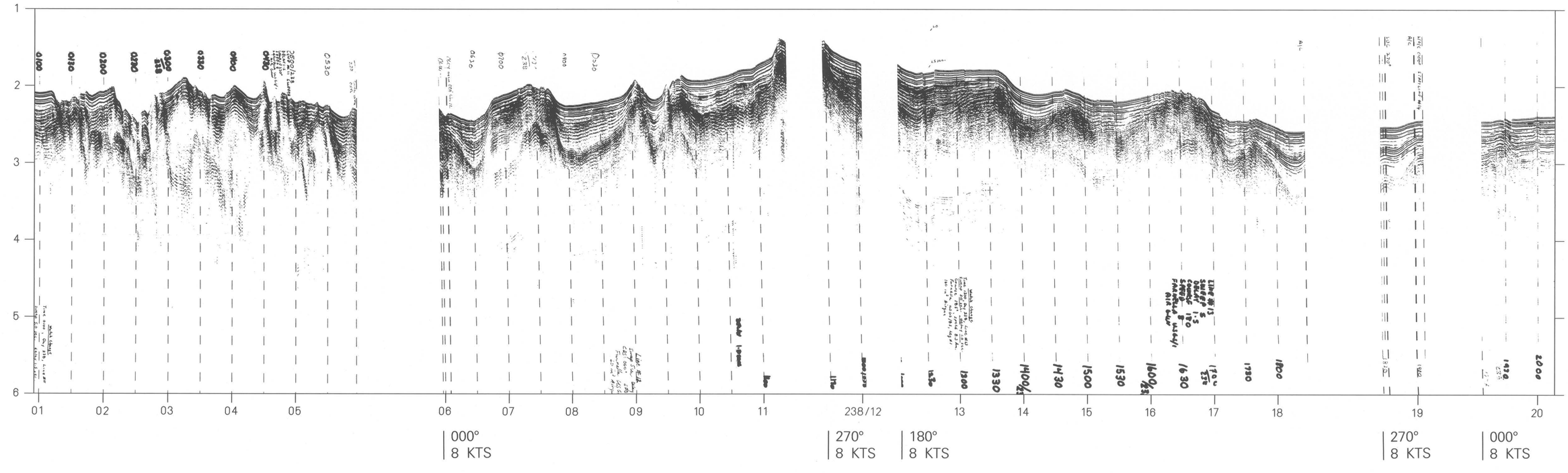


ALAMINOS CANYON

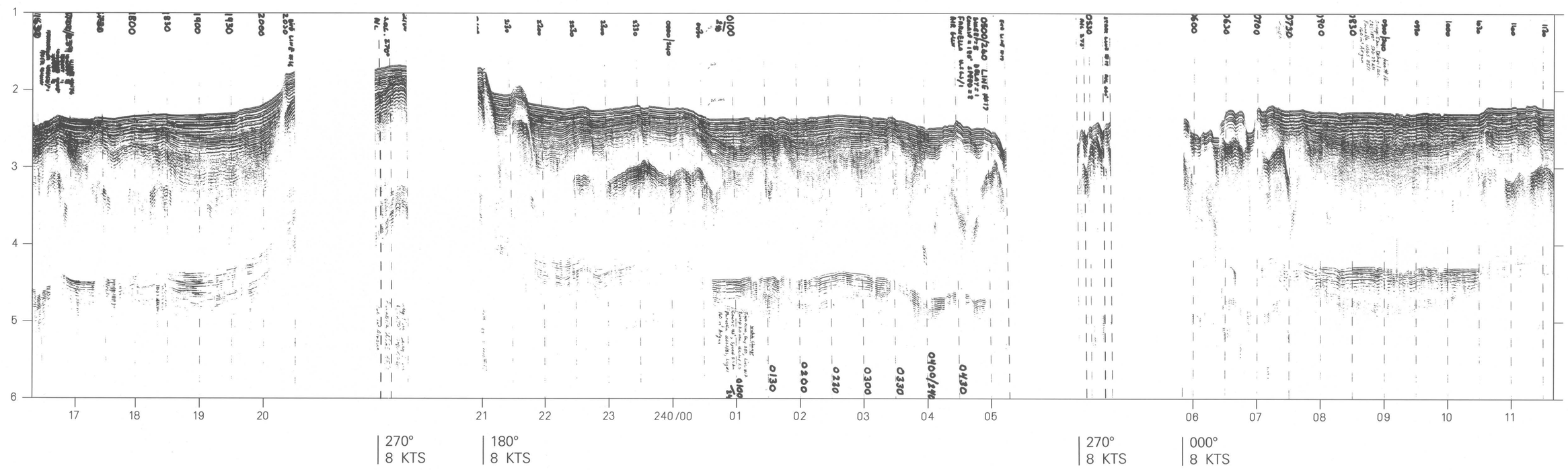


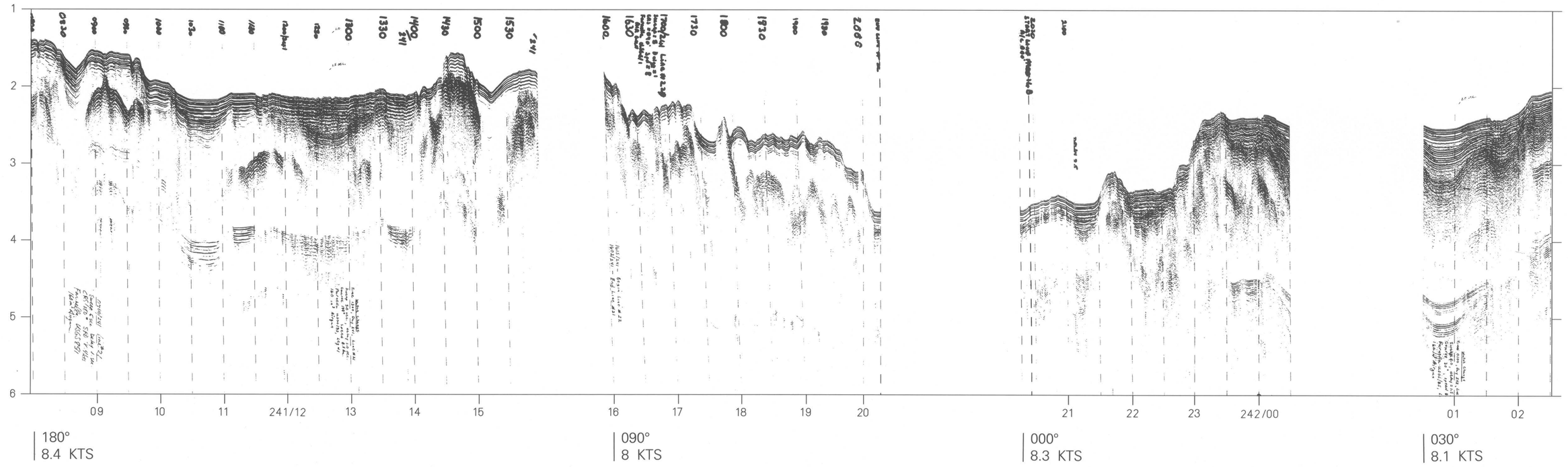
HOURS

DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

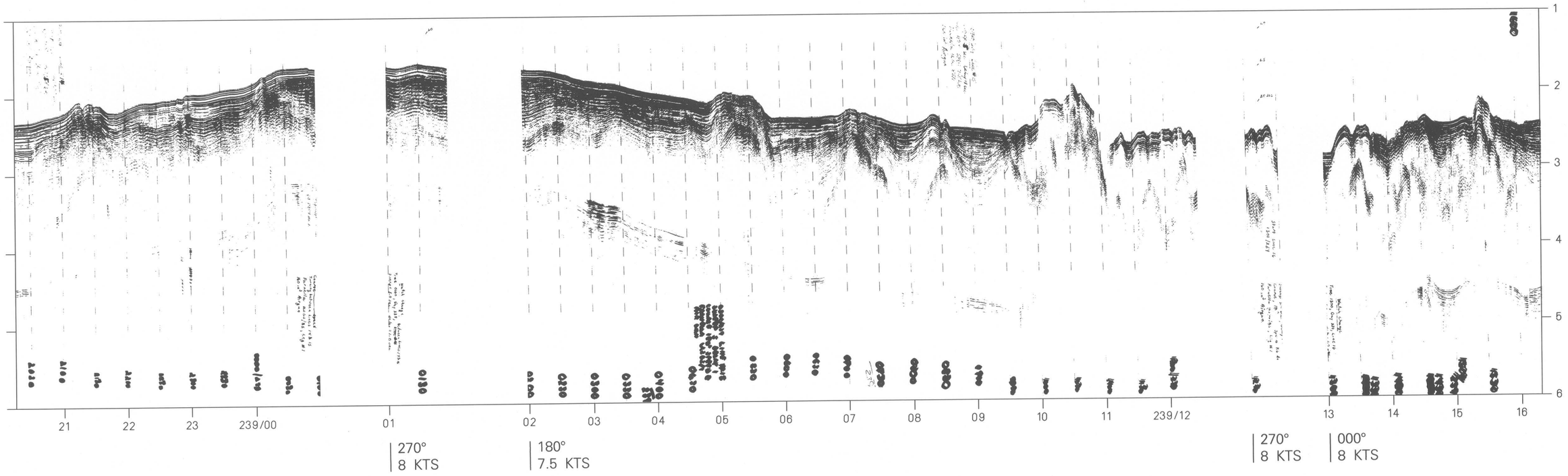


TWO-WAY TRAVELTIME, IN SECONDS





HOURS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239/00
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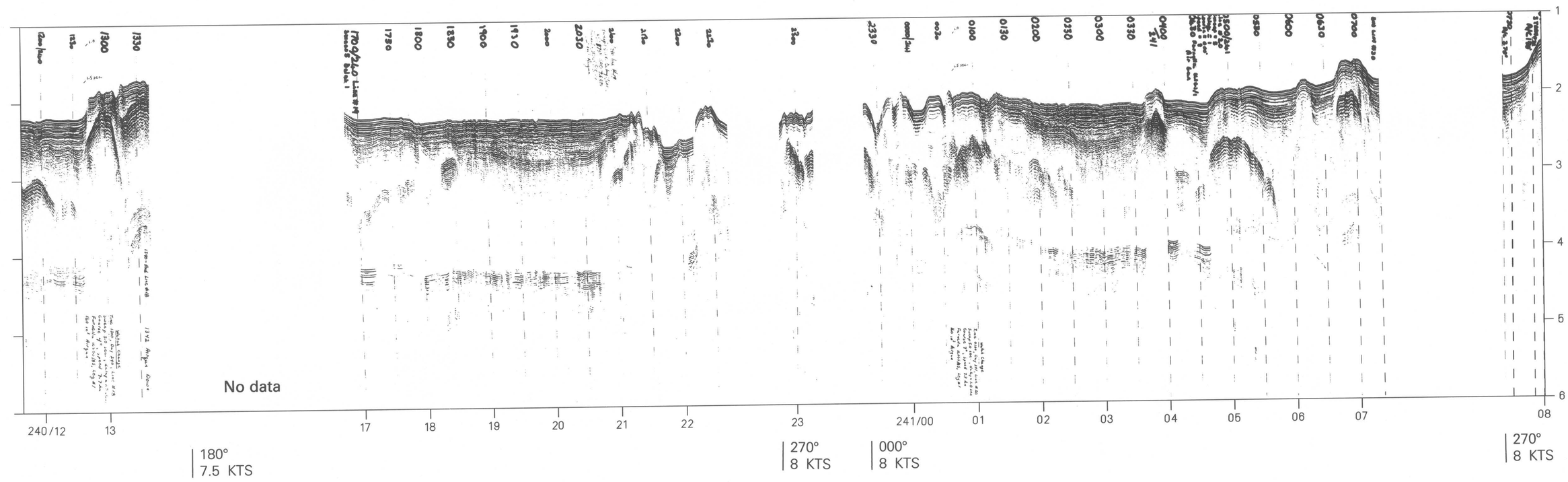
270°
8 KTS
180°
7.5 KTS
270°
8 KTS
000°
8 KTS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No data
240/12
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241/00
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180°
7.5 KTS
270°
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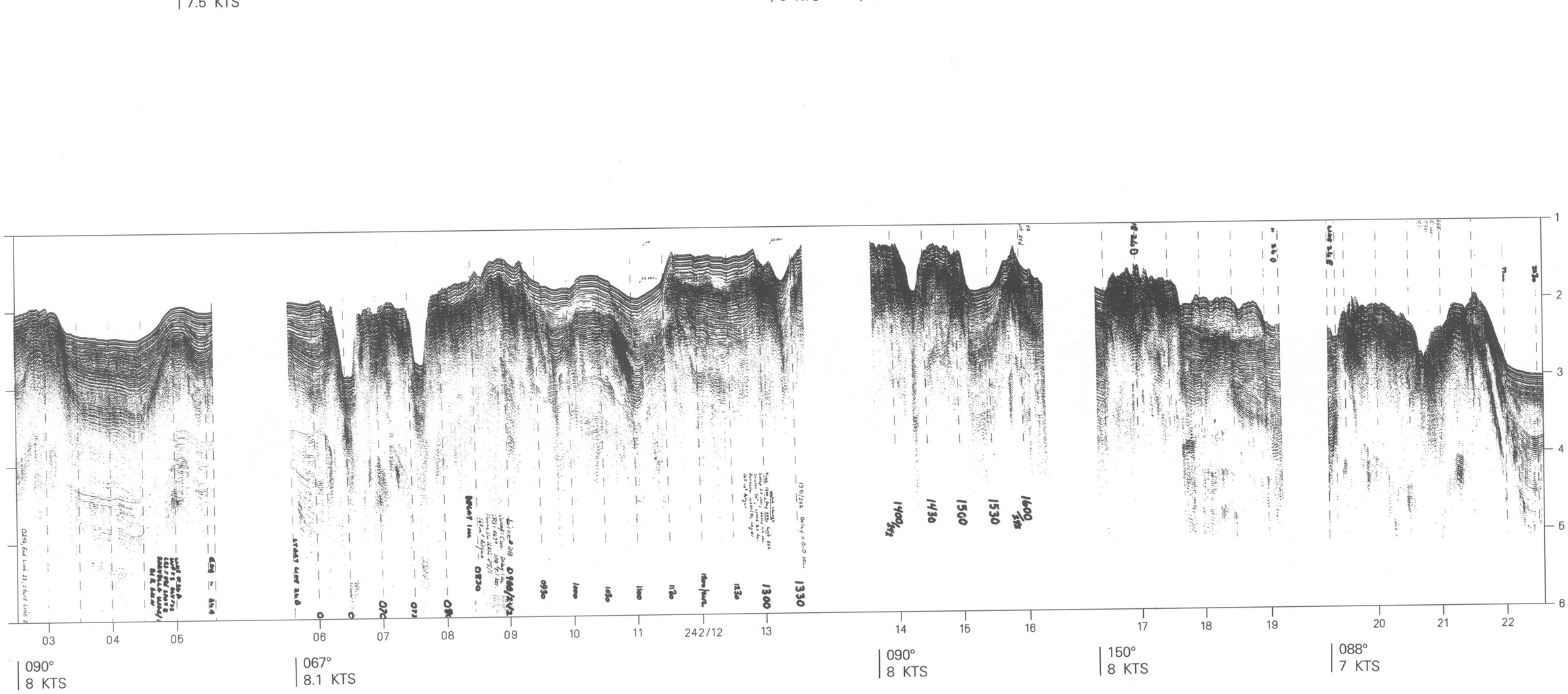
8 KTS
270°
8 KTS
TWO-WAY TRAVELTIME, IN SECONDS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242/12
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090°
8 KTS
067°
8.1 KTS
090°
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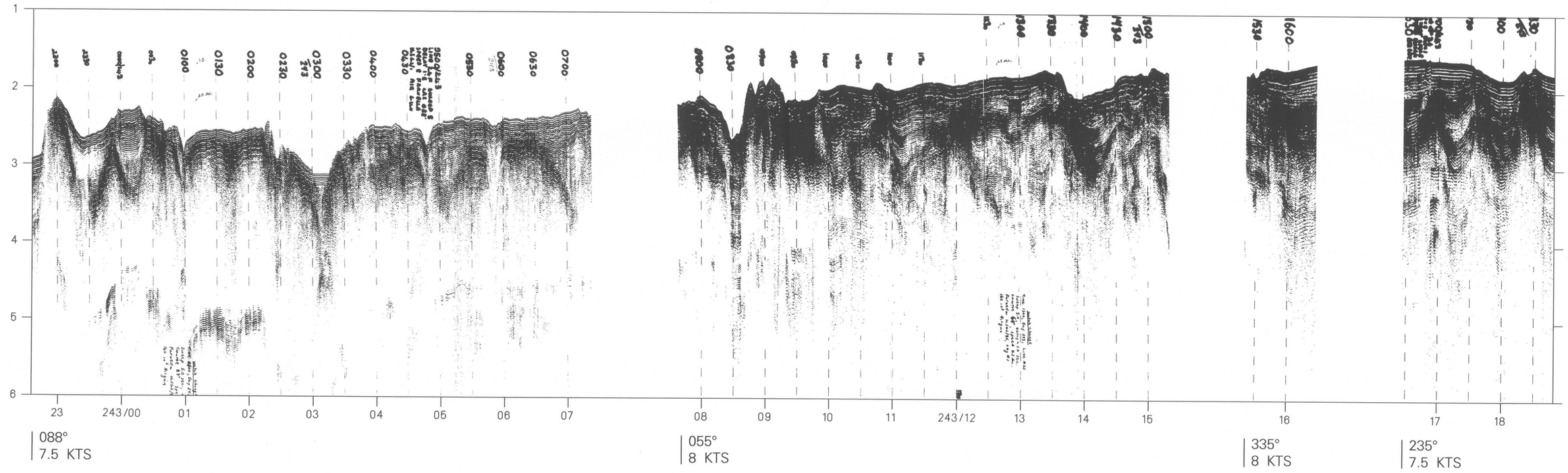
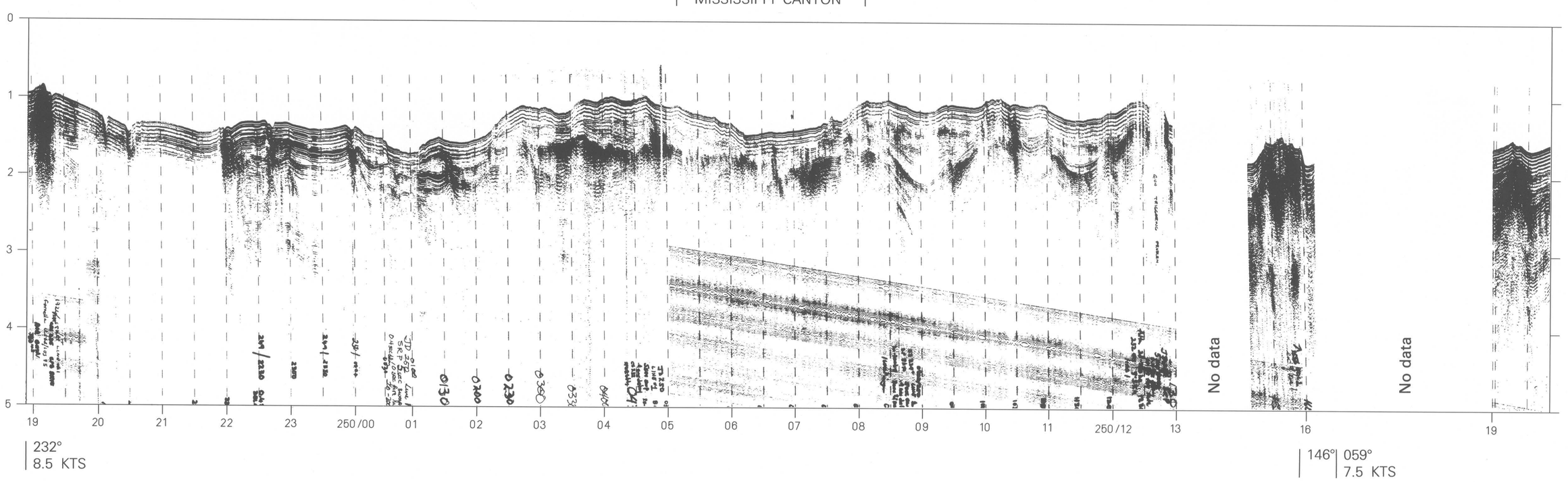
150°
8 KTS
088°
7 KTS
HOURS

ORCA BASIN

GREEN CANYON

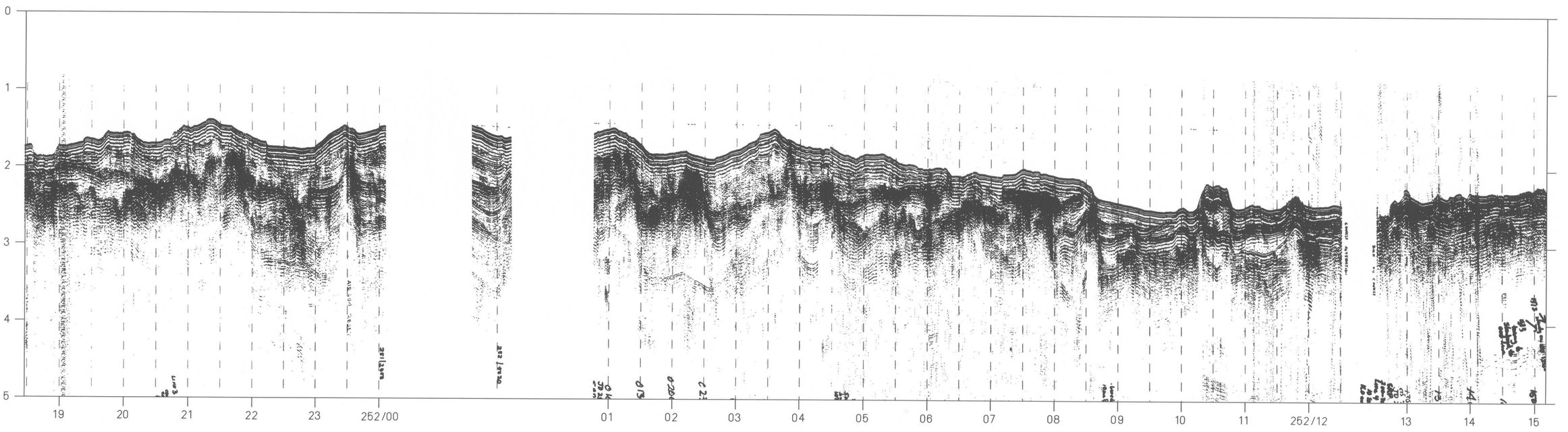


MISSISSIPPI CANYON

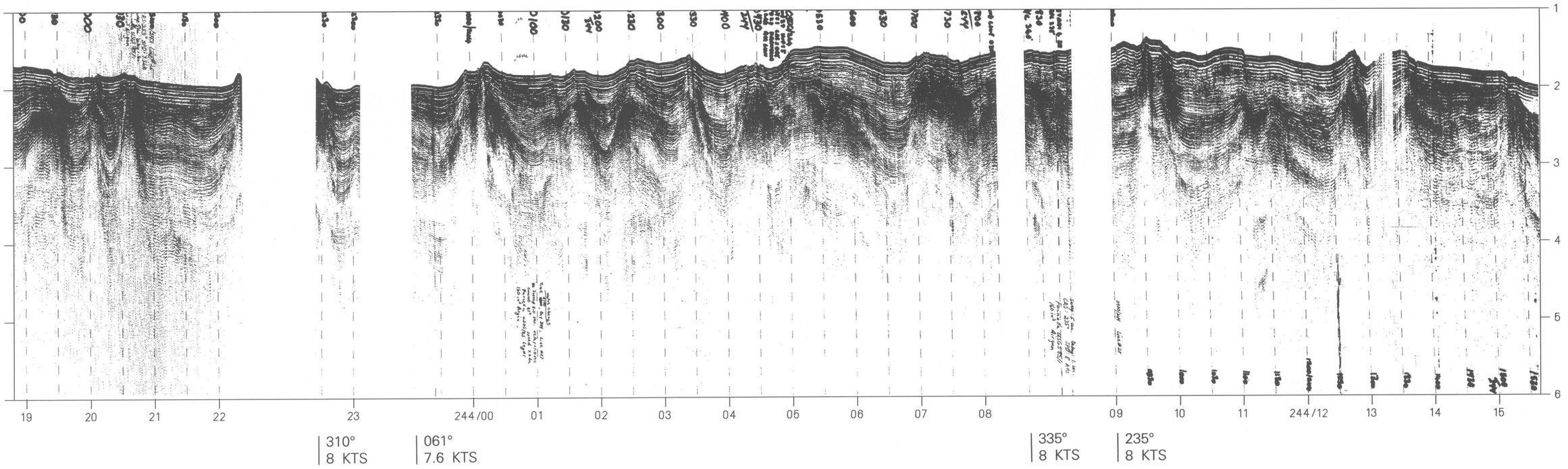


MISSISSIPPI CANYON

MISSISSIPPI CANYON



HOURS



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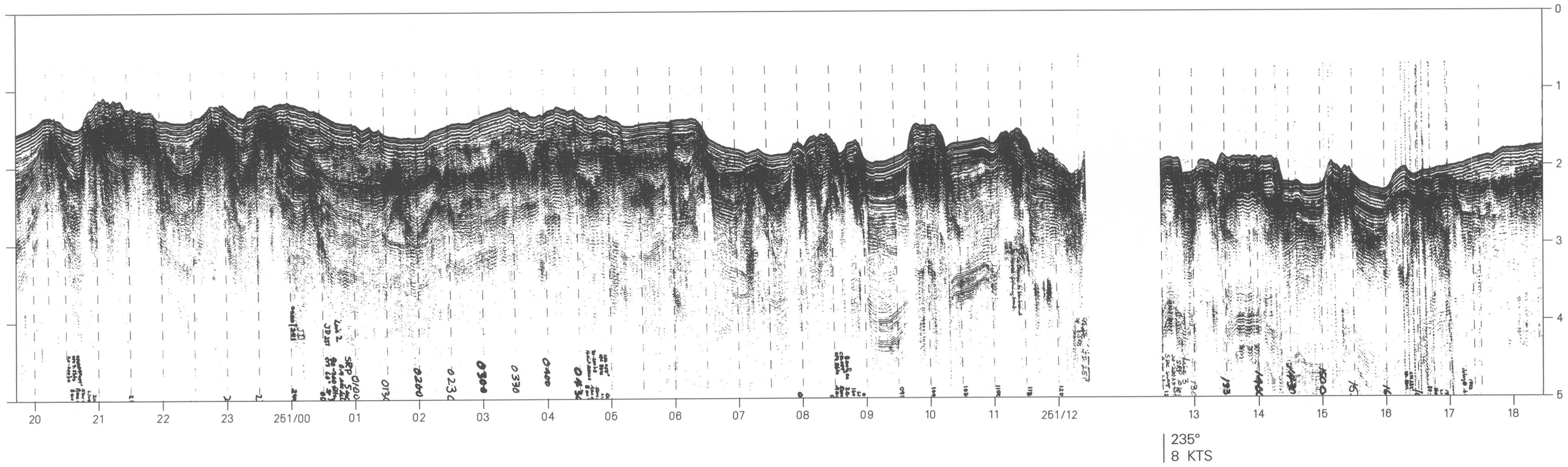
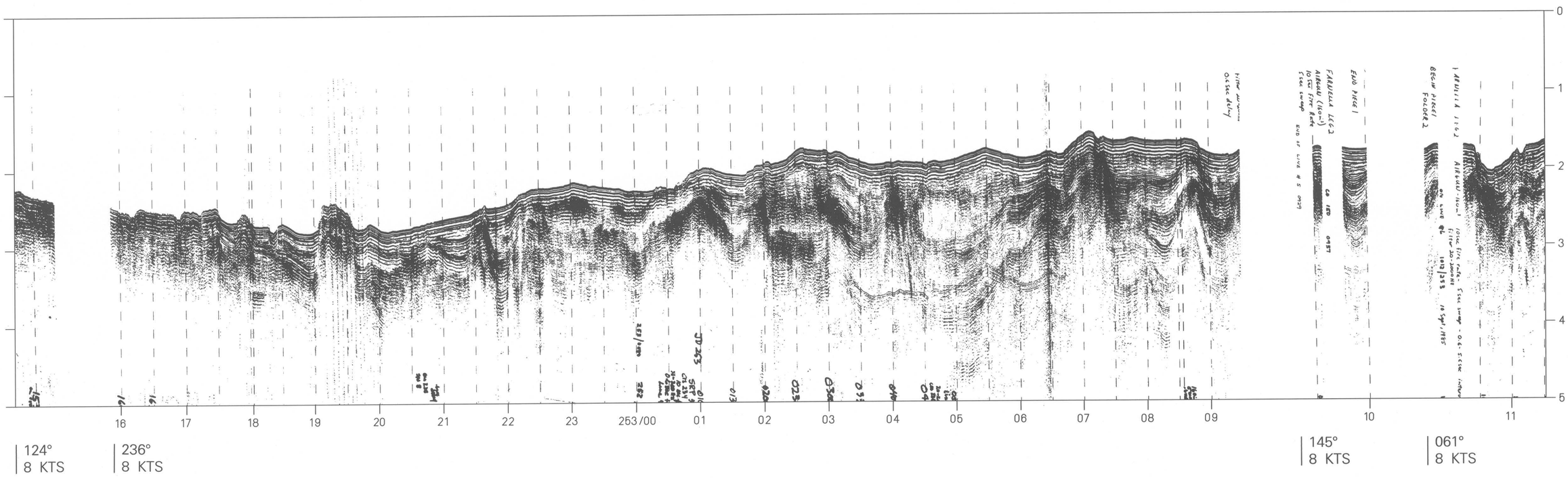
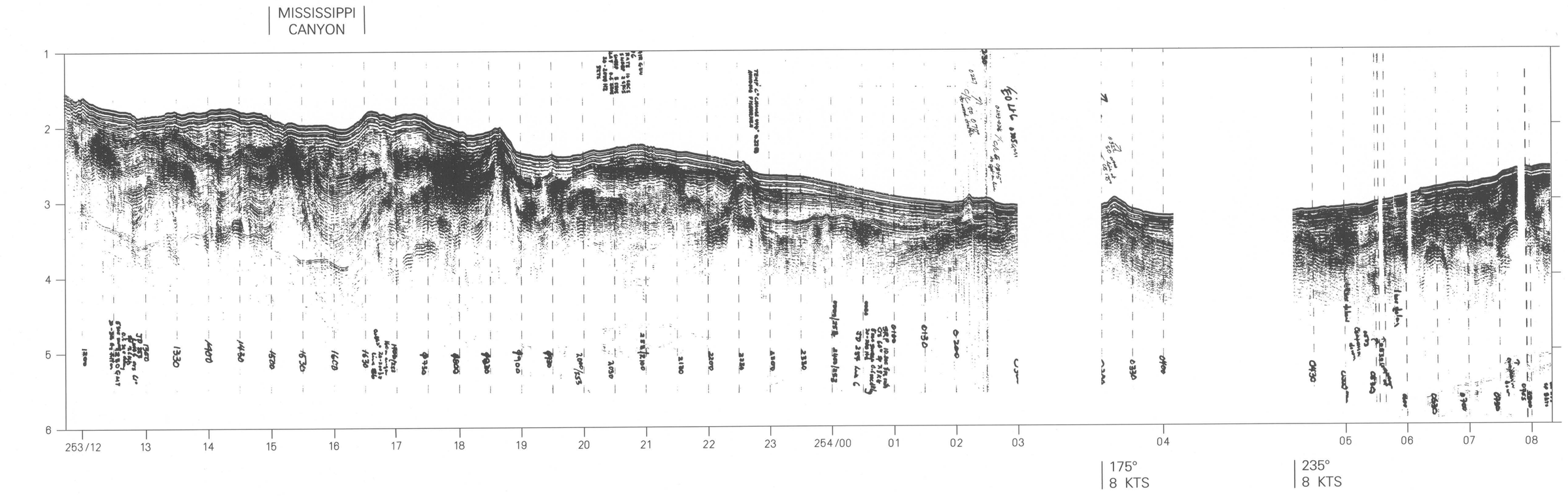


TWO-WAY TRAVELTIME, IN SECONDS

MISSISSIPPI CANYON



HOURS


MISSISSIPPI CANYON
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253/12
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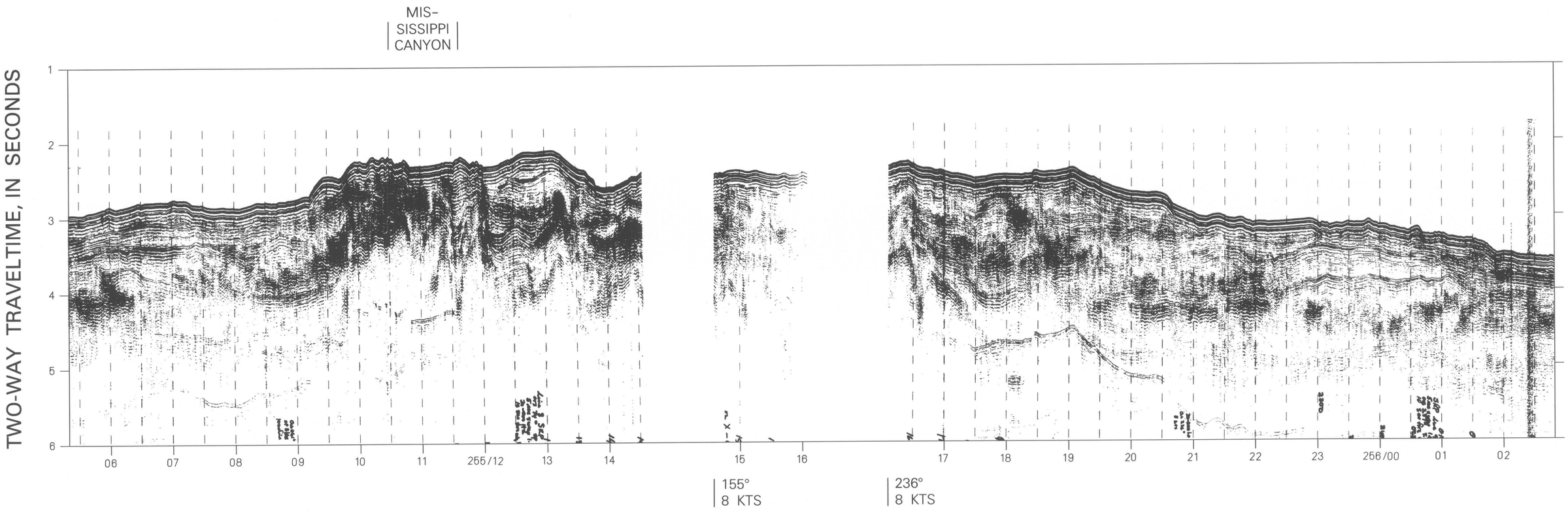
175°
8 KTS
235°
8 KTS


MIS-
SISSIPPI
CANYON
TWO-WAY TRAVELTIME, IN SECONDS
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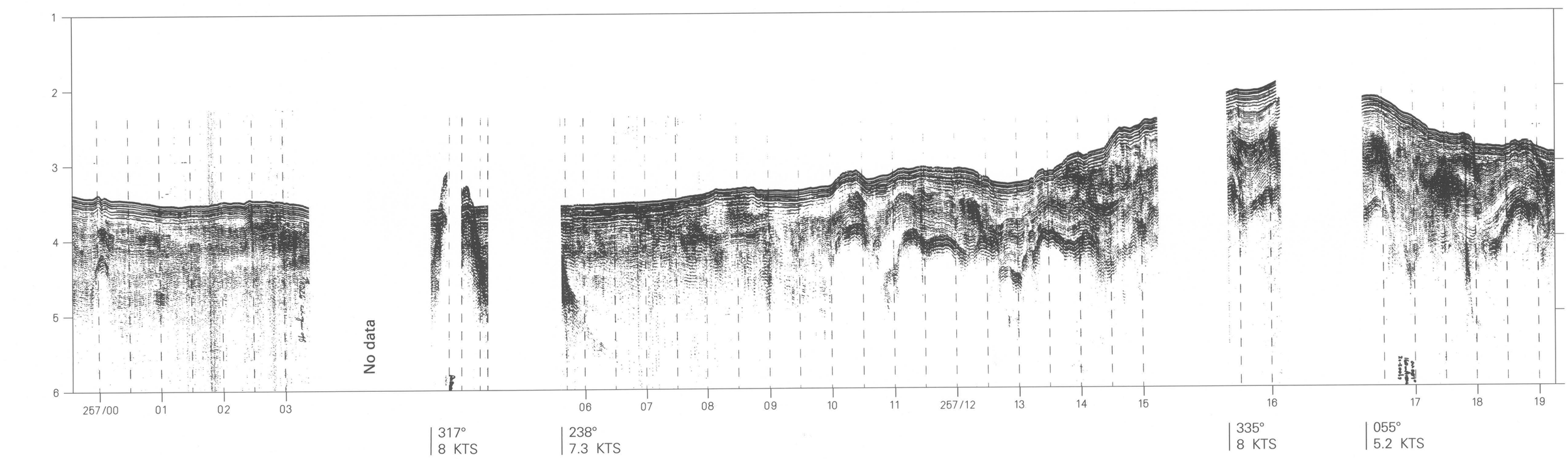
236°
8 KTS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335°
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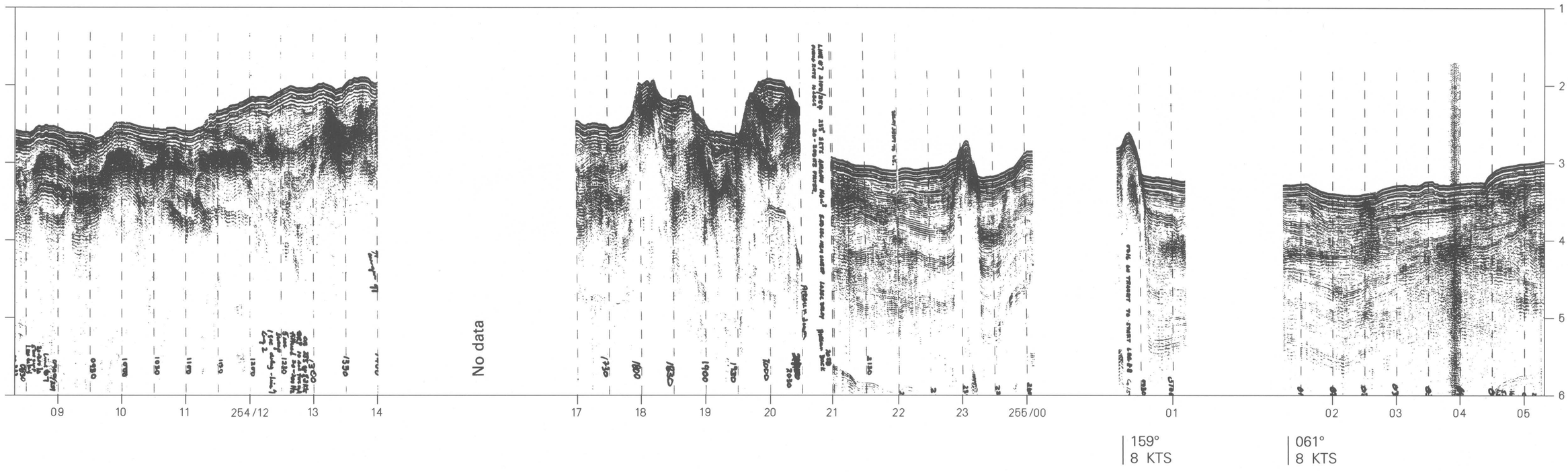
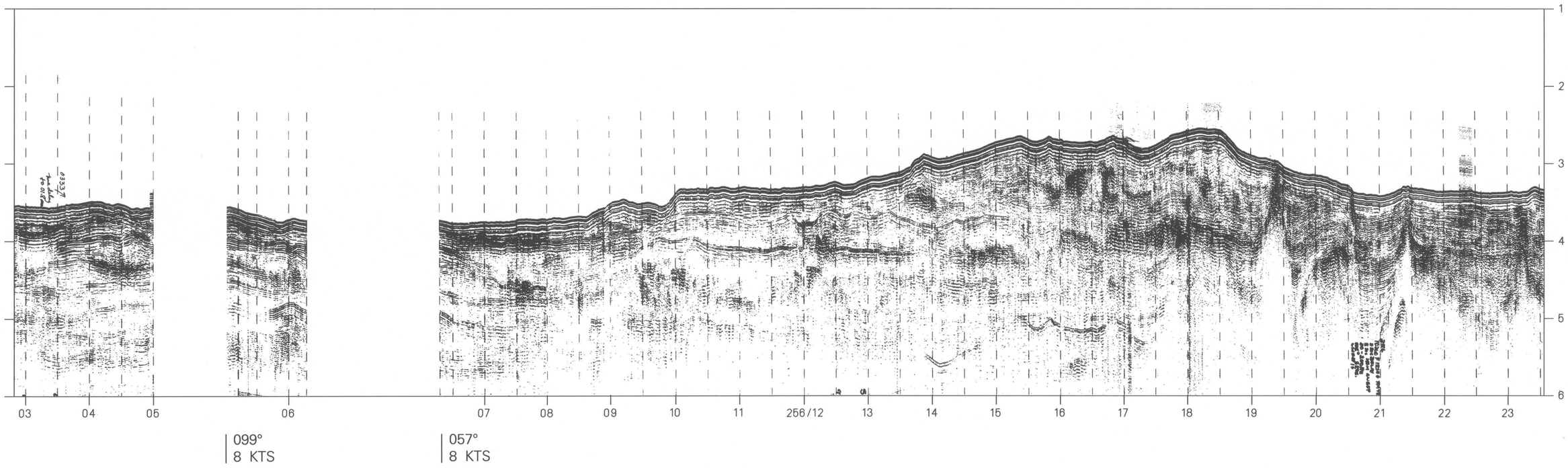
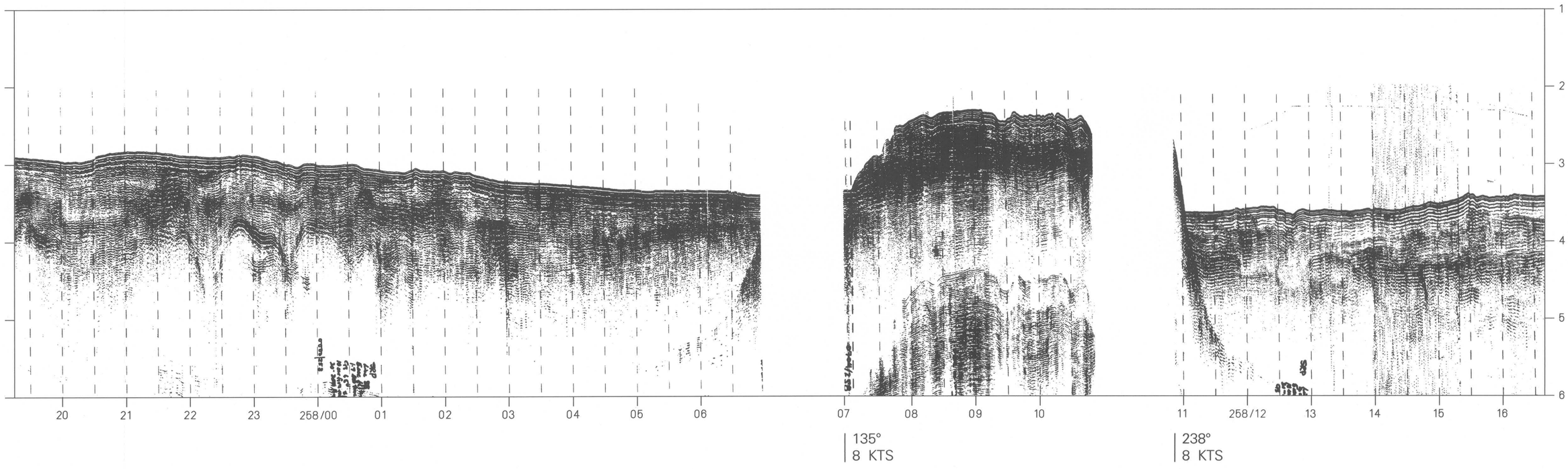
055°
5.2 KTS
HOURS

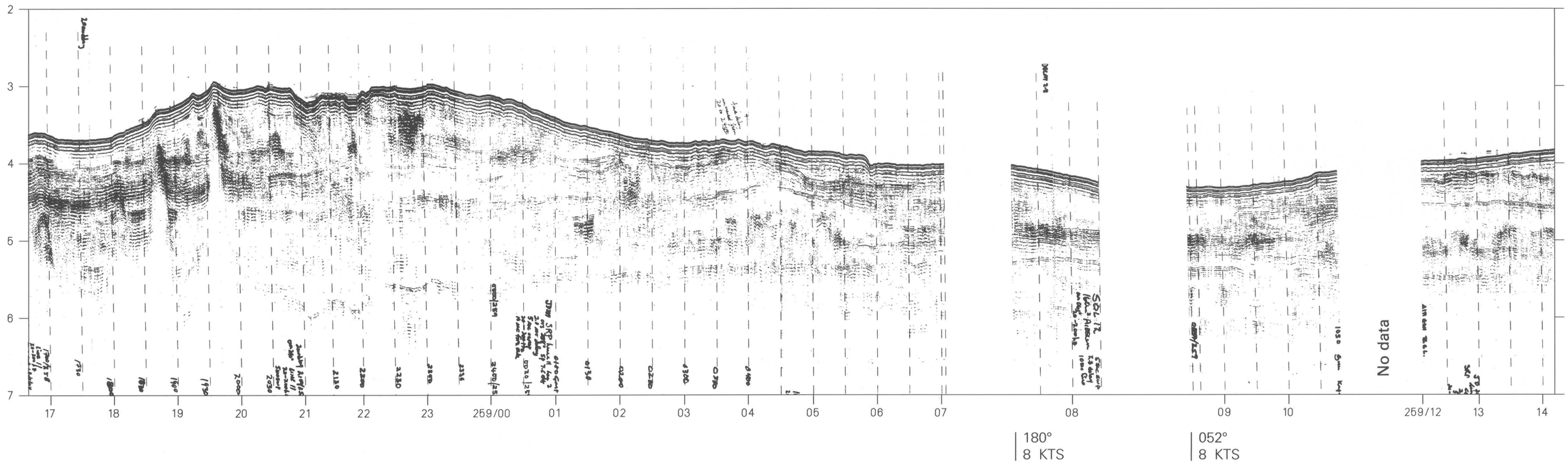




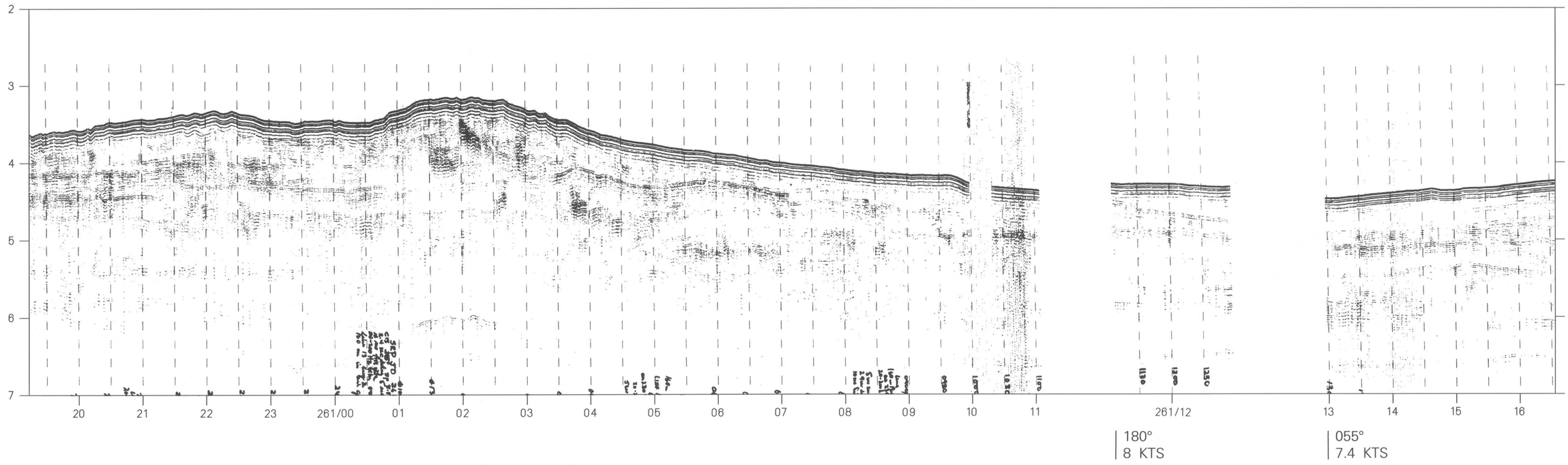
TWO-WAY TRAVELTIME, IN SECONDS

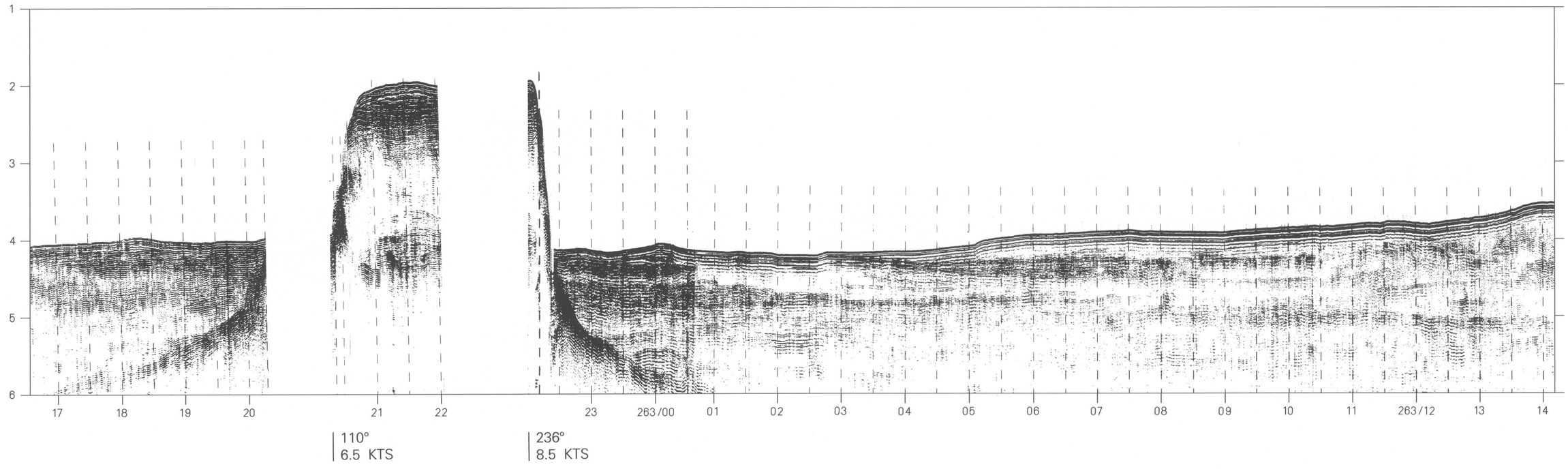


HOURS

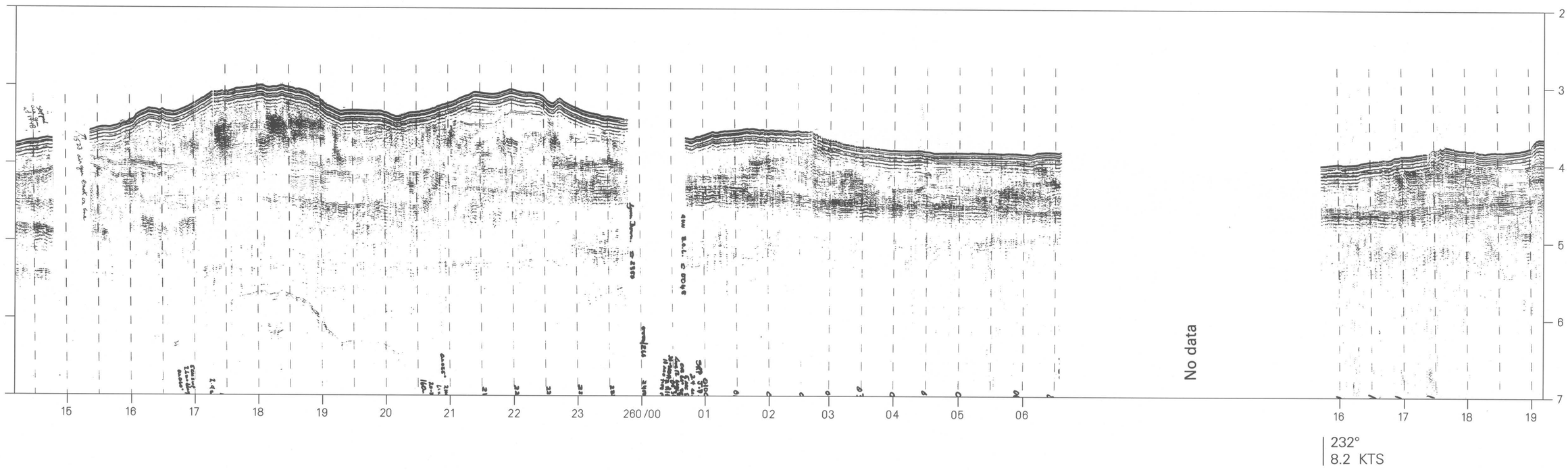


TWO-WAY TRAVELTIME, IN SECONDS





HOURS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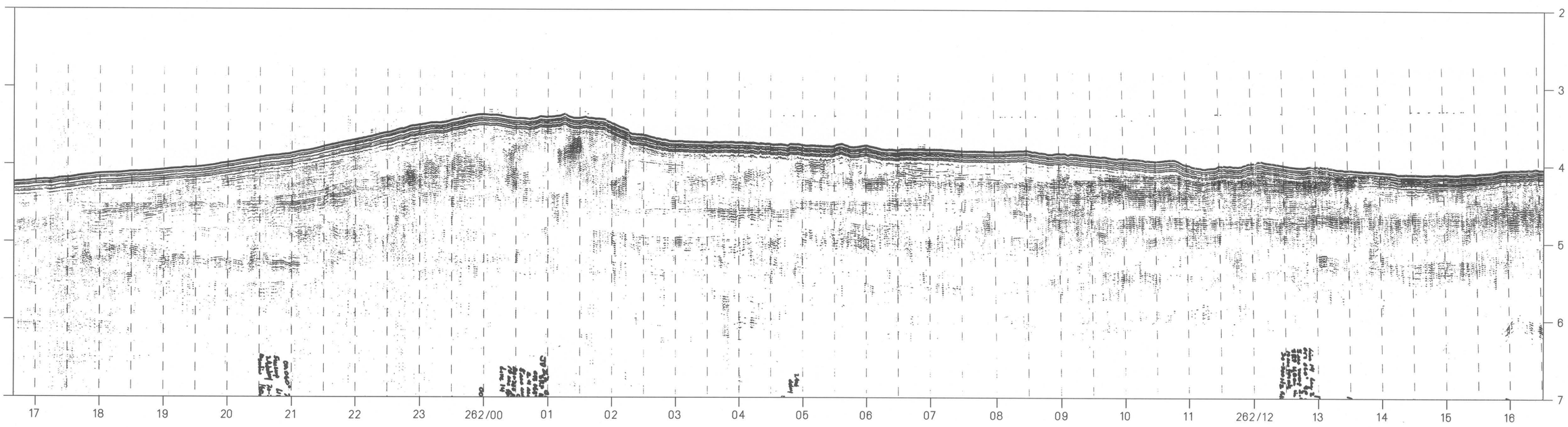
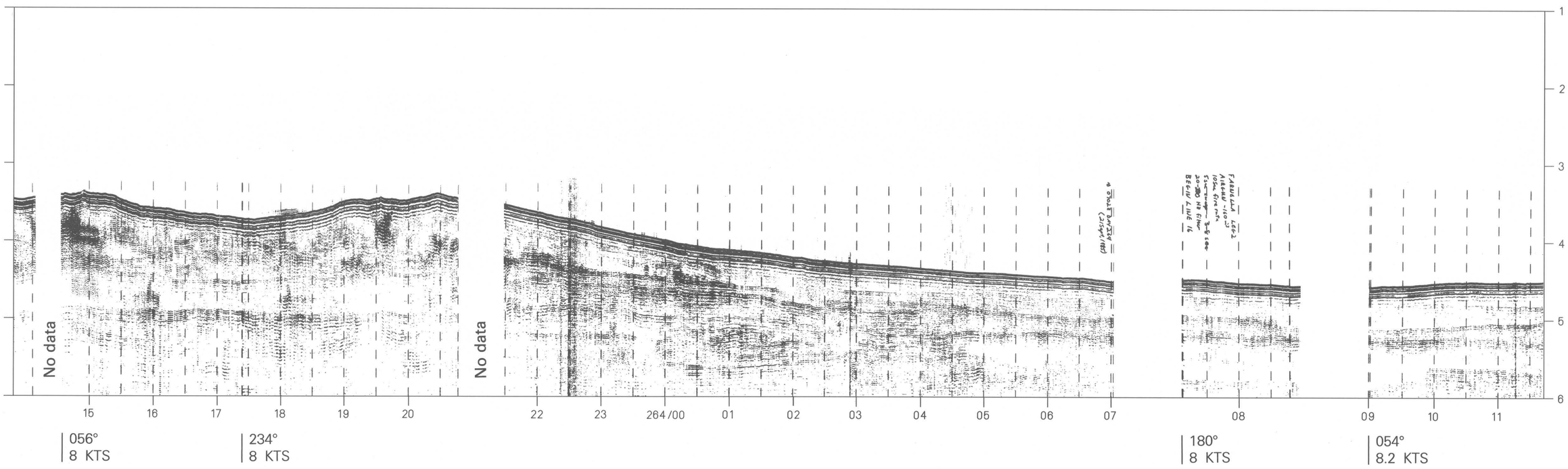
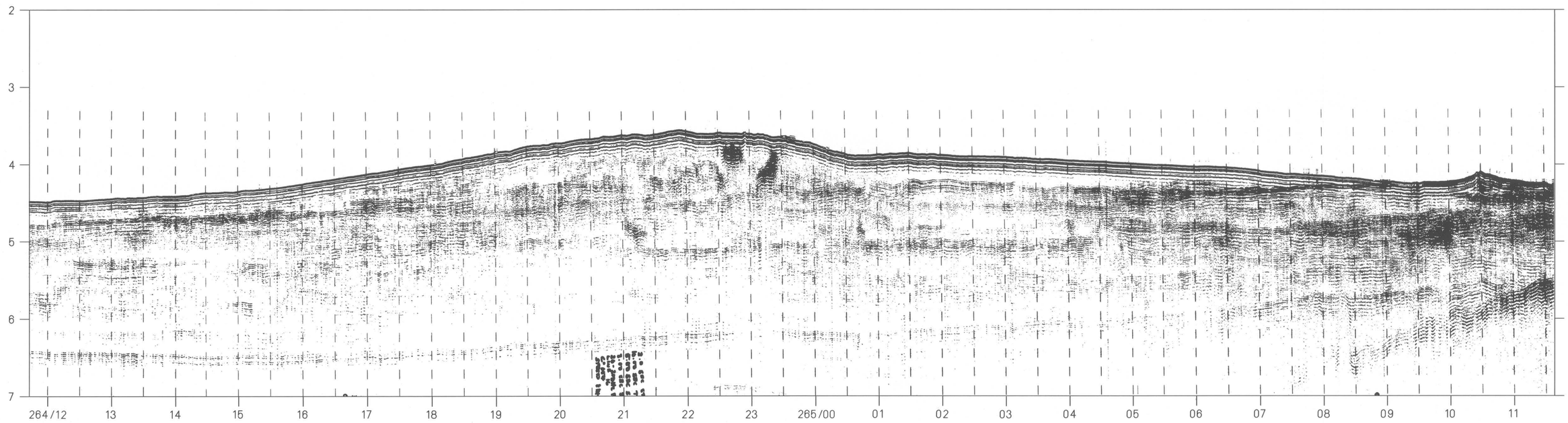
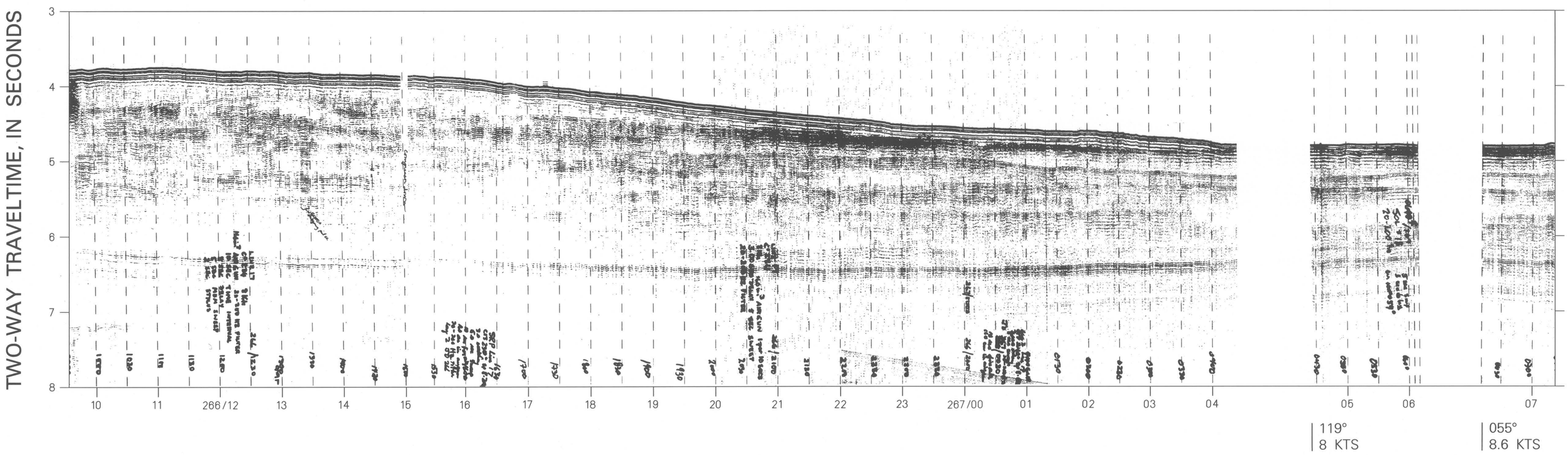
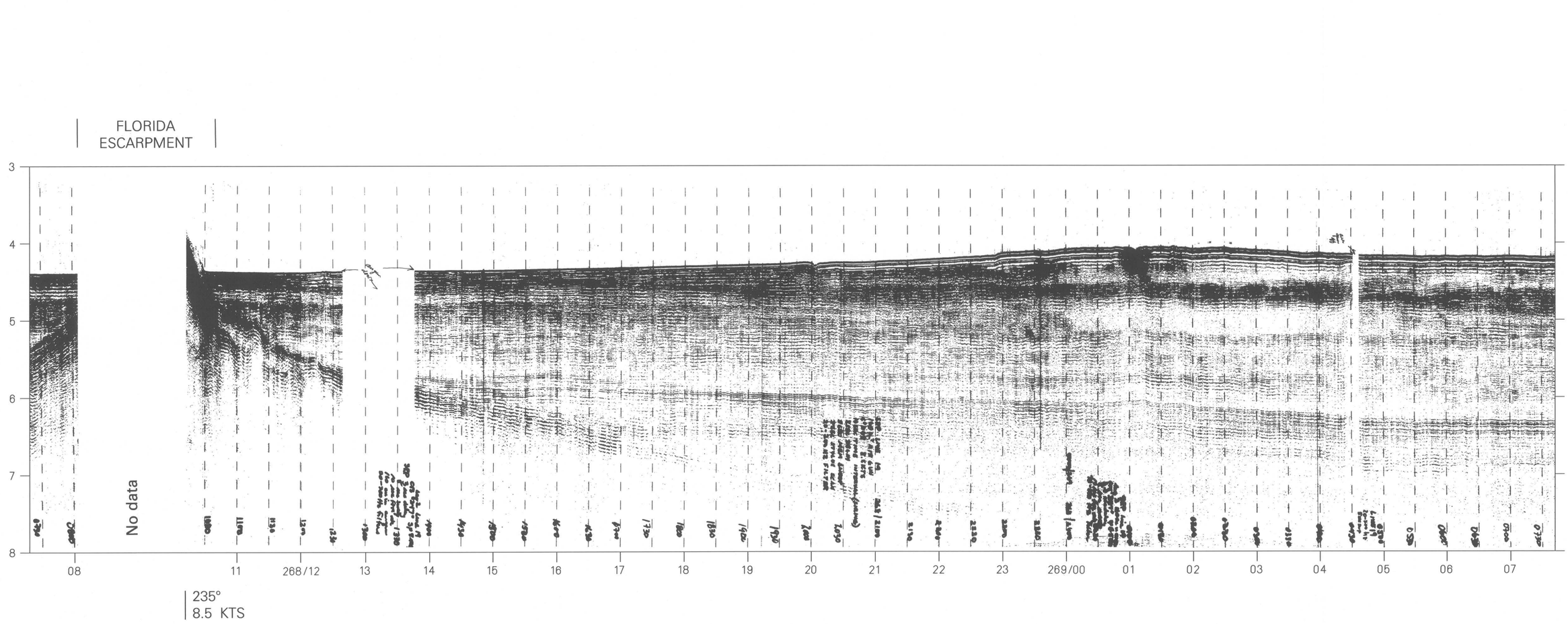
232°
8.2 KTS


2
3
4
5
6
7
17
18
19
20
21
22
23
262/00
01
02
03
04
05
06
07
08
09
10
11
262/12
13
14
15
16
TWO-WAY TRAVELTIME, IN SECONDS

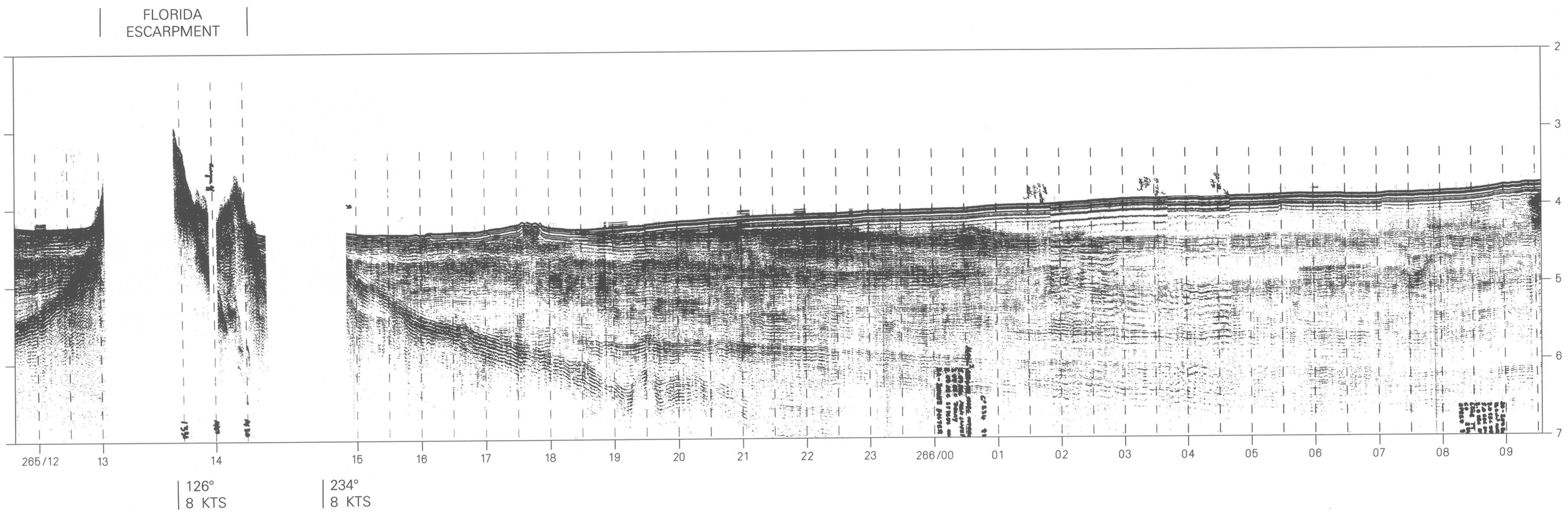

1
2
3
4
5
6
No data
No data
15
16
17
18
19
20
22
23
264/00
01
02
03
04
05
06
07
08
09
10
11
056°
8 KTS
234°
8 KTS
180°
8 KTS
054°
8.2 KTS
HOURS

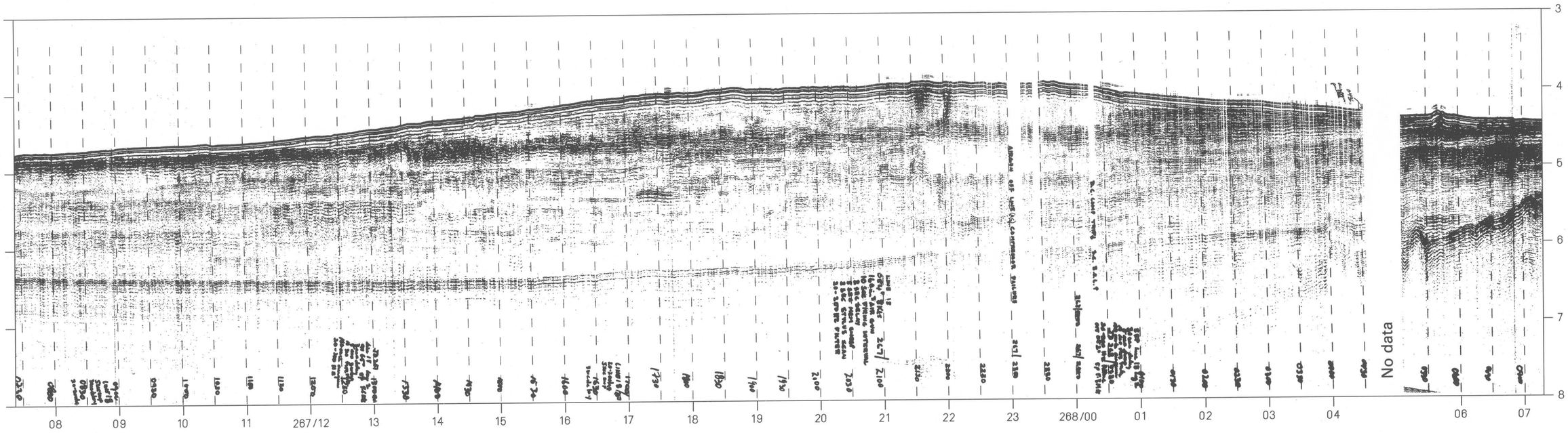

2
3
4
5
6
7
264/12
13
14
15
16
17
18
19
20
21
22
23
265/00
01
02
03
04
05
06
07
08
09
10
11

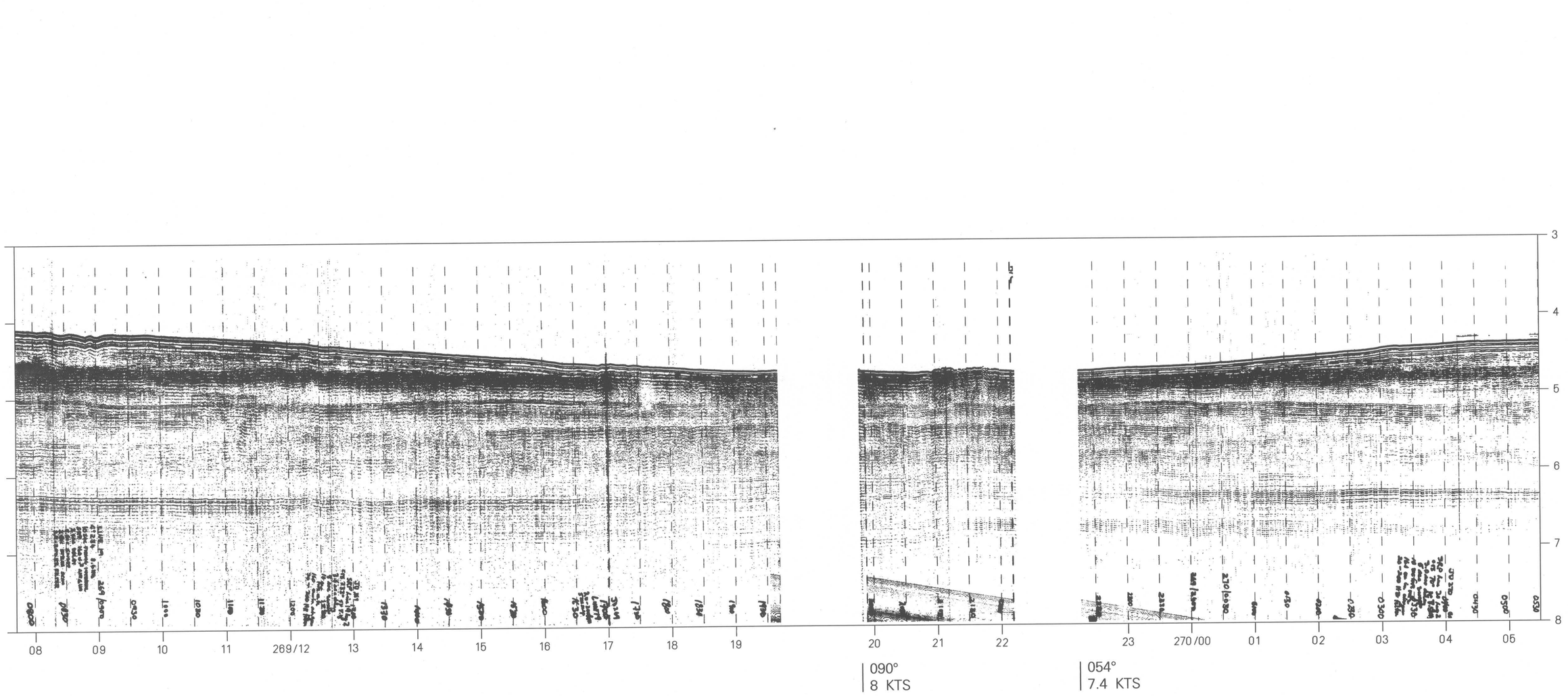

TWO-WAY TRAVELTIME, IN SECONDS
3
4
5
6
7
8
10
11
266/12
13
14
15
16
17
18
19
20
21
22
23
267/00
01
02
03
04
05
06
07
119°
8 KTS
055°
8.6 KTS

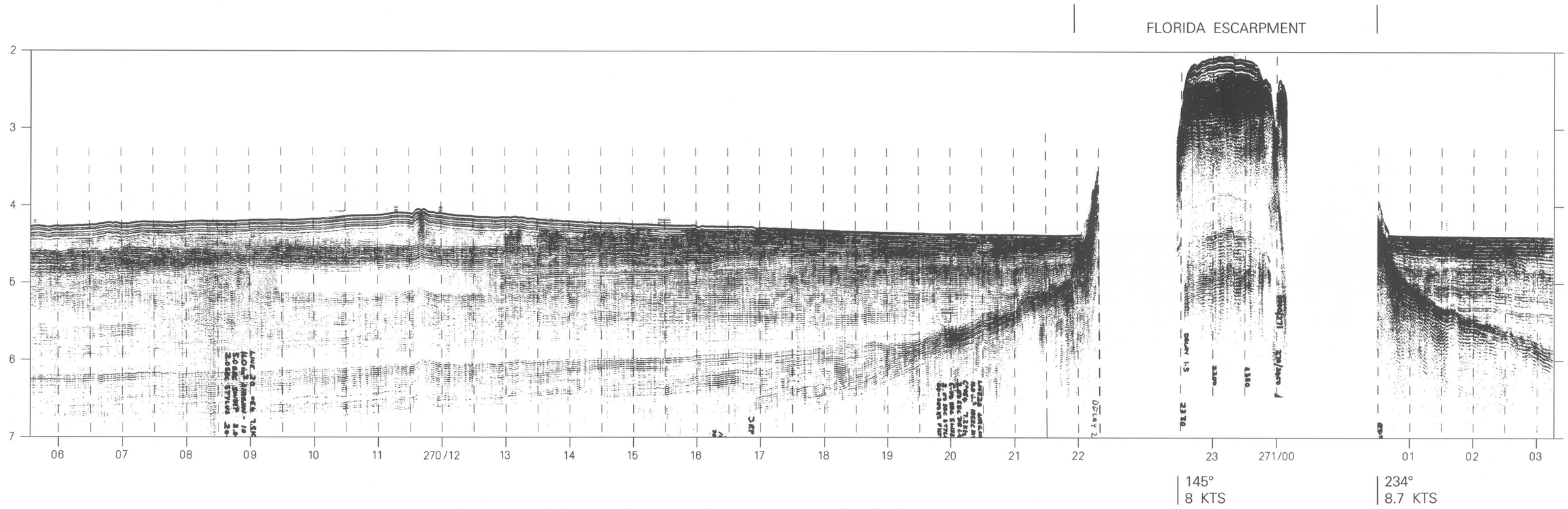

FLORIDA
ESCARPMENT
3
4
5
6
7
8
No data
08
11
268/12
13
14
15
16
17
18
19
20
21
22
23
269/00
01
02
03
04
05
06
07
235°
8.5 KTS

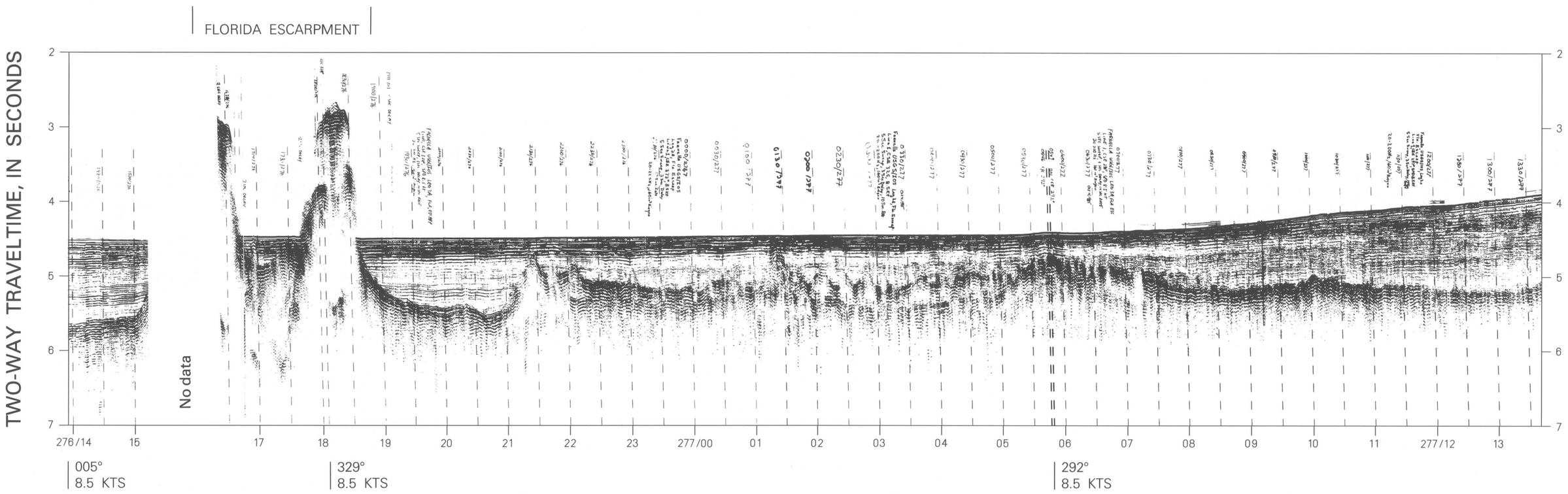
HOURS

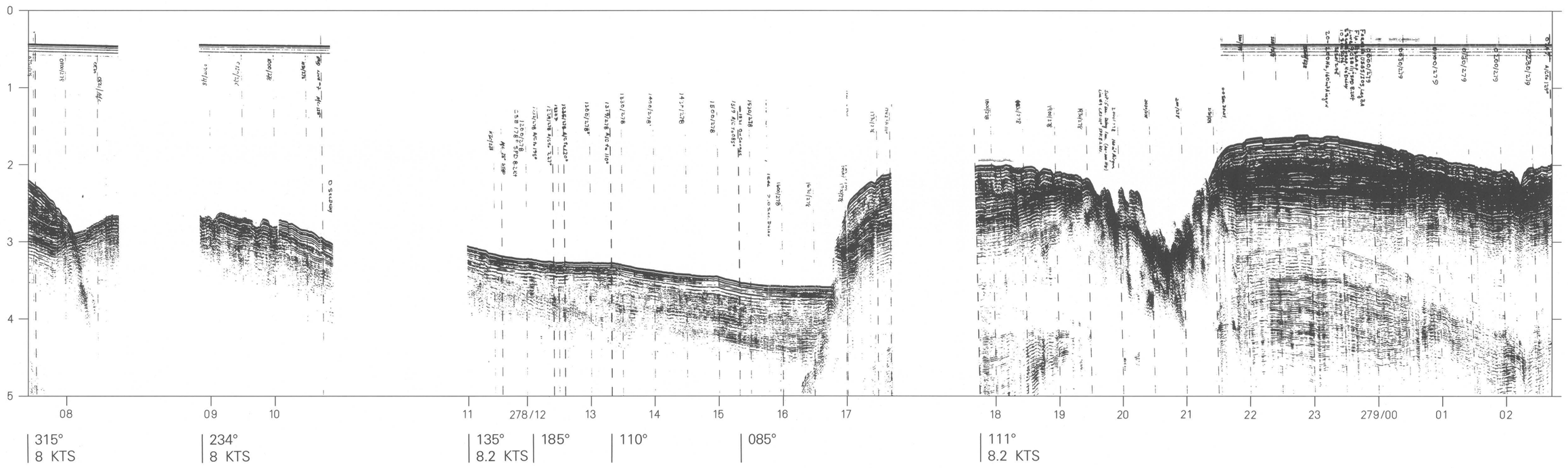

FLORIDA ESCARPMENT
2
3
4
5
6
7
265/12
13
14
15
16
17
18
19
20
21
22
23
266/00
01
02
03
04
05
06
07
08
09
126°
8 KTS
234°
8 KTS

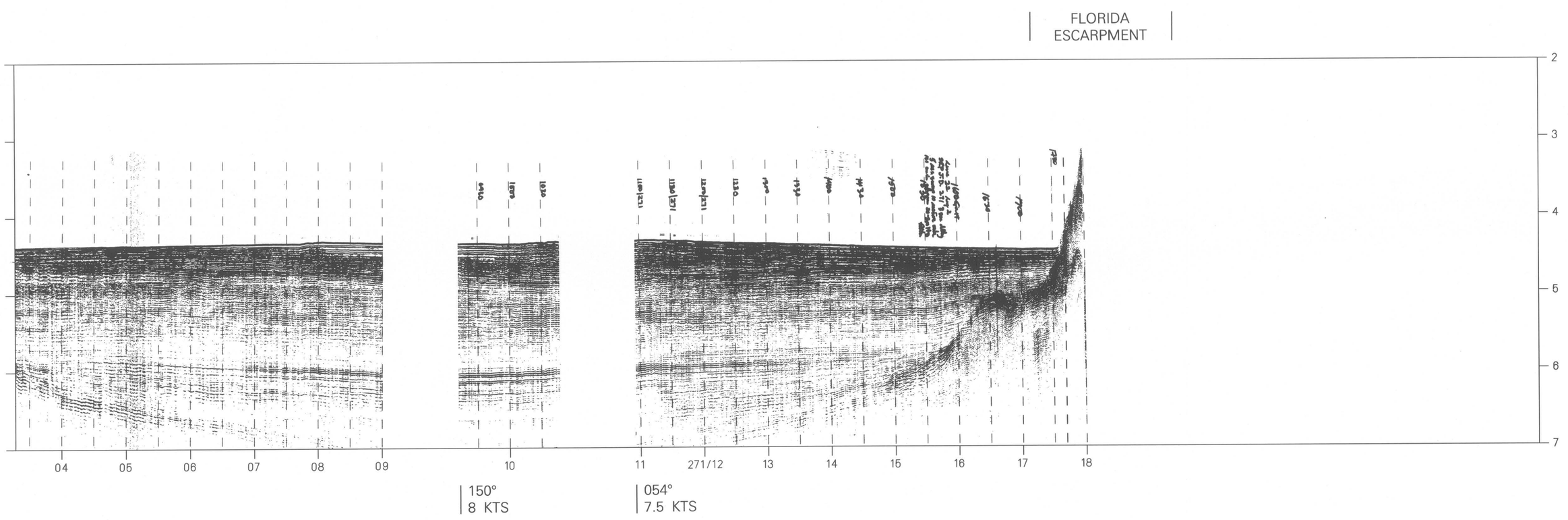

3
4
5
6
7
8
08
09
10
11
267/12
13
14
15
16
17
18
19
20
21
22
23
268/00
01
02
03
04
No data
06
07
TWO-WAY TRAVELTIME, IN SECONDS

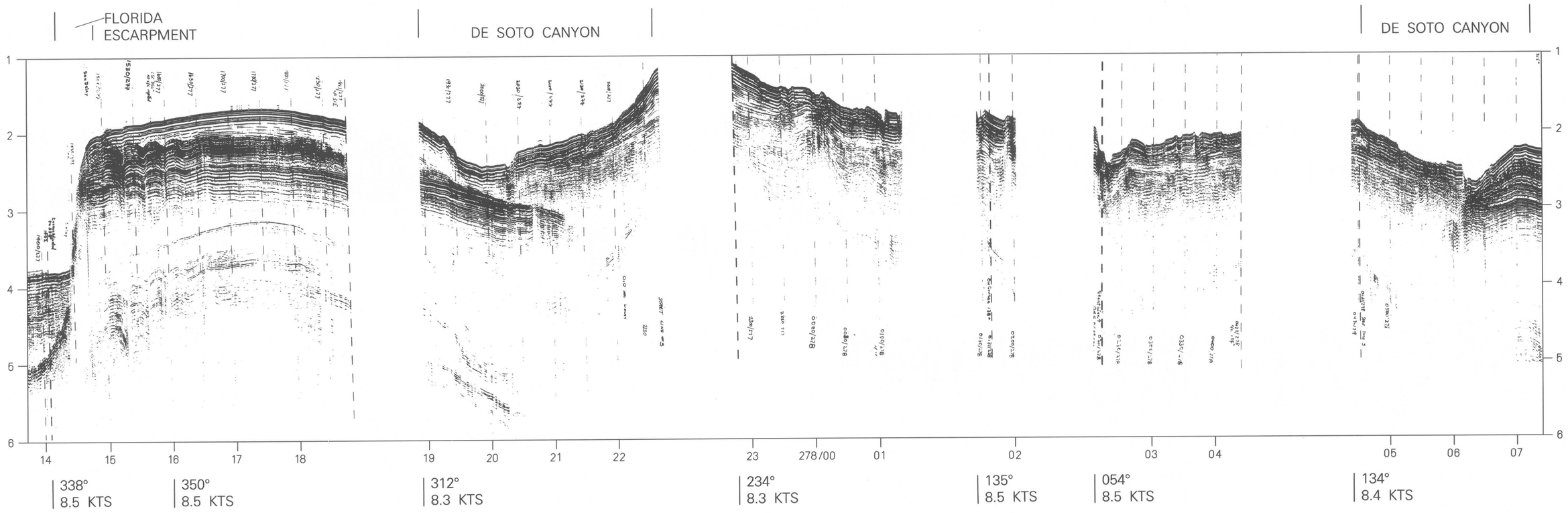

3
4
5
6
7
8
08
09
10
11
269/12
13
14
15
16
17
18
19
20
21
22
23
270/00
01
02
03
04
05
090°
8 KTS
054°
7.4 KTS
HOURS

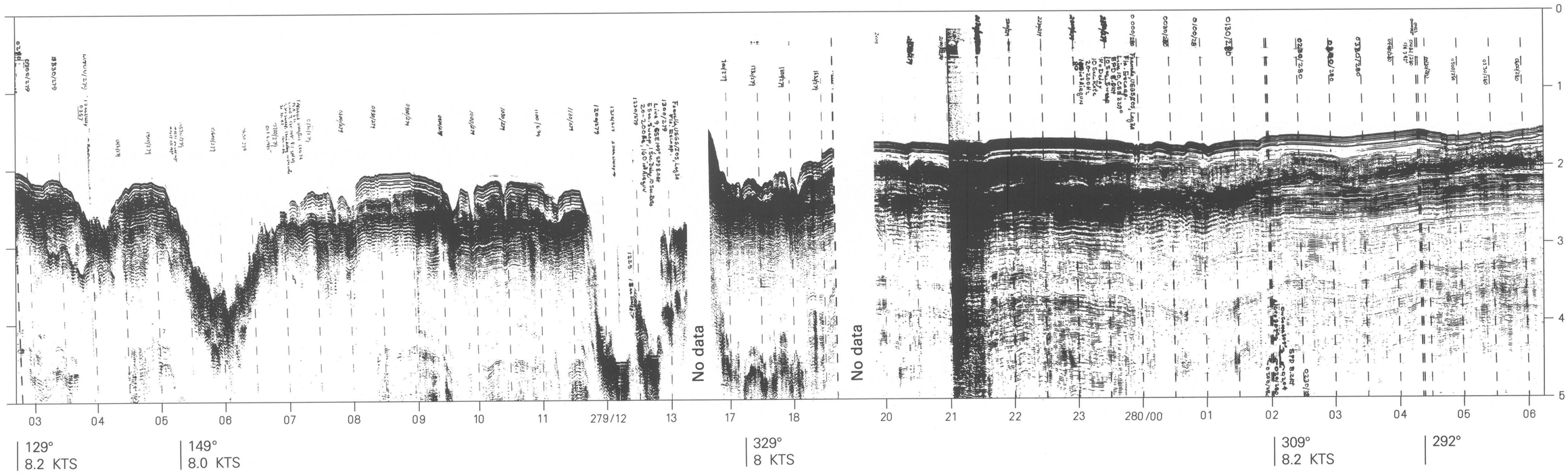

FLORIDA ESCARPMENT
2
3
4
5
6
7
06
07
08
09
10
11
270/12
13
14
15
16
17
18
19
20
21
22
23
271/00
01
02
03
145°
8 KTS
234°
8.7 KTS


TWO-WAY TRAVELTIME, IN SECONDS
FLORIDA ESCARPMENT
2
3
4
5
6
7
No data
276/14
15
17
18
19
20
21
22
23
277/00
01
02
03
04
05
06
07
08
09
10
11
277/12
13
005°
8.5 KTS
329°
8.5 KTS
292°
8.5 KTS


DE SOTO CANYON
FLORIDA ESCARPMENT
0
1
2
3
4
5
08
09
10
11
278/12
13
14
15
16
17
18
19
20
21
22
23
279/00
01
02
315°
8 KTS
234°
8 KTS
135°
8.2 KTS
185°
110°
085°
111°
8.2 KTS
HOURS


FLORIDA ESCARPMENT
2
3
4
5
6
7
04
05
06
07
08
09
10
11
271/12
13
14
15
16
17
18
150°
8 KTS
054°
7.5 KTS


FLORIDA ESCARPMENT
DE SOTO CANYON
DE SOTO CANYON
1
2
3
4
5
6
14
15
16
17
18
19
20
21
22
23
278/00
01
02
03
04
05
06
07
338°
8.5 KTS
350°
8.5 KTS
312°
8.3 KTS
234°
8.3 KTS
135°
8.5 KTS
054°
8.5 KTS
134°
8.4 KTS
TWO-WAY TRAVELTIME, IN SECONDS


No data
No data
0
1
2
3
4
5
03
04
05
06
07
08
09
10
11
279/12
13
17
18
20
21
22
23
280/00
01
02
03
04
05
06
129°
8.2 KTS
149°
8.0 KTS
329°
8 KTS
309°
8.2 KTS
292°
HOURS

DE SOTO CANYON

DE SOTO CANYON

FLORIDA ESCARPMENT

TWO-WAY TRAVELTIME, IN SECONDS

315°
8.5 KTS

049°

135°
8.2 KTS

112°

163°

150°
8.5 KTS

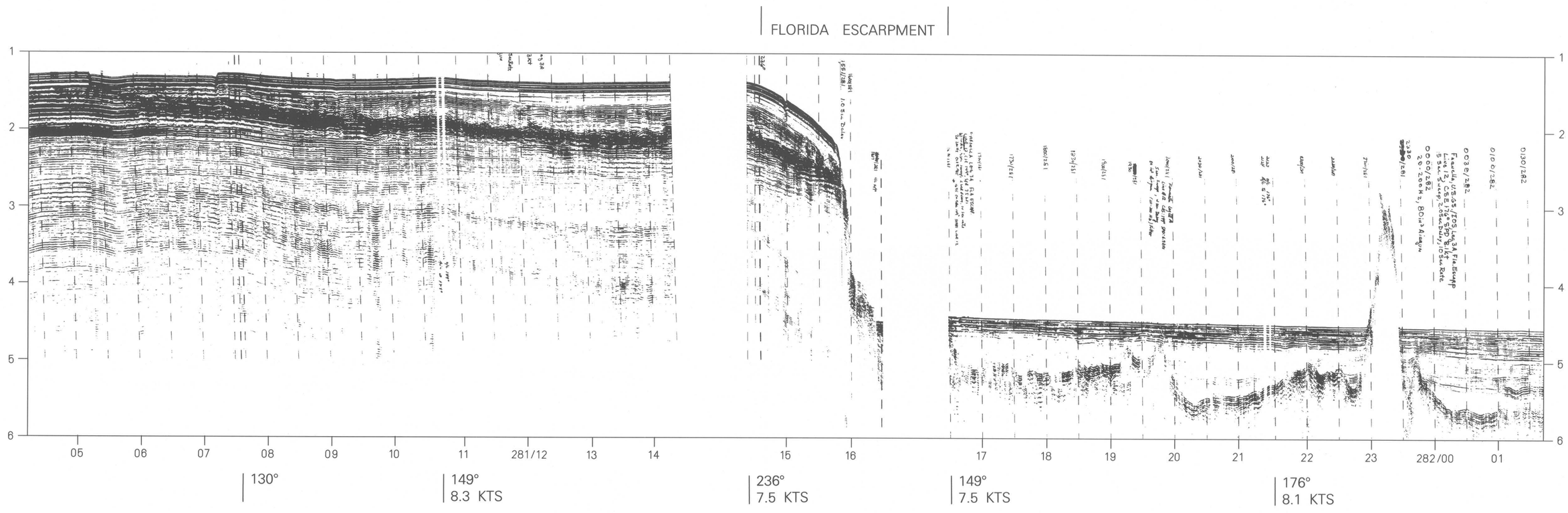
090°
8 KTS

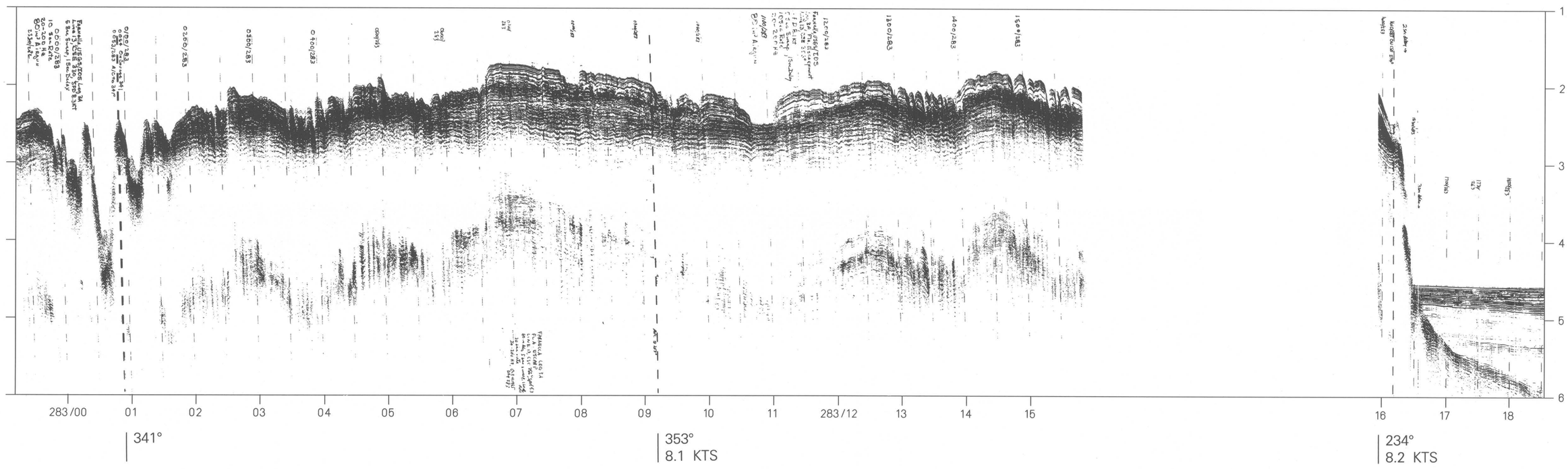
330°
8.3 KTS

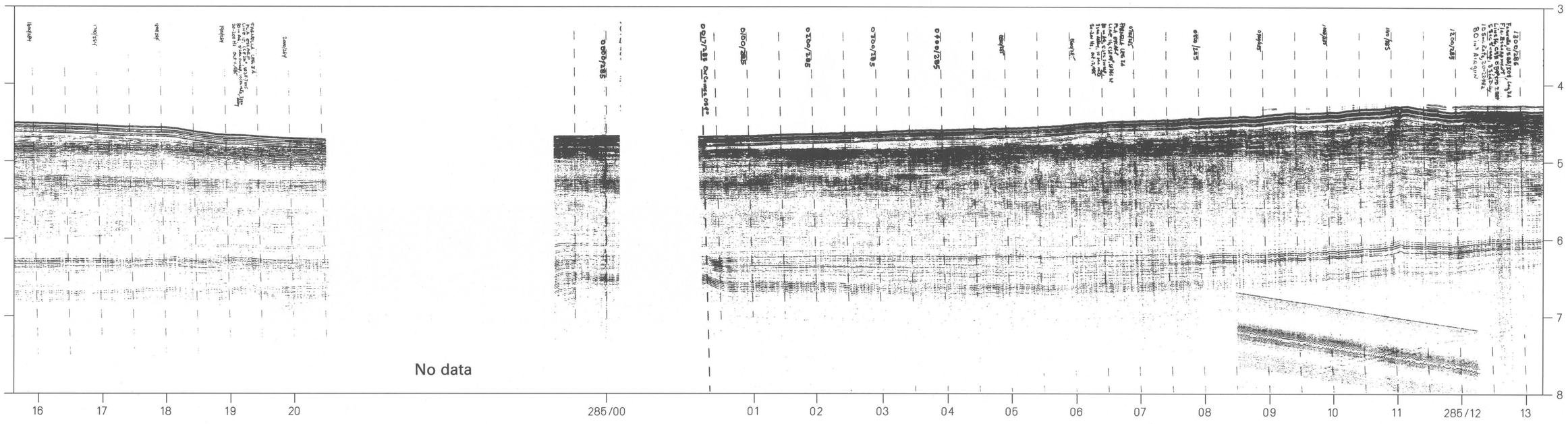
326°
8.2 KTS

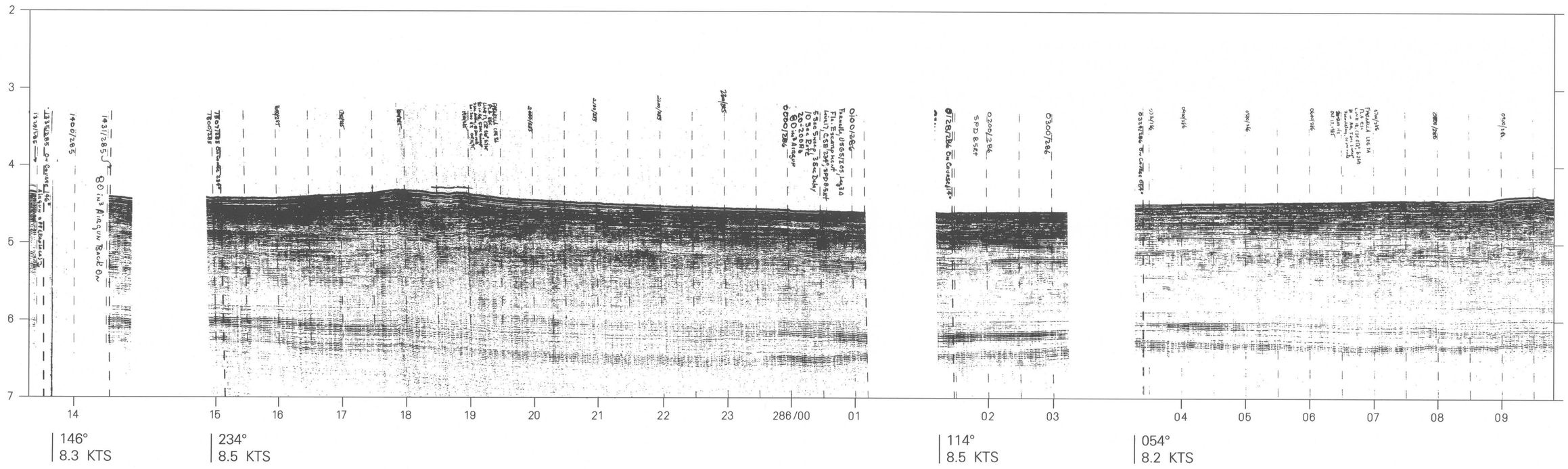
234°
8.7 KTS

HOURS

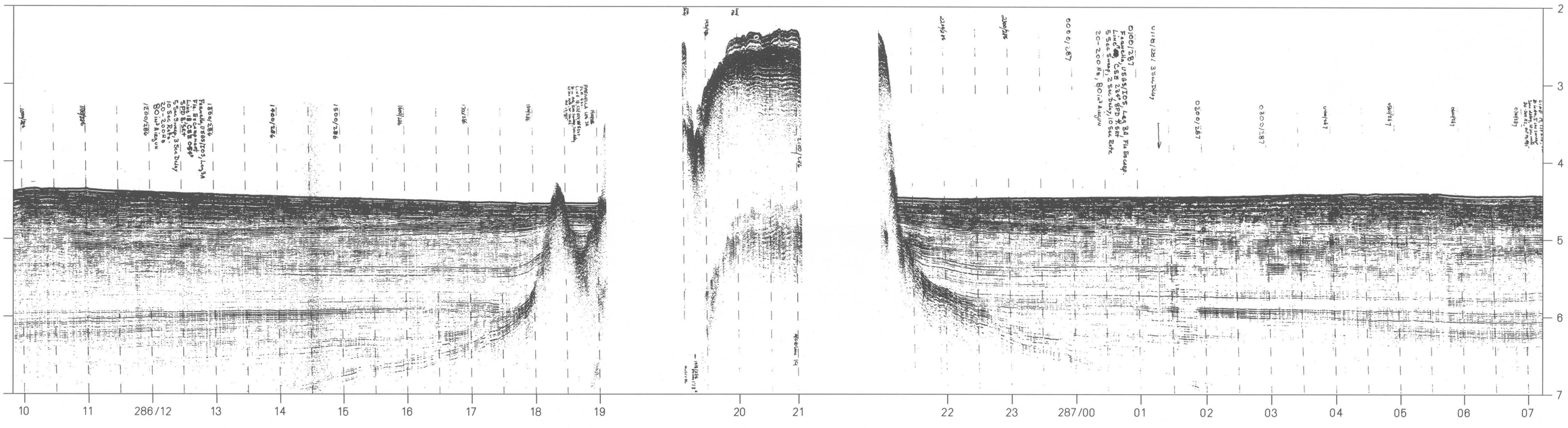

FLORIDA ESCARPMENT
1
2
3
4
5
6
05
06
07
08
09
10
11
281/12
13
14
15
16
17
18
19
20
21
22
23
282/00
01
130°
149°
8.3 KTS
236°
7.5 KTS
149°
7.5 KTS
176°
8.1 KTS


FLORIDA ESCARPMENT
1
2
3
4
5
6
283/00
01
02
03
04
05
06
07
08
09
10
11
283/12
13
14
15
16
17
18
341°
353°
8.1 KTS
234°
8.2 KTS
TWO-WAY TRAVELTIME, IN SECONDS

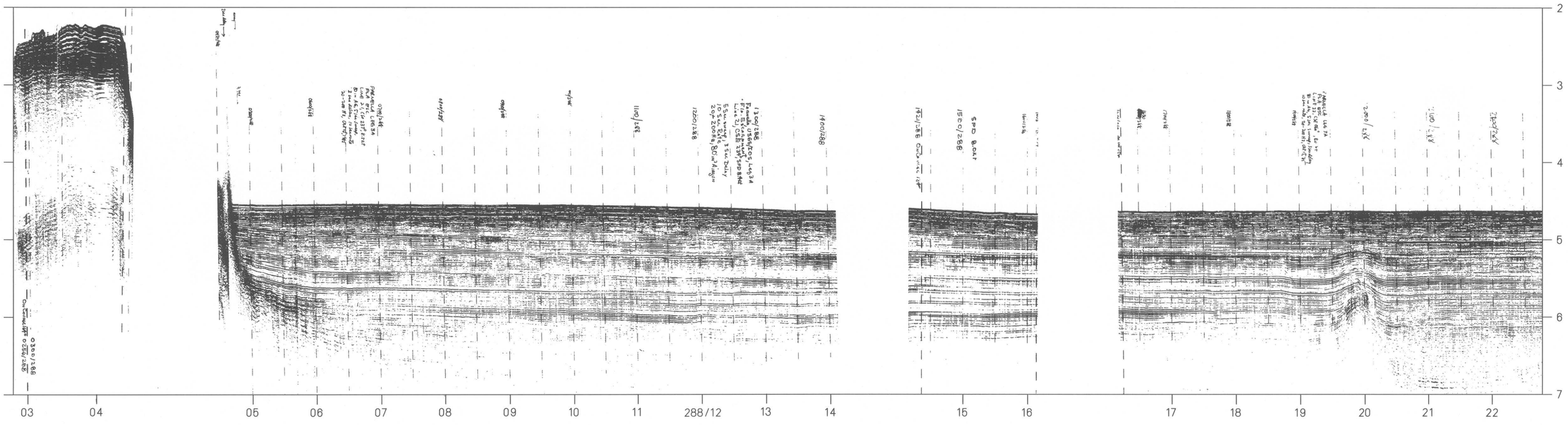

3
4
5
6
7
8
16
17
18
19
20
285/00
01
02
03
04
05
06
07
08
09
10
11
285/12
13
No data
090°
8 KTS
054°
8.3 KTS
HOURS


TWO-WAY TRAVELTIME, IN SECONDS
2
3
4
5
6
7
14
15
16
17
18
19
20
21
22
23
286/00
01
02
03
04
05
06
07
08
09
10
11
287/12
13
14
15
16
17
18
19
20
21
22
23
288/00
01
02
08
09
10
146°
8.3 KTS
234°
8.5 KTS
114°
8.5 KTS
054°
8.2 KTS
116°
7.5 KTS
054°
7.6 KTS
FLORIDA ESCARPMENT
161°
8.5 KTS
234°
8.5 KTS
136°
7.5 KTS
HOURS

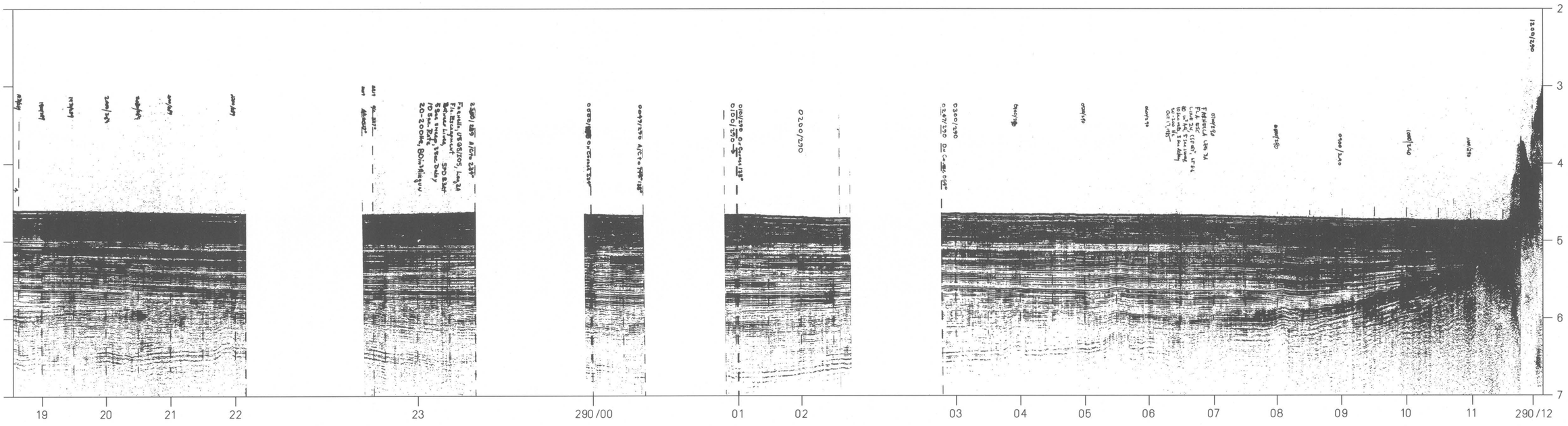
FLORIDA ESCARPMENT



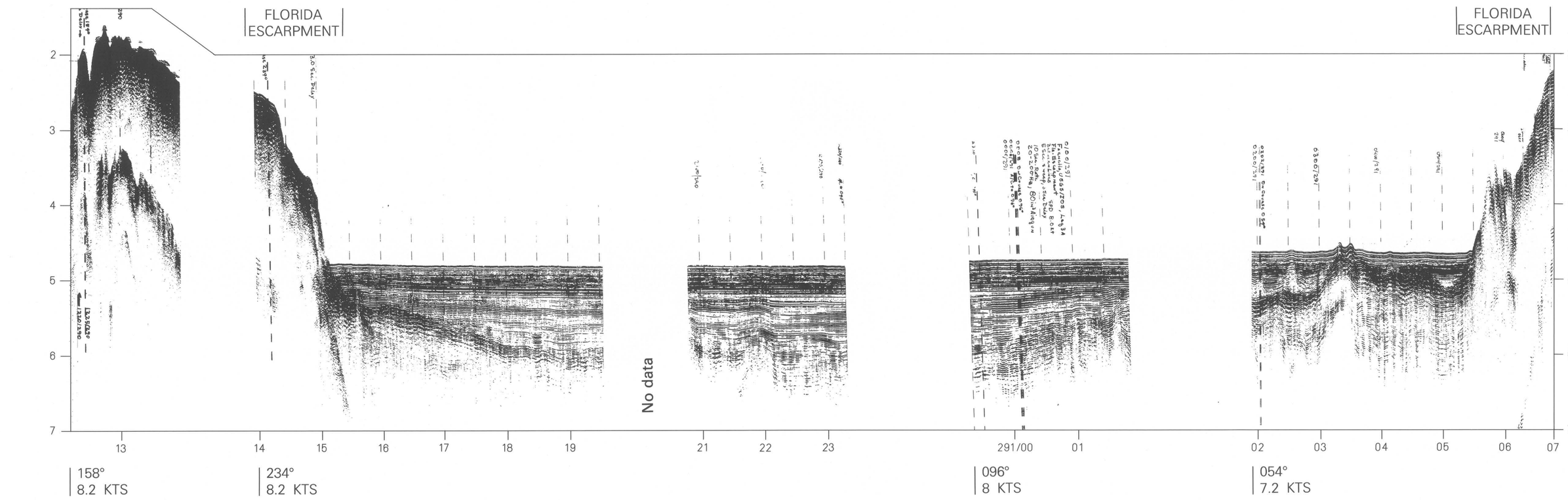
FLORIDA ESCARPMENT

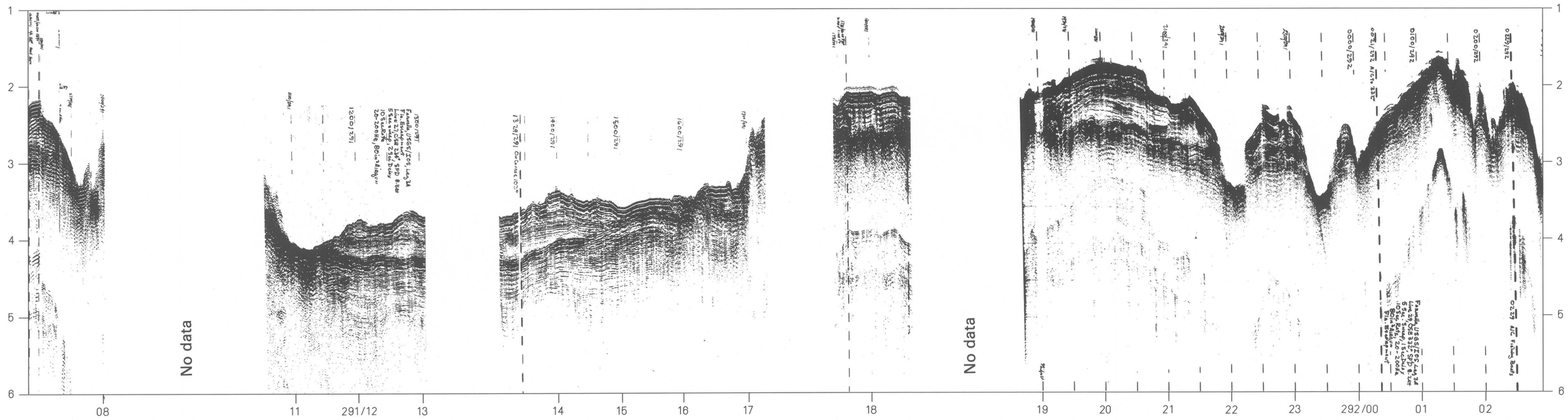


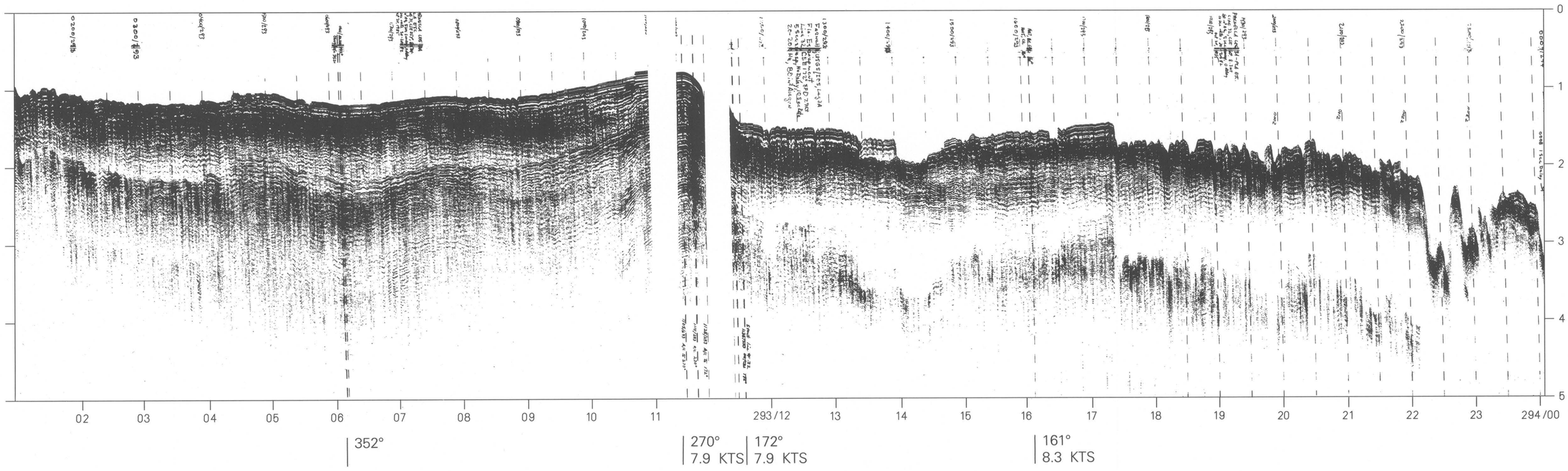
TWO-WAY TRAVELTIME, IN SECONDS



HOURS


FLORIDA ESCARPMENT
FLORIDA ESCARPMENT
No data
No data
TWO-WAY TRAVELTIME, IN SECONDS
158° 8.2 KTS
234° 8.2 KTS
096° 8 KTS
054° 7.2 KTS
130° 8.2 KTS
150° 8.2 KTS
100° 8.0 KTS
325° 8.0 KTS
309°
341° 8.4 KTS
100° 8.2 KTS
150° 8.2 KTS
090° 7.4 KTS
000° 7.4 KTS
270° 7.4 KTS
HOURS


No data
No data
08
11
291/12
13
14
15
16
17
18
19
20
21
22
23
292/00
01
02
169°
8 KTS
234°
8.5 KTS
102°
7.7 KTS
330°
8 KTS
332°
8.2 KTS


02
03
04
05
06
07
08
09
10
11
293/12
13
14
15
16
17
18
19
20
21
22
23
294/00
352°
270°
7.9 KTS
172°
7.9 KTS
161°
8.3 KTS
TWO-WAY TRAVELTIME, IN SECONDS

HOURS

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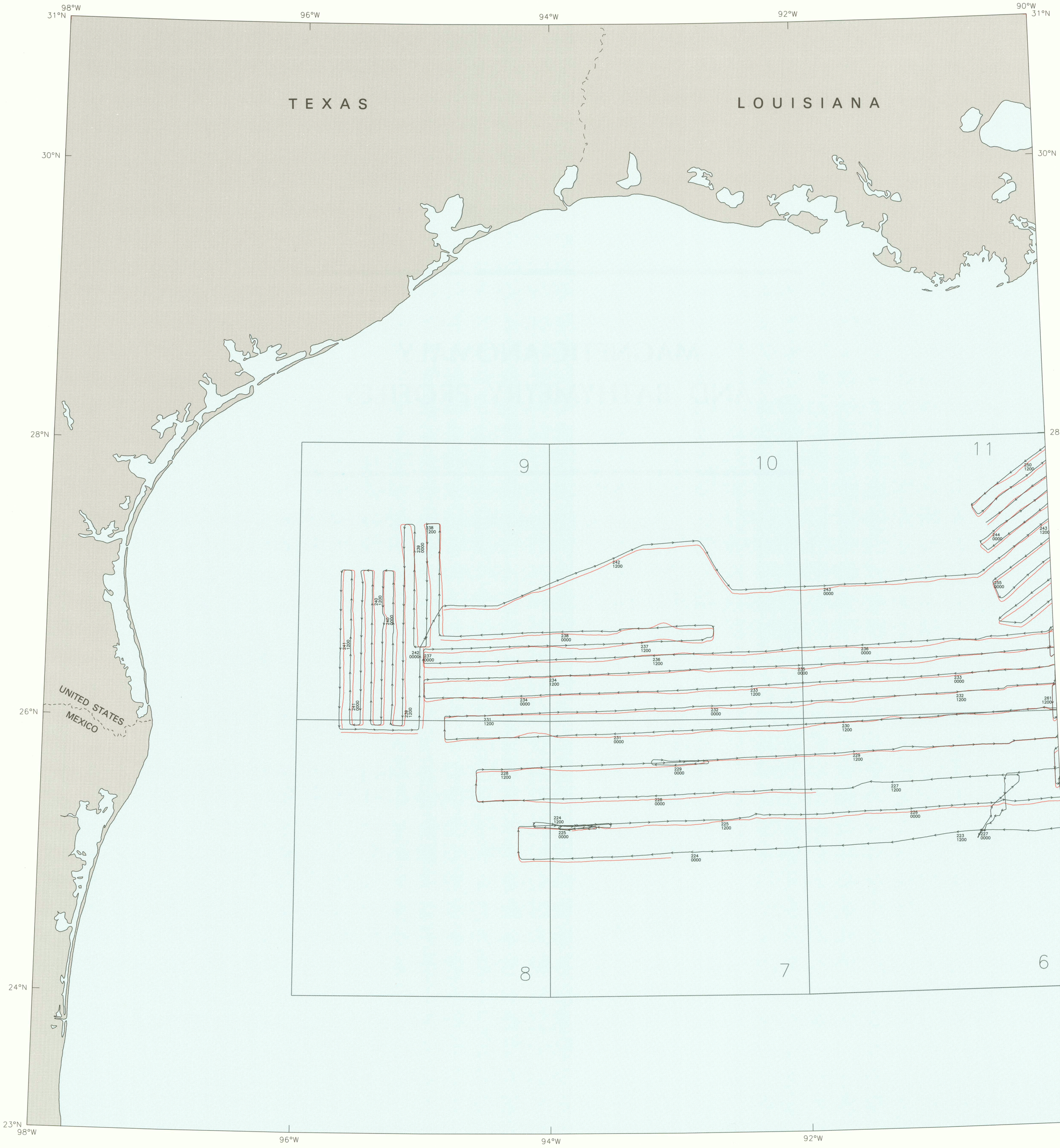
MAGNETIC-ANOMALY AND BATHYMETRY PROFILES

DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY



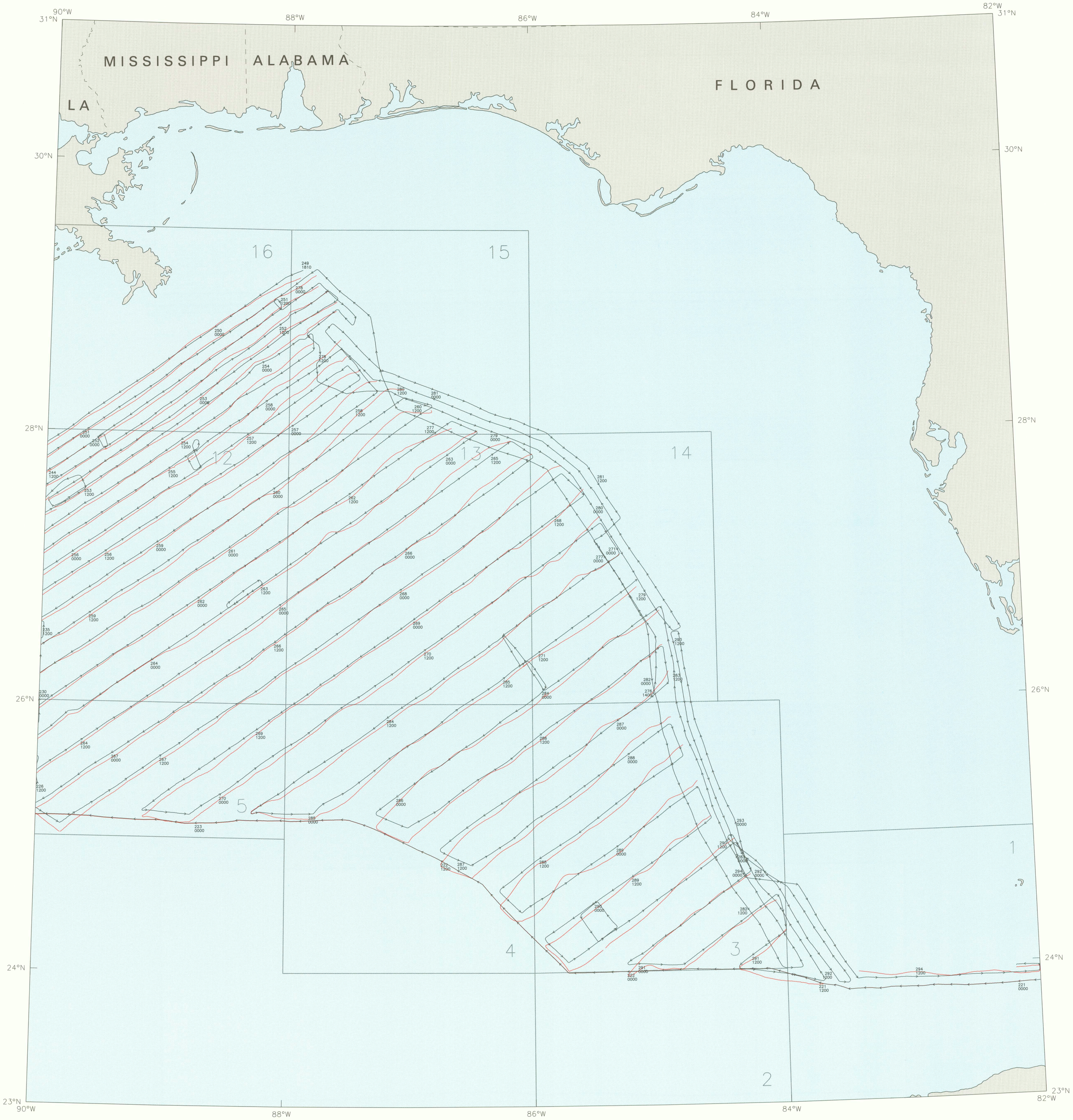
SCALE 1:2 000 000

50 0 50 100 150 NAUTICAL MILES

50 0 50 100 150 200 250 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

Map showing generalized magnetic-anomaly profiles (in red) along tracklines in the western Gulf of Mexico. Profiles are scaled so that a 1–cm offset from the trackline (0 gammas) represents 500 gammas.



SCALE 1:2 000 000

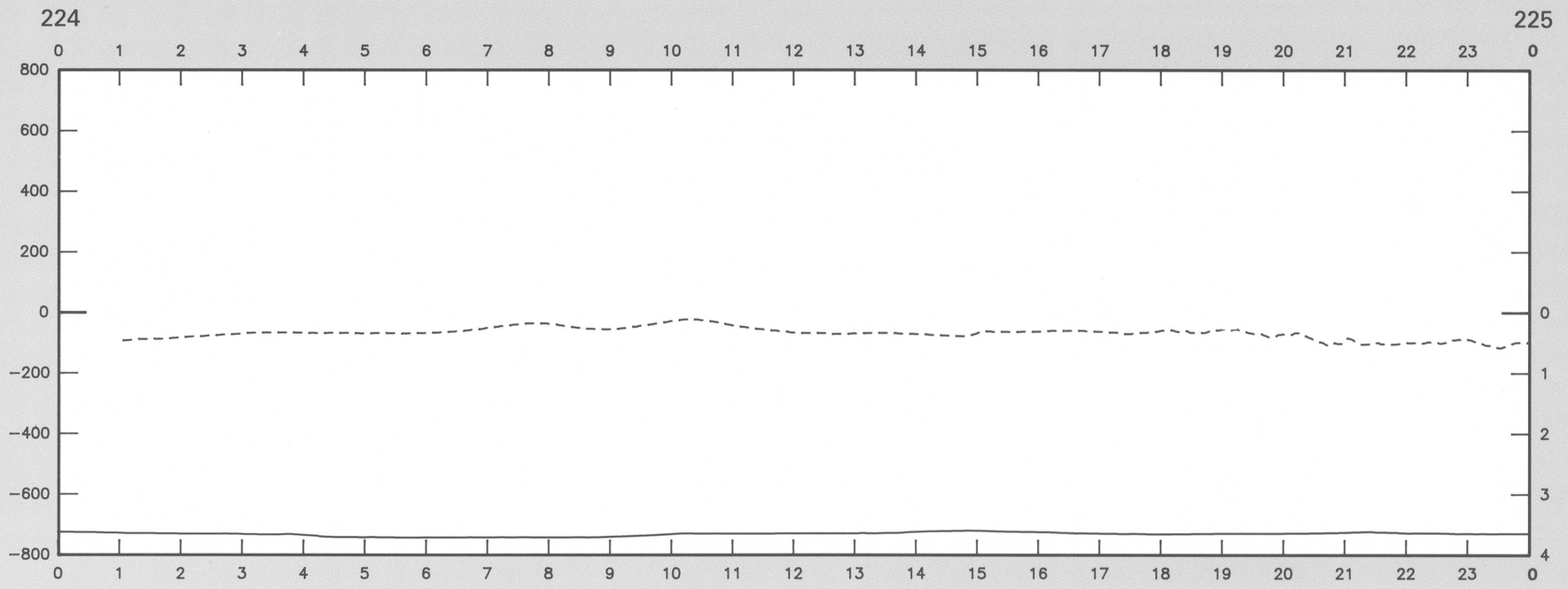
50 0 50 100 150 NAUTICAL MILES

50 0 50 100 150 200 250 KILOMETERS

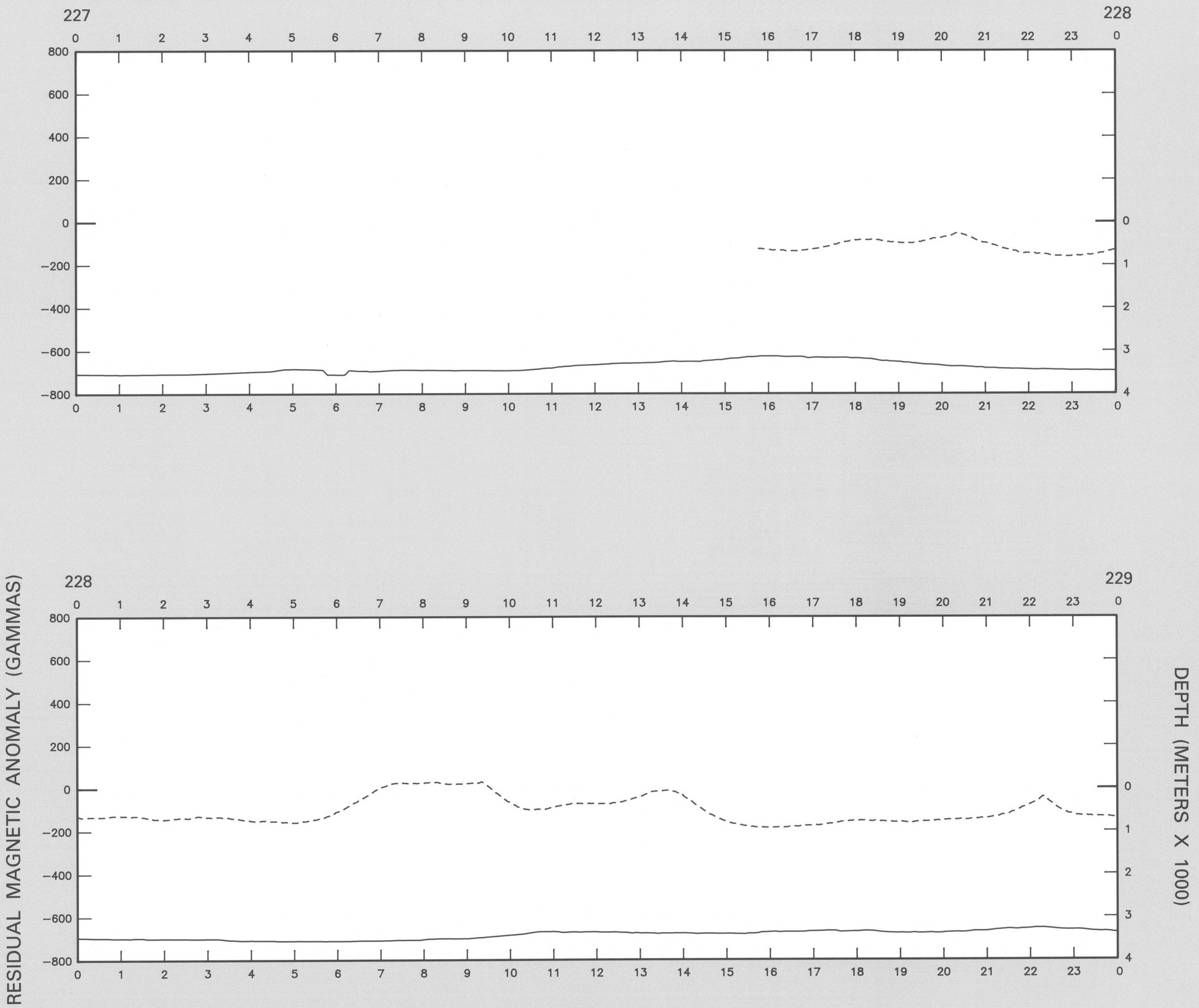
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

Map showing generalized magnetic-anomaly profiles (in red) along tracklines in the eastern Gulf of Mexico. Profiles are scaled so that a 1–cm offset from the trackline (0 gammas) represents 500 gammas.

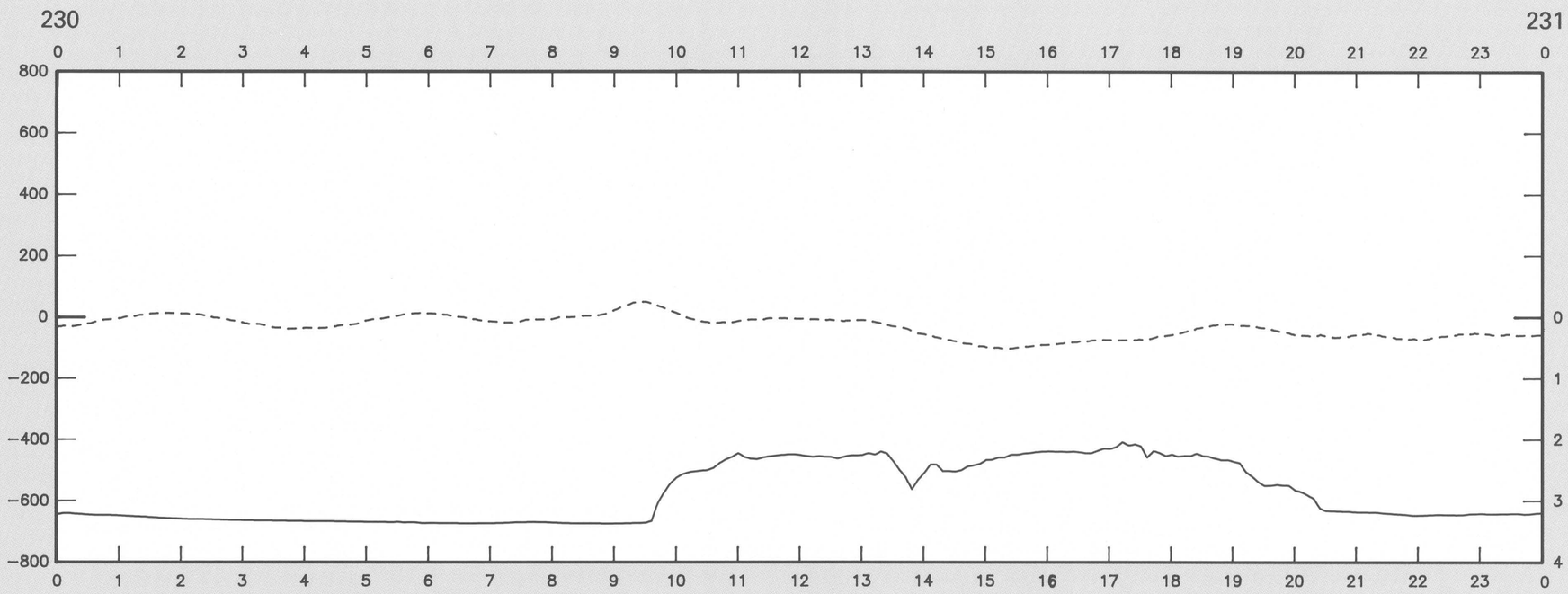
DAY 224–227


224
225
226
227
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0
1
2
3
4
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
HOURS
EXPLANATION
Bathymetry
Magnetics

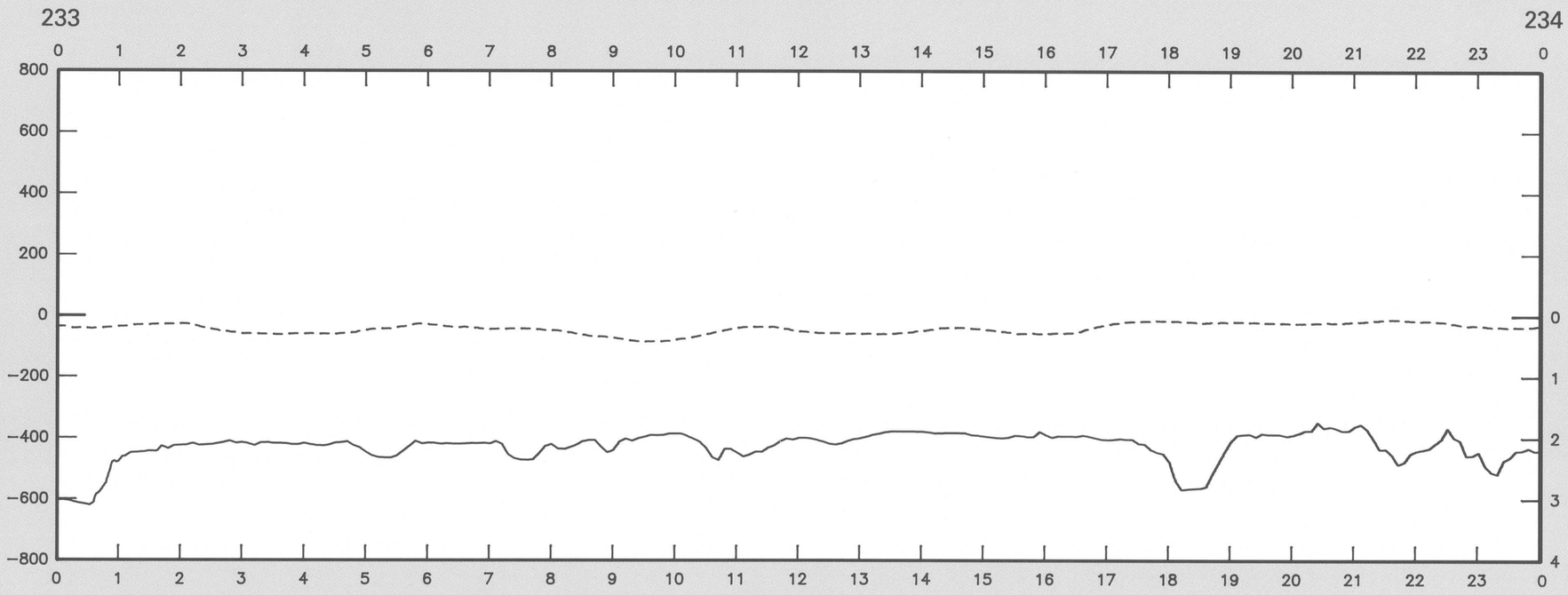
DAY 227–230

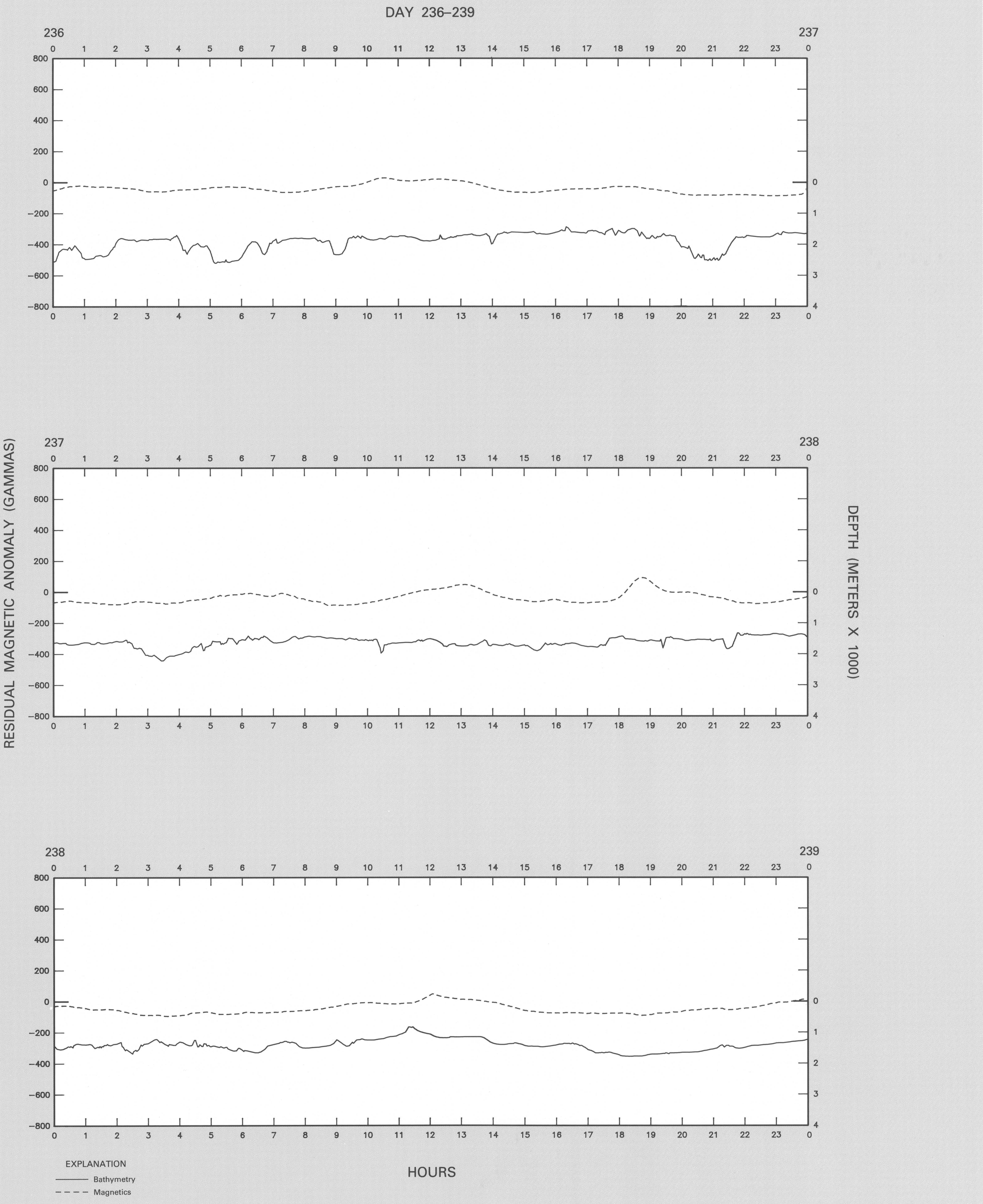

227
228
229
230
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0
1
2
3
4
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
EXPLANATION
Bathymetry
Magnetics
HOURS

DAY 230–233

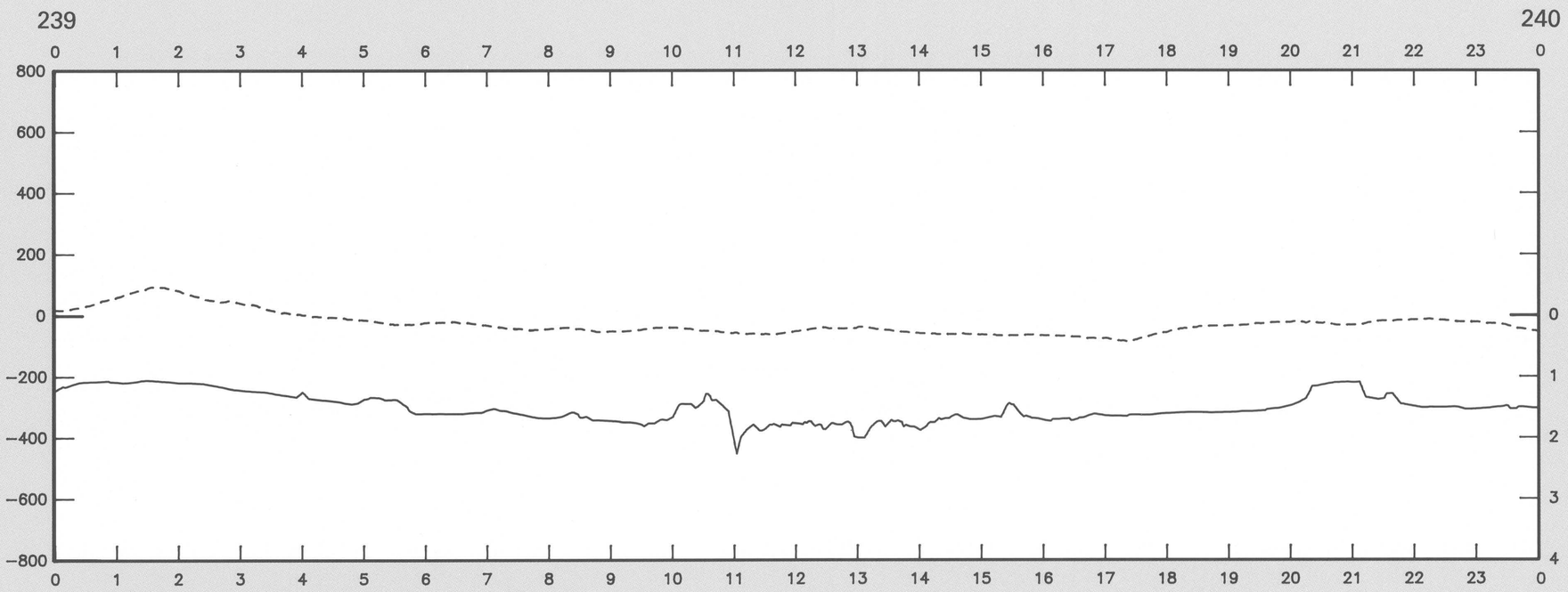

230
231
232
233
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0
1
2
3
4
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
HOURS
EXPLANATION
Bathymetry
Magnetics

DAY 233–236


233
234
235
236
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0
1
2
3
4
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
HOURS
EXPLANATION
Bathymetry
Magnetics


DAY 236–239
236
237
238
239
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0
1
2
3
4
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
EXPLANATION
Bathymetry
Magnetics
HOURS

DAY 239–242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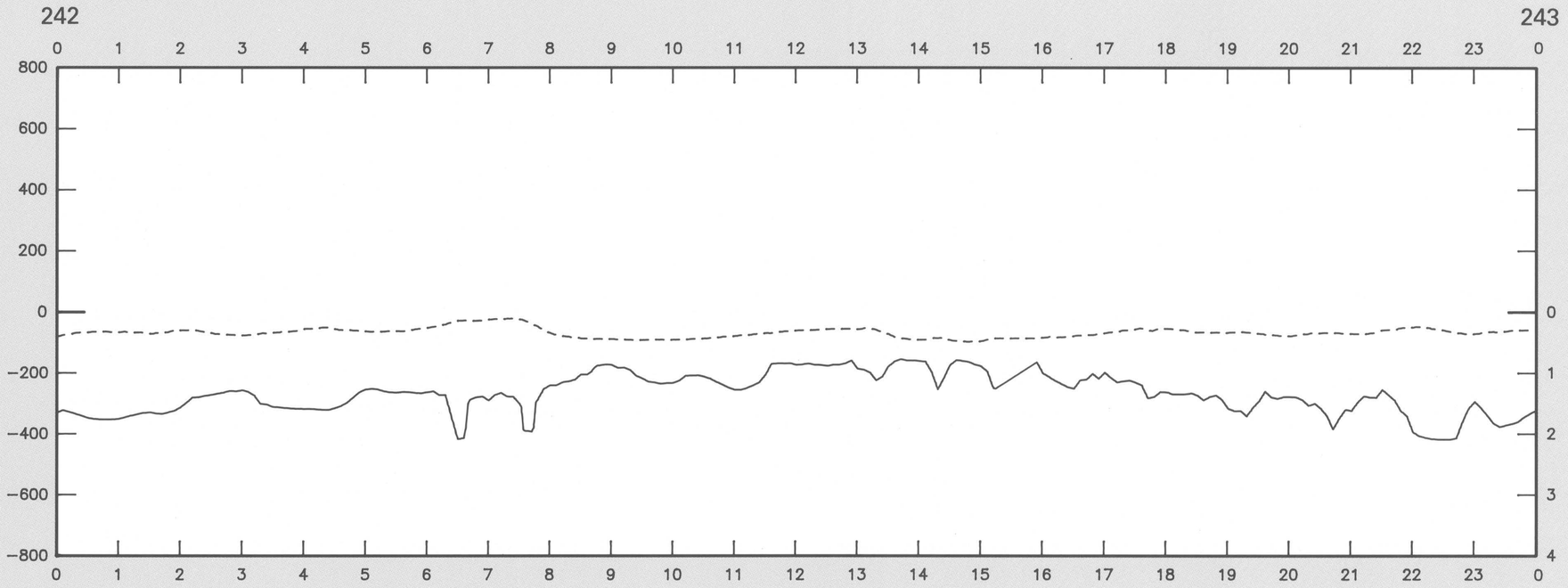
DEPTH (METERS X 1000)
HOURS
EXPLANATION
Bathymetry
Magnetics

DAY 242–245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DEPTH (METERS X 1000)
HOURS
EXPLANATION
Bathymetry
Magnetics

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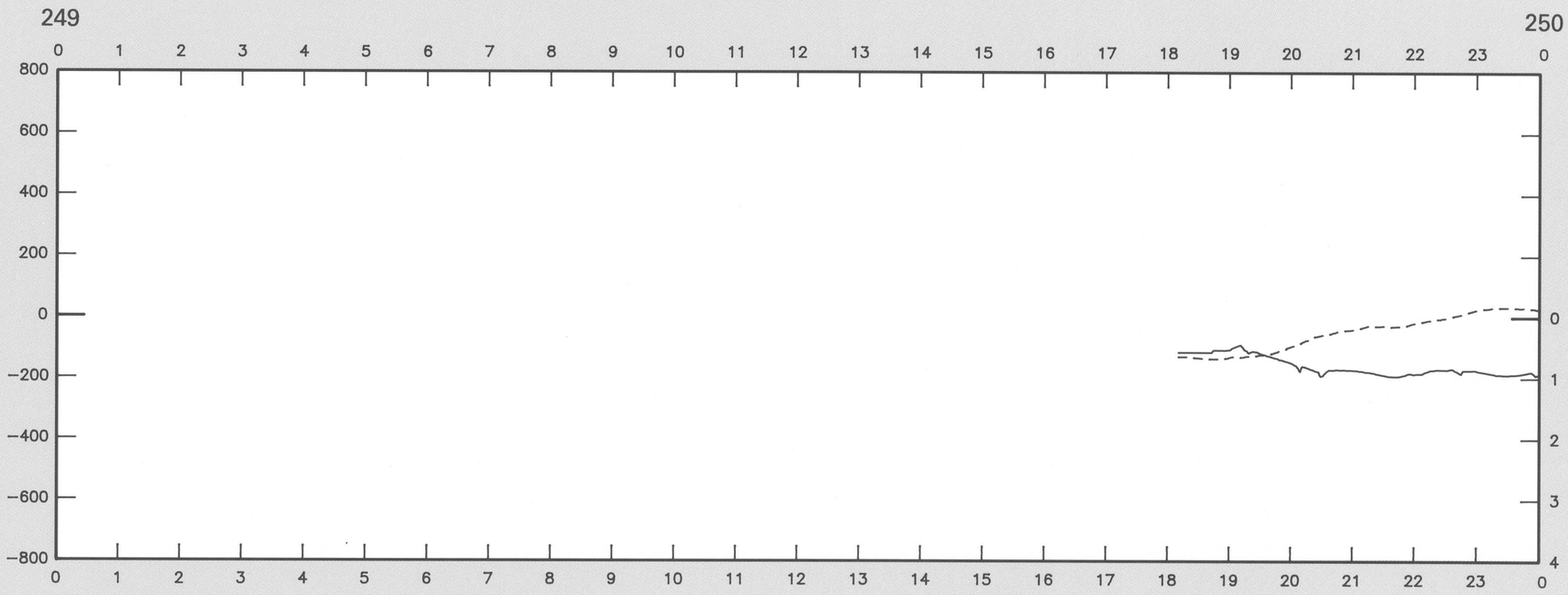
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DEPTH (METERS X 1000)
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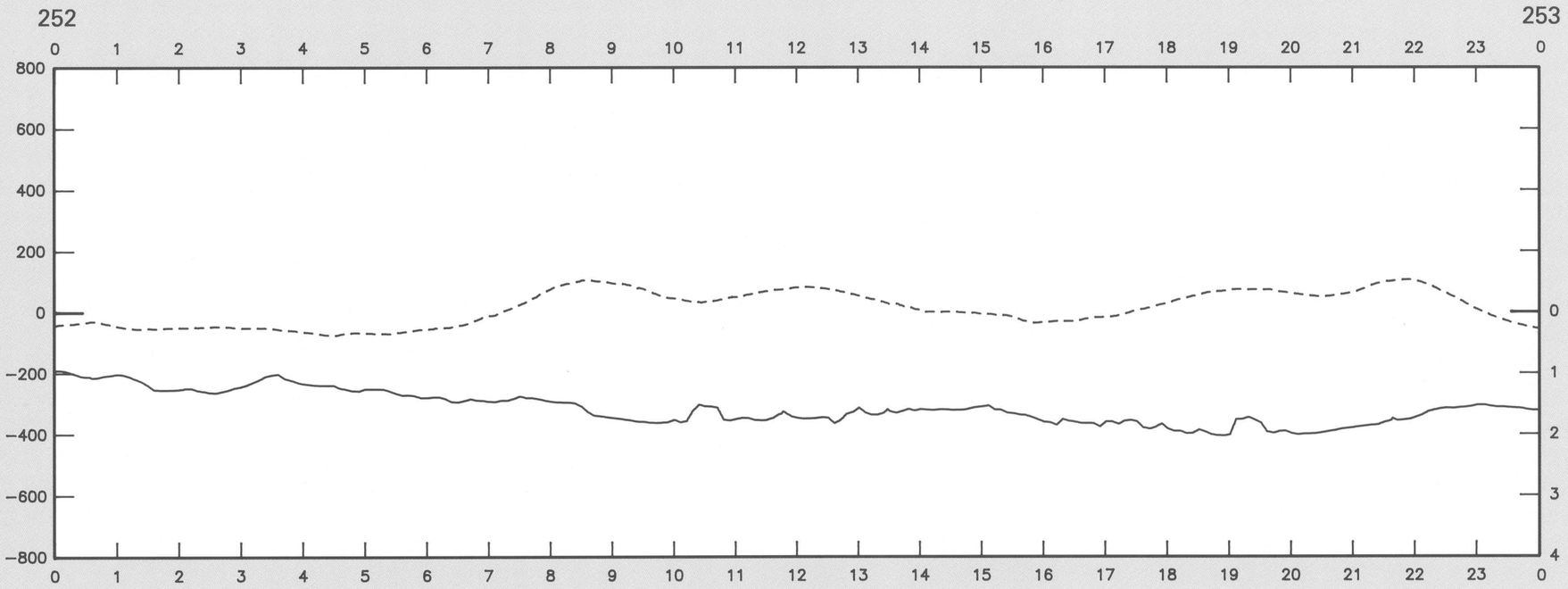
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DEPTH (METERS X 1000)
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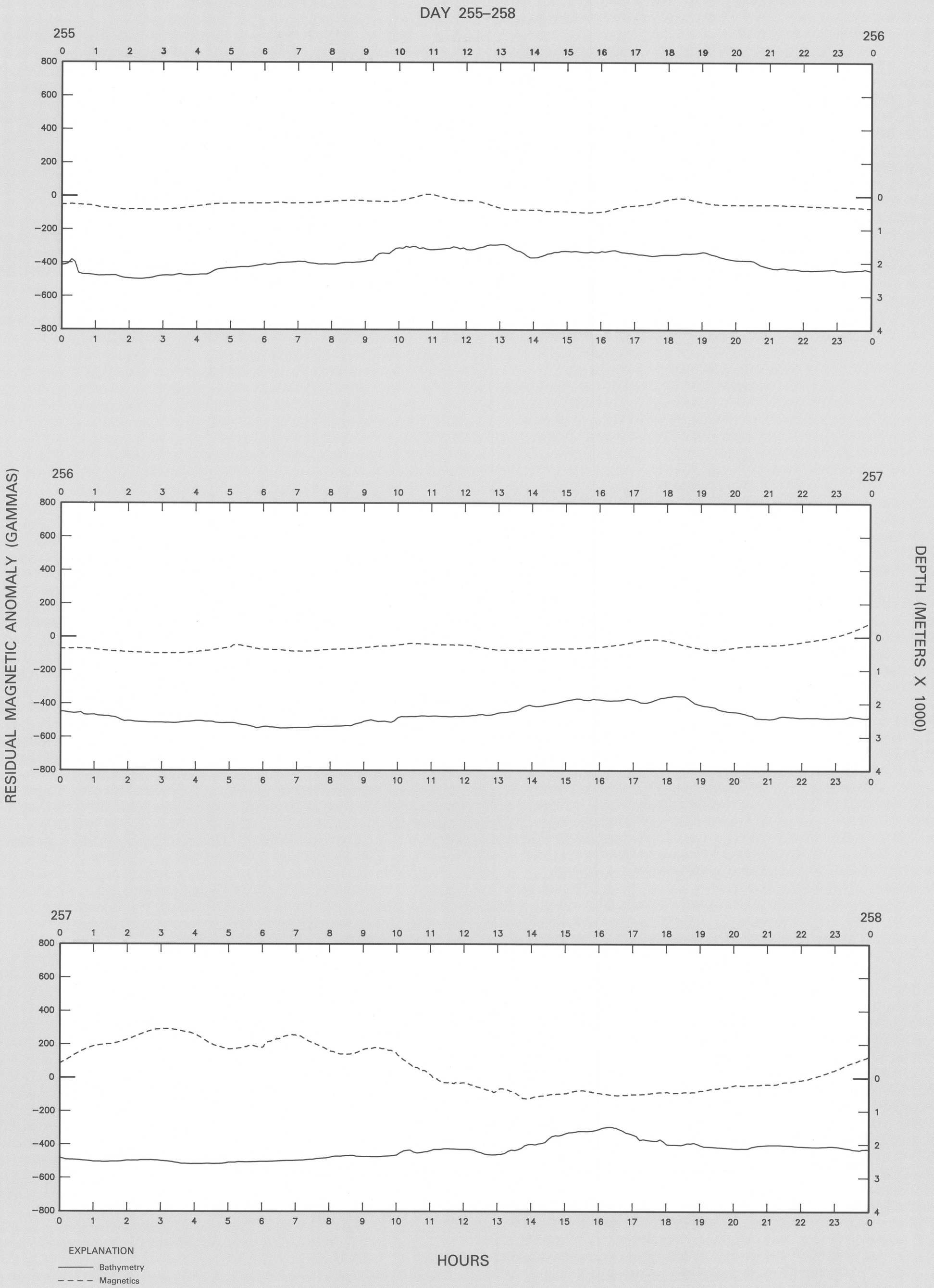
EXPLANATION
Bathymetry
Magnetics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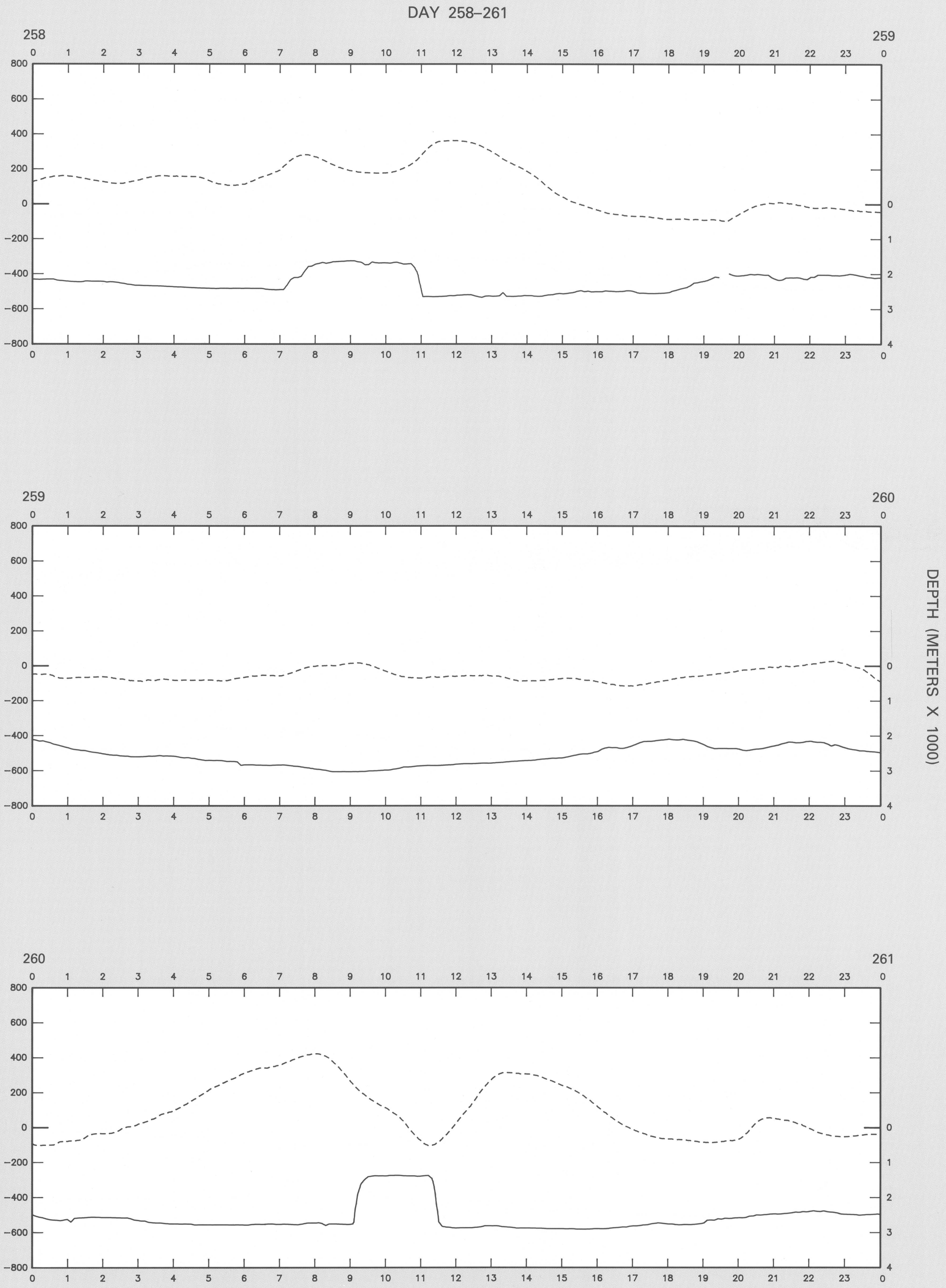
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DEPTH (METERS X 1000)
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HOURS

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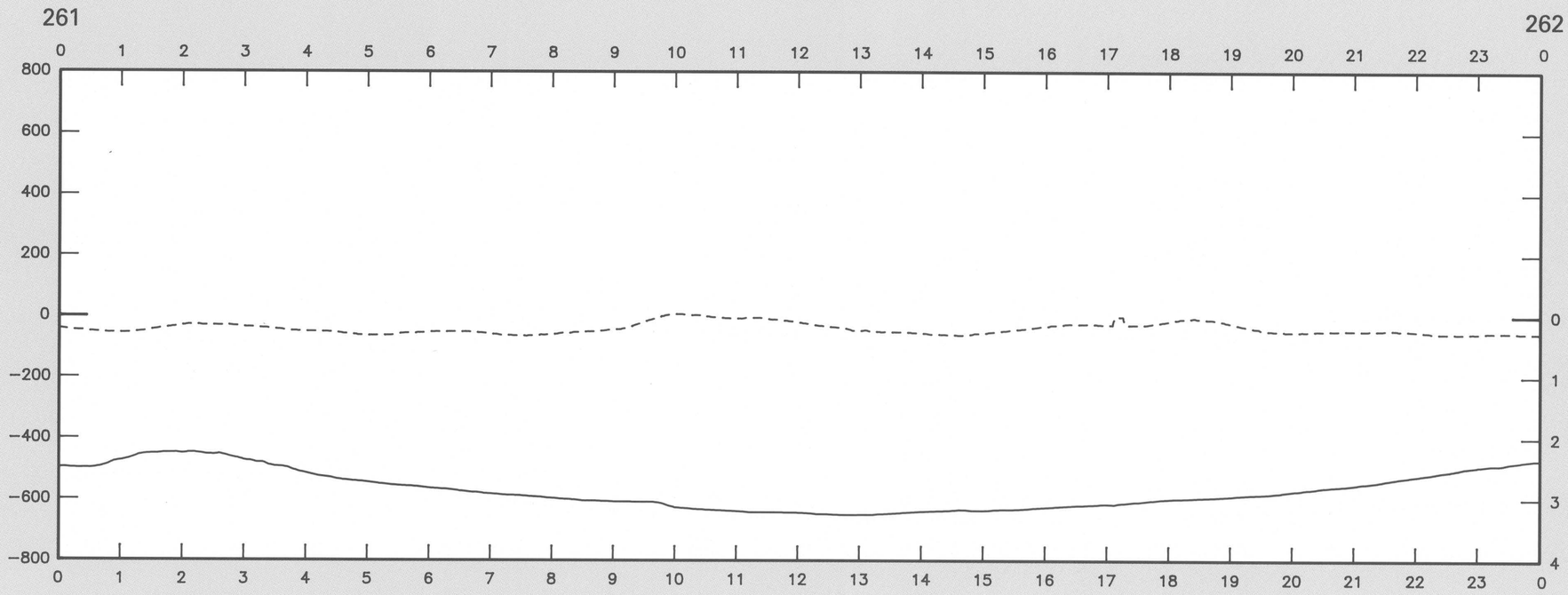
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DEPTH (METERS X 1000)
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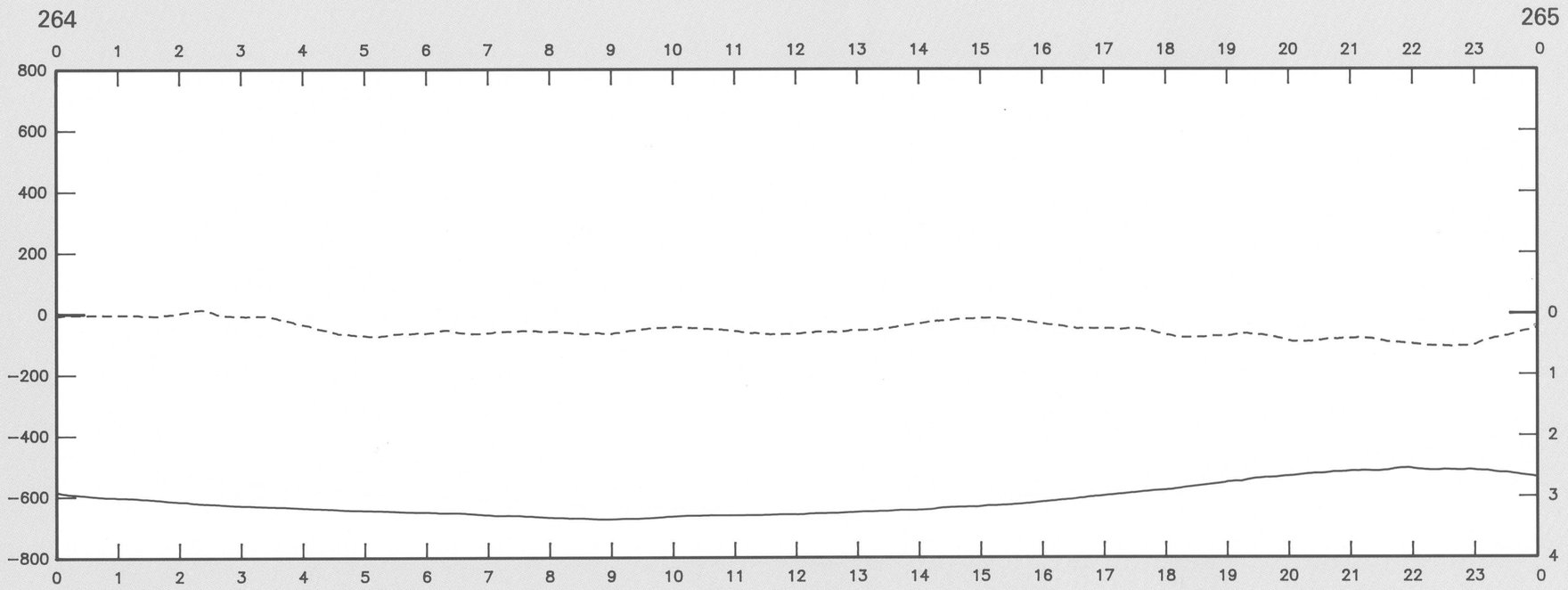
Magnetics

DAY 264–267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DEPTH (METERS X 1000)
EXPLANATION
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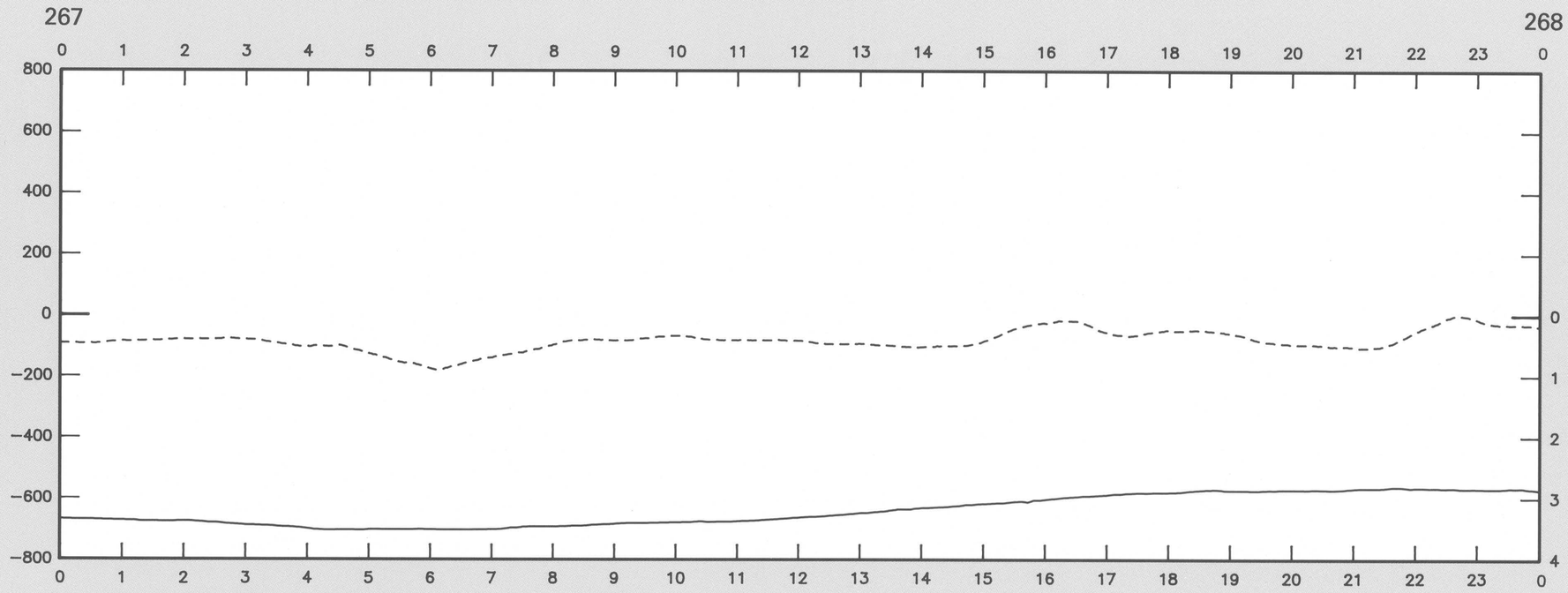
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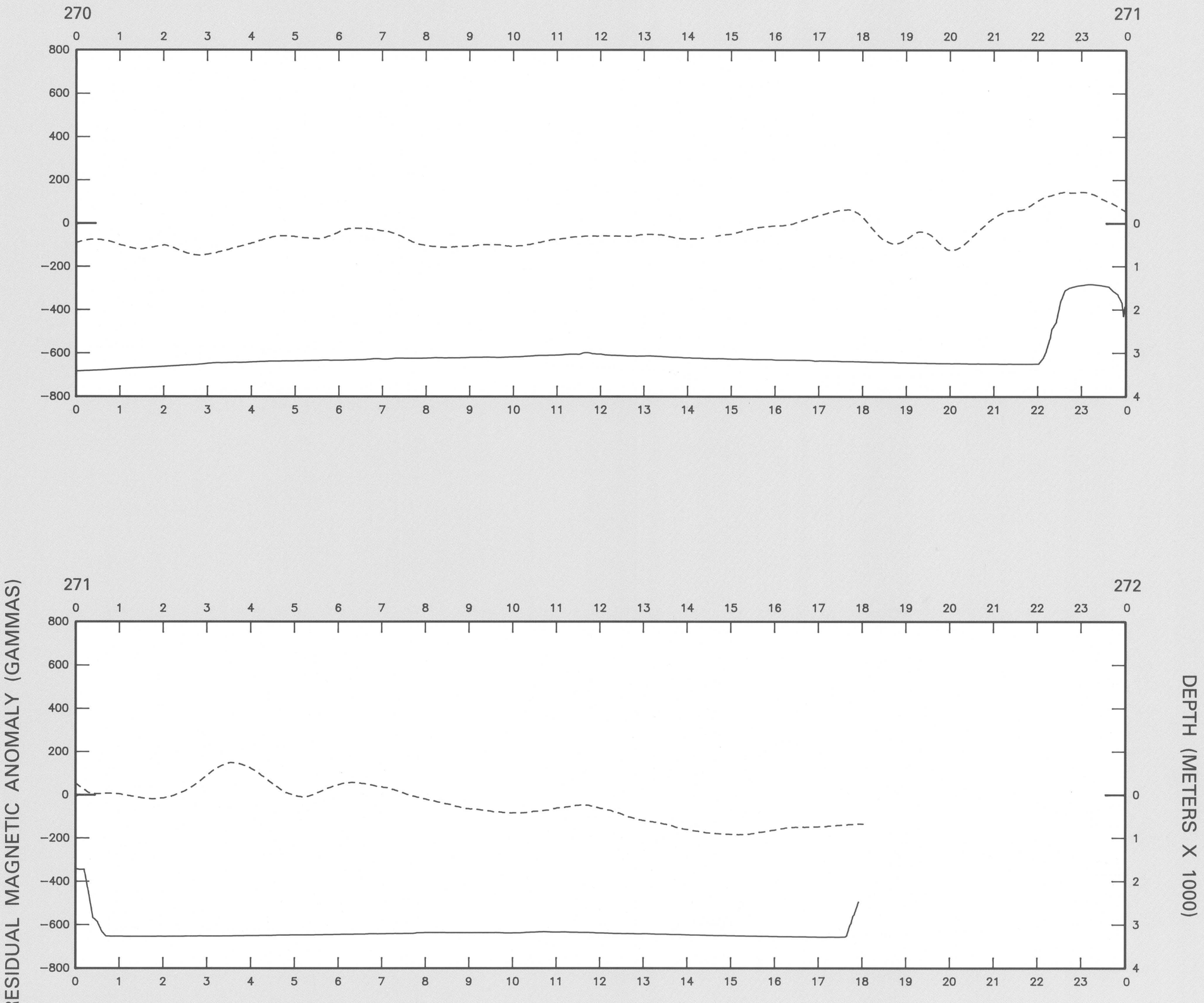

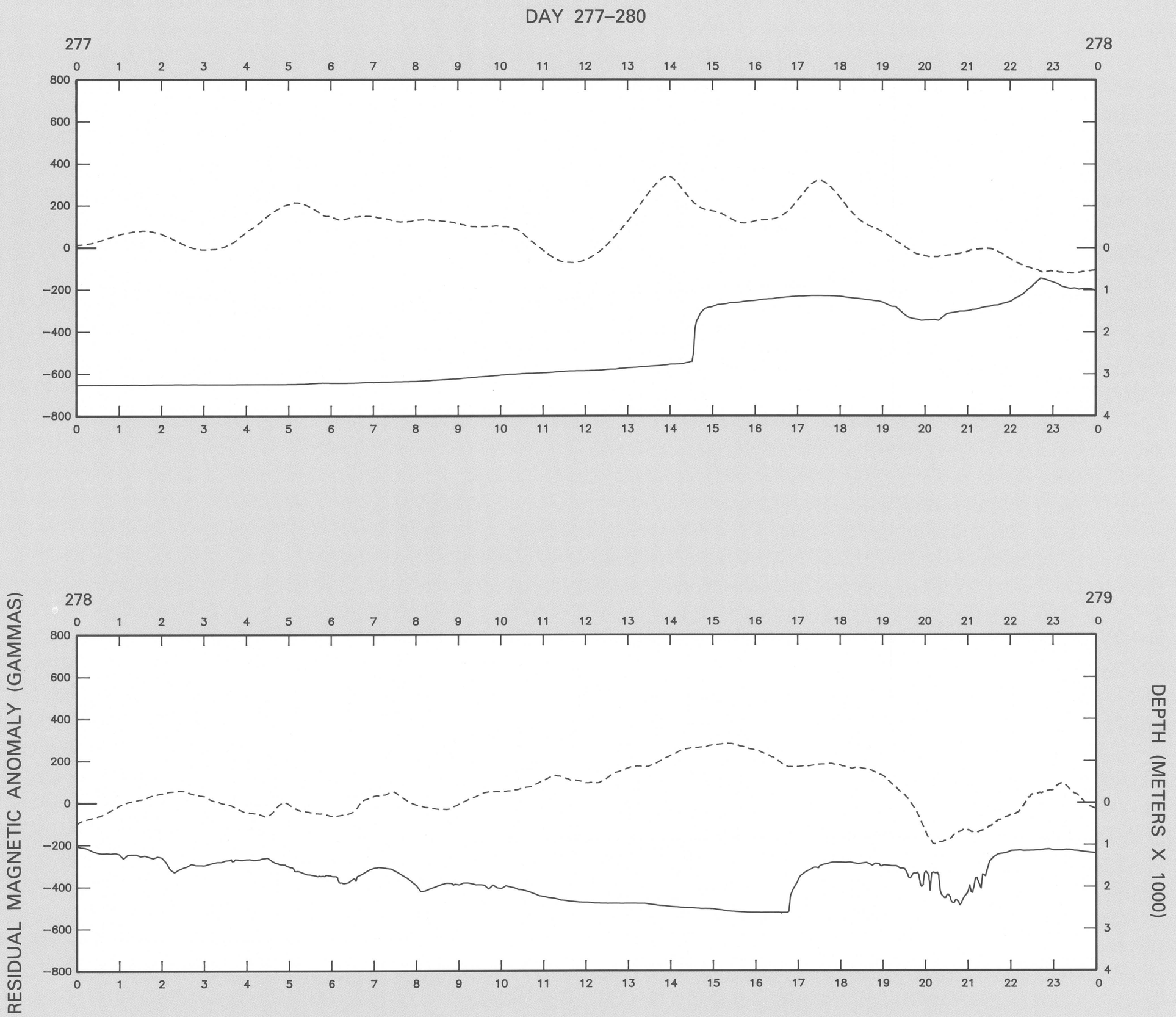
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DEPTH (METERS X 1000)
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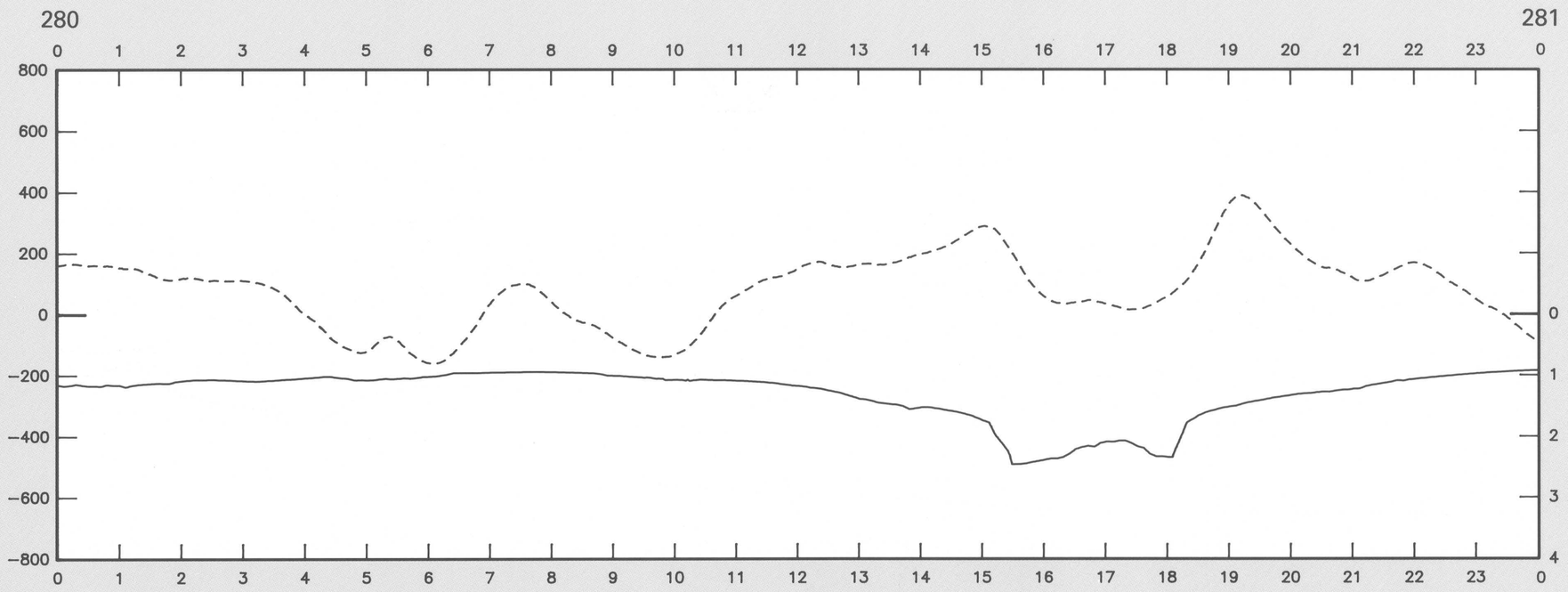
DAY 280–283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RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
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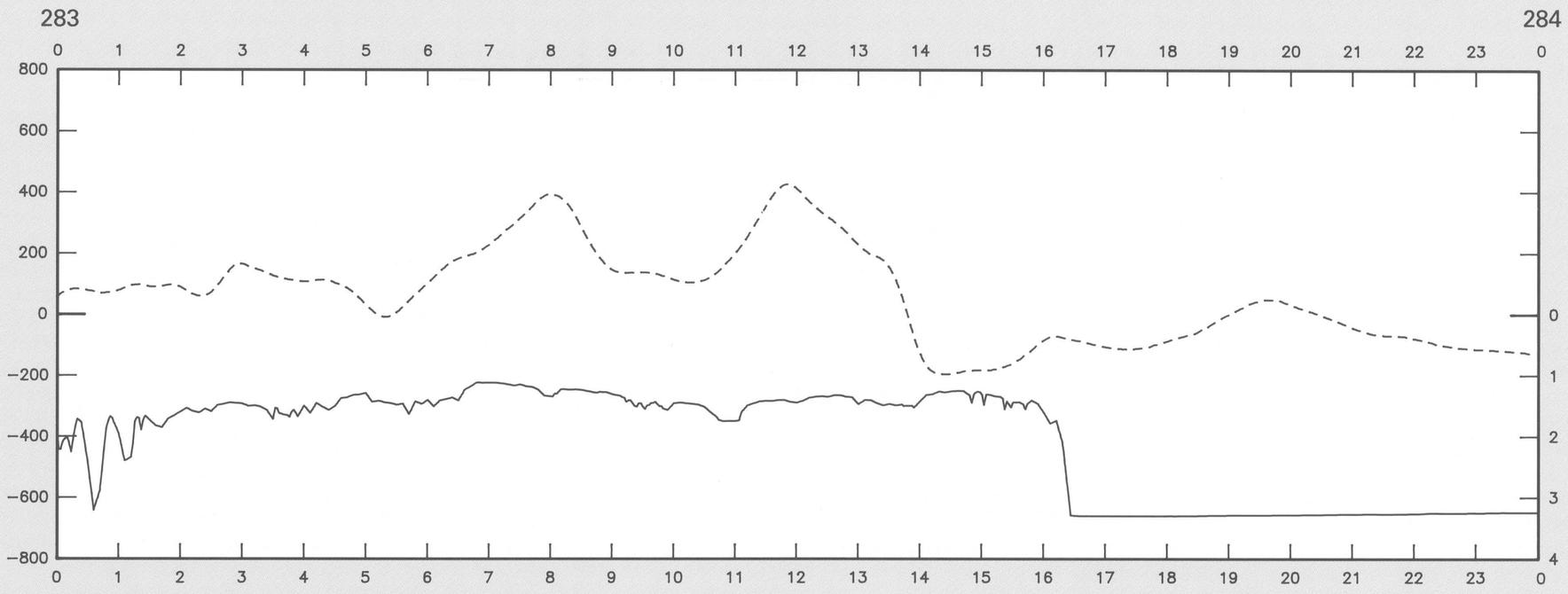
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DEPTH (METERS X 1000)
EXPLANATION
Bathymetry
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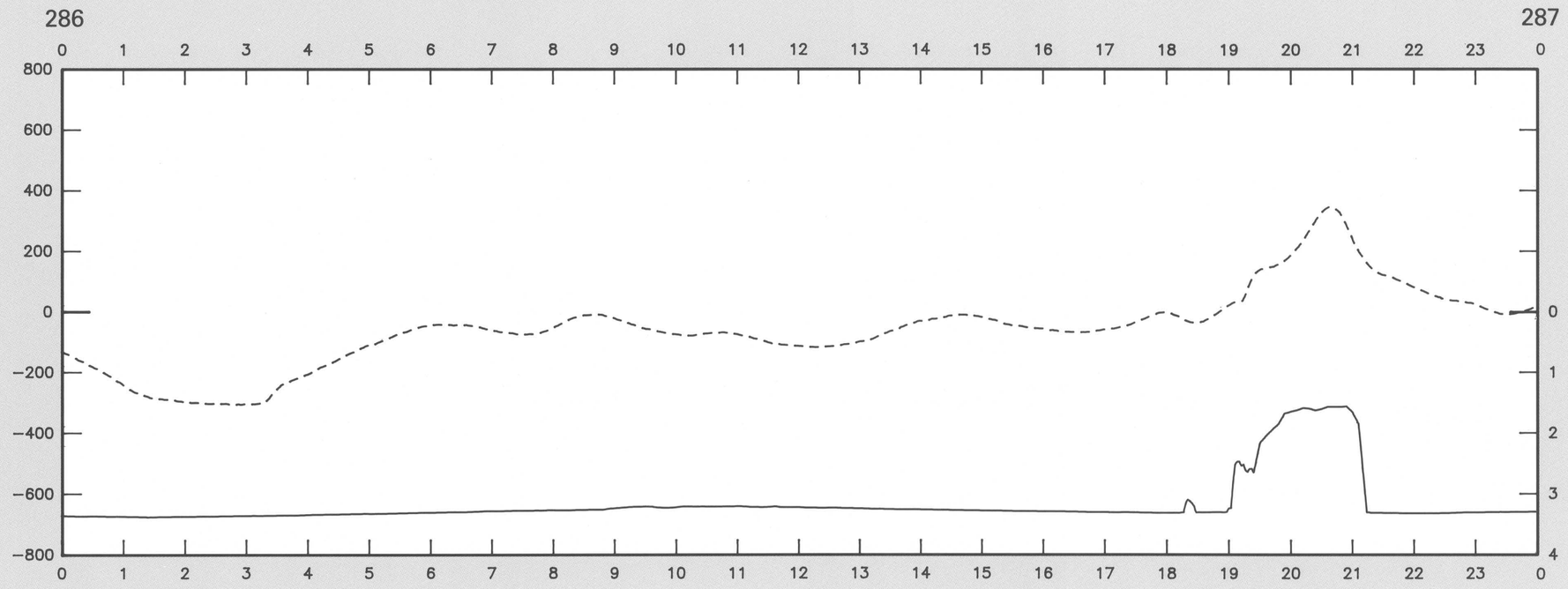
DAY 286–289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RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
HOURS
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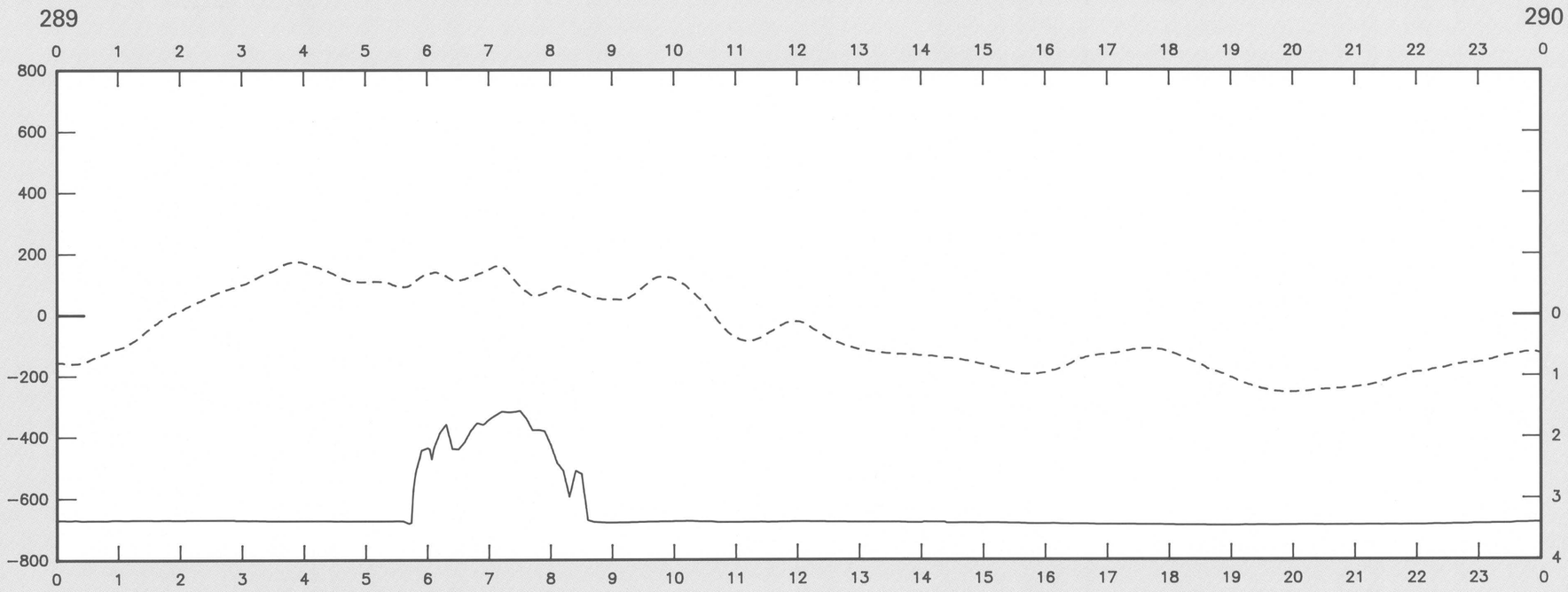
DAY 289–292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DEPTH (METERS X 1000)
HOURS
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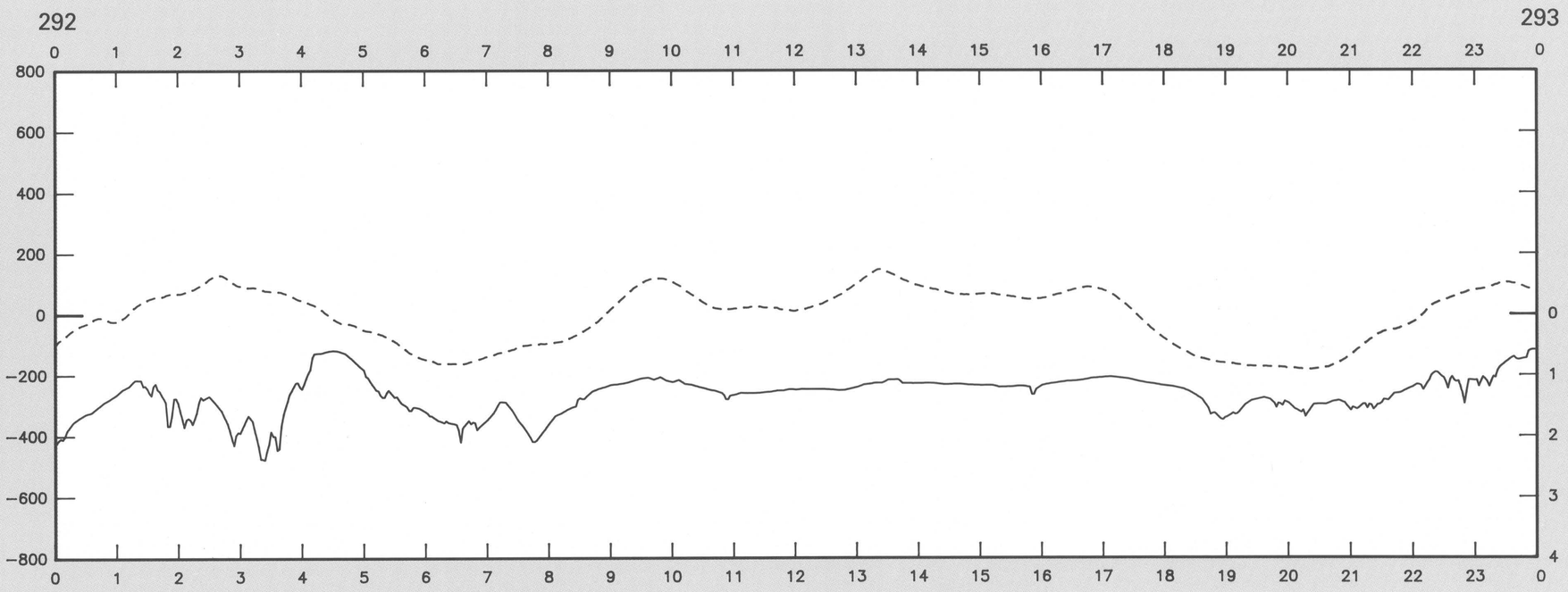
DAY 292–295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RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
EXPLANATION
Bathymetry
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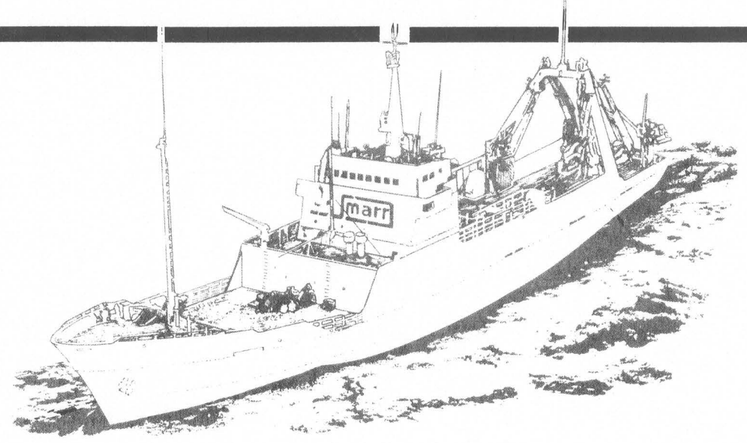
Atlas of the U.S. Exclusive Economic Zone, Eastern Caribbean



By EEZ-SCAN 85 Scientific Staff

U.S. Geological Survey
Miscellaneous Investigations Series I-1864-B

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INTRODUCTION

On March 10, 1983, President Reagan signed a proclamation establishing an Exclusive Economic Zone (EEZ) extending 200 nautical miles seaward from the coasts of the United States, the Commonwealths of Puerto Rico and the Northern Mariana Islands, and the U.S. territories and possessions. Within this zone, the United States claimed jurisdiction over the seabed and its resources (fig. 1). In 1984 the U.S. Geological Survey (USGS), in keeping with its mission to map the federal lands and to determine their resource potential, began a program to provide maps of the EEZ. For reconnaissance-scale mapping the USGS selected the long-range sidescan-sonar system, GLORIA (Geologic LOng-Range Inclined Asdic), owned and operated by British colleagues at the United Kingdom's Institute of Oceanographic Sciences (IOS).

Sidescan sonar was selected for the mapping because it can be used to obtain information on geologic processes. The intensity of the backscattered sound from the sea floor is a function of the gradient or slope of the sea floor, of the microtopography or surface roughness, and of the sediment characteristics such as texture or induration. Because sidescan sonar provides information from a swath of sea floor, large areas can be mapped quickly.

In the summer of 1984 the USGS began its sidescan-sonar survey of the EEZ off the coasts of Washington, Oregon, and California. In 100 days, the EEZ was mapped from the Canadian to the Mexican border, extending from the continental shelf edge (approximately 200 meters (m) water depth) to the seaward boundary of the EEZ. Results of this survey were published by the USGS in the *Atlas of the Exclusive Economic Zone, Western Conterminous United States* (EEZ-SCAN 84 Scientific Staff, 1986) (fig. 2). Continuing the mapping effort in the late summer and fall of 1985, the USGS conducted surveys of the EEZ in the Gulf of Mexico and around Puerto Rico and the U.S. Virgin Islands.

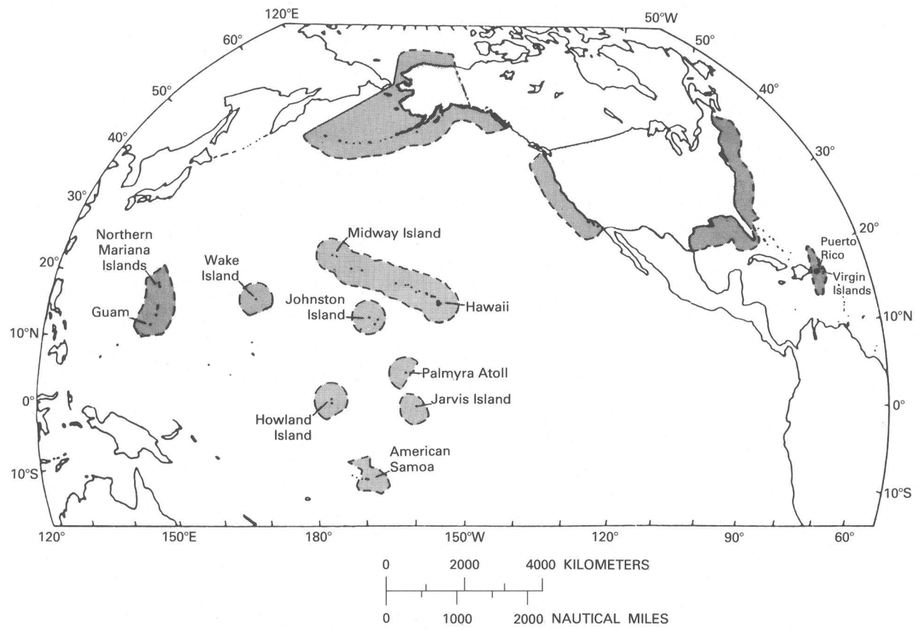

Figure 1—Exclusive Economic Zone (EEZ) of the United States, Commonwealth of Puerto Rico, Commonwealth of the Northern Mariana Islands, and United States overseas territories and possessions (outlines of map are approximate).

DATA COLLECTION

The data for the eastern Caribbean area were collected during a single 30-day cruise in November and December 1985. Sidescan-sonar coverage was obtained over the entire EEZ of Puerto Rico and the U.S. Virgin Islands, from the insular shelf edge to the EEZ boundary (fig. 3). Seismic-reflection profile data and total-magnetic-field data were also collected along all of the ship's tracks during this survey.

The eastern Caribbean survey was carried out during the last cruise (Leg 4) of a series of four cruises on the research vessel *Farnella*. The first three cruises were devoted to surveying the EEZ in the Gulf of Mexico; they are reported on in the first part of this publication (atlas I-1864-A). Leg 4 began and ended in San Juan, Puerto Rico.

Navigational control for this survey was provided by transit satellites and the Global Positioning System (GPS). We estimate the accuracy of our navigation to be no worse than 1 kilometer (km).

Trackline orientation in the eastern Caribbean (fig. 3; also see p. B6 (fig. 13)) was determined by several factors, including weather conditions, water depth and regional slope, and the expected orientations of major bathymetric and structural features. Tracklines were spaced closely enough to achieve overlap between adjacent sidescan swaths. For safety reasons and because of the reduced swath width in shallow water, the GLORIA system was not operated on the insular shelves.

Data from this cruise are annotated with Julian dates. On the Julian calendar, days are numbered consecutively from 1 (January 1) to 365 (December 31). The eastern Caribbean GLORIA survey began on Julian day 309 and ended on Julian day 336.

GLORIA II Sidescan-Sonar System

GLORIA is a long-range sidescan-sonar system developed by IOS to map the morphology and texture of sea-floor features in the deep ocean. Sidescan-sonar images (sonographs) are a record of the acoustic backscatter properties of the sea floor. To create these images, sound pulses are transmitted from two sets of transducers mounted in a towed vehicle, which look to port and starboard respectively. The transducers are tuned so that their beams form a narrow arc (2.7°) in the horizontal plane and a broad arc in the vertical plane. Each transmitted sound signal thus insonifies a narrow band of sea floor perpendicular to the ship's track and extending from directly beneath the towed vehicle to the maximum range on each side (fig. 4). The sound signal is reflected by the sea floor and travels back to the transducers on the towed vehicle. The time and intensity of the returning signal are recorded on the ship. As the ship moves, successive bands of sea floor are insonified, and in this way an acoustic map of the sea floor is recorded.

A few of the important technical features of the GLORIA system are provided here. For more detailed information and specifications, the reader is referred to Somers and others (1978). The sidescan vehicle, or "fish", is 8 m long, weighs 2.25 tons in air, and is almost neutrally buoyant. The sonar arrays consist of a total of 120 transducers, 30 to a row, 60 to each side. The vehicle is towed about 400 m behind the ship with no active depth control, but at the normal survey speed of 8 knots (kts), or 15 km/hour (hr), the vehicle depth is about 50 m (fig. 4). The operating frequency of the GLORIA system is about 6.5 kiloHertz (kHz), with the port array at 6.8 kHz and the starboard array at 6.2 kHz to eliminate cross-talk between the two sides. Each array is 5.3 m long by 40 centimeters (cm) high, a configuration that gives a horizontal acoustic beam 2.7° wide and a vertical beam of 35°. The beam width is specified between half-power points, and considerable energy actually radiates outside these limits. The arrays are designed to confine the energy as nearly as possible to the plane perpendicular to the track and to fill the quadrant from nadir (the point on the sea floor directly beneath the towed vehicle) up to near horizontal.

The maximum swath width largely depends on the prevailing acoustic propagation conditions of the water column. For GLORIA the swath width can be as great as 30 km on each side of the track. Under normal conditions, however, it is usually somewhat less. If acoustic conditions are unfavorable and the water depth is less than about 1,500 m, then the range may be less than 10 km on each side of the track. In the Gulf of Mexico during August through October, the pronounced thermocline reflected the far-range, low-incident-angle sound waves, restricting the swath width. No such problems restricted the swath width during the Caribbean survey, where a total swath of 40 km (20 km to each side) was achieved in the deepest areas. In the shallow water of the insular slope the maximum range obtained was considerably less.

The acoustic energy reflected from the sea floor is recorded in digital format on magnetic tape. Each pixel (digital picture element) of the image has a size, measured along the track, that is proportional to the range and that increases to hundreds of meters at extreme range because the sound beam diverges at 2.7°. The recording system was designed so that one complete scan is subdivided into 1,000 pixels. The cross-range pixel size represents about 50 m, which is smaller than the along-track pixel size; thus features in the raw data are elongated parallel to the track, particularly at extreme range. This and other distortions were corrected by the post-cruise processing, discussed under "Geometric corrections" below.

Other Geophysical Data

A suite of geophysical data was collected simultaneously with the sidescan-sonar data to aid in the geologic interpretation of the sidescan imagery. Seismic-reflection profile data were collected along the ship's track by means of three systems: a 10-kHz echo sounder, a 3.5-kHz high-resolution subbottom profiler, and an airgun system. The airgun system consisted of one 160- or 80-cubic-inch airgun fired every 15 seconds (s) using air compressed to 1500 pounds per square inch (psi), and a two-channel hydrophone receiver with 48 elements in each of two active sections. Each type of data was recorded on analog recorders.

A proton-precession magnetometer was towed to collect total magnetic field values of the Earth along the ship's track during the survey.

ATLAS FORMAT AND KINDS OF DATA PRESENTED

This atlas is composed of three data sections. The first section presents the sonar-imagery mosaics of the EEZ sea floor, along with generalized geologic interpretations and bathymetry. Following the mosaics is a section providing seismic-reflection data collected during the surveys. The third section presents data on bathymetry and residual magnetic anomalies.

Map Projection and Scale

The sidescan-sonar imagery is displayed on 9 sheets, which cover the EEZ of Puerto Rico and the U.S. Virgin Islands. The latitude and longitude boundaries of each sheet are shown on p. B6 (fig. 13). An Albers Equal-Area projection was used for the sheets of imagery data and their companion overlays of bathymetry and geologic interpretation. The standard parallels used were 29.5° and 45.5° N. Since shape distortion in an Albers projection increases with increasing distance from the standard parallels, the maximum distortion in the Caribbean is in the southernmost sheets. The imagery sheets are printed at a scale of 1:500,000. At this scale one centimeter of distance on the sheet represents 5 km on the Earth's surface or 1 inch equals approximately 7 nautical miles. The Albers projection was selected for the imagery data display to be compatible with the USGS Continental Margin Map Series (fig. 2). This map series is a compilation of offshore geologic data into a digital data base (Escowitz, 1985).

Sonar-Imagery Mosaics

The sidescan-sonar data were mosaicked to produce 9 sheets, which provide continuous imagery of the sea floor of the EEZ in the eastern Caribbean. Each of the imagery sheets has a complementary facing page showing the imagery under an overlay of generalized geologic interpretation and bathymetric contour data. Each sheet is composed of data segments approximately 6 hr in length that were image processed by computer, then mosaicked end-to-end along the ship's track, producing swaths. Adjacent swaths were stenciled together also by computer, to create each of the nine mosaic sheets.

In order to prevent saturation of the digital values in highly reflective areas such as insular slopes and shallow banks, gain settings on the GLORIA system were kept low during the eastern Caribbean survey. Parts of the EEZ of Puerto Rico and the U.S. Virgin Islands had unexpectedly low backscattering properties, which, combined with the low gain settings, resulted in no signal being recorded during the weak, power-buildup phase of the sonar pulse. This created a black band of no data on either side of the ship's track. The effect is most obvious in the Venezuelan Basin and in the area north of the Puerto Rico Trench. Because of the relatively large percentage of low digital values in these mosaics, data gaps within the mosaics were left black instead of changing them to the medium gray used for the regions outside the data coverage.

In areas of high backscatter the ship's track is less obvious. In these areas it appears as a grainy band of enlarged pixels, resulting from the major geometric corrections necessary in the area directly below the sidescan vehicle. It is useful to identify the ship's track, and thereby the direction of insonification, when interpreting the mosaics. Identification of the ship's track also allows correlation of the seismic-reflection and magnetic-anomaly data with the imagery.

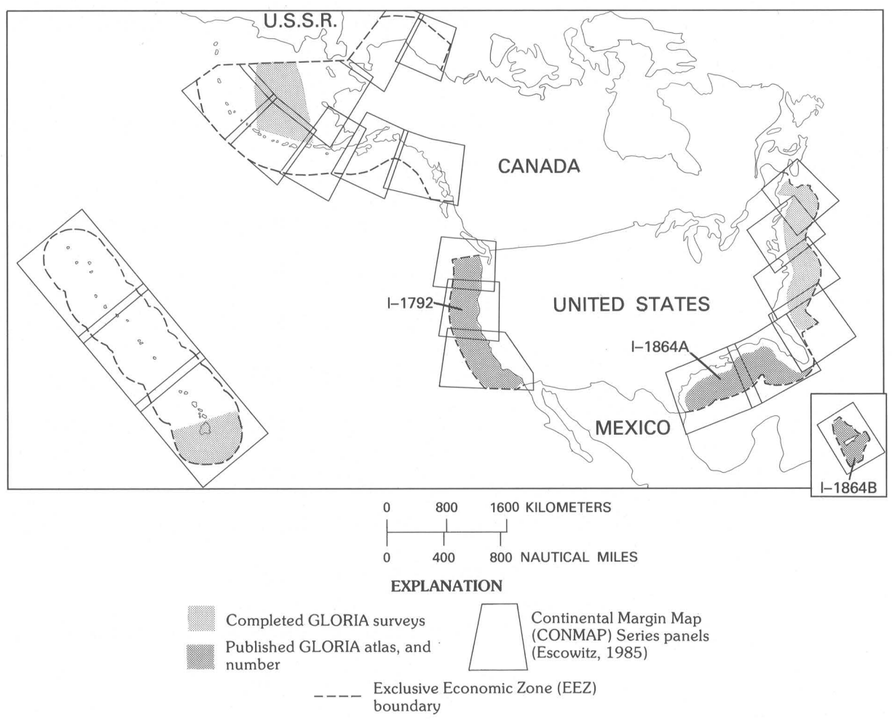

Figure 2—Status of the GLORIA mapping program.

Each mosaic sheet is a halftone black and white print of the acoustic reflectivity of the sea floor. White represents the strongest acoustic reflectivity and black represents the weakest acoustic return. The darkness or lightness of a feature or an area on the mosaics, therefore, is a function of how much sound is reflected from the sea floor. Reflectivity, in turn, is controlled by the relief of the sea floor (height and gradient), by the microtopography and roughness of the sea floor (for example, sediment waves, and pressure features on submarine landslide deposits), and by the physical properties of the sea floor (such as sediment type, compaction, and induration). When viewed from the trackline, positive-relief features such as ridges and escarpments usually appear as a bright zone when facing the slope, whereas when looking down the slope, dark zones (shadows) result (fig. 5). Negative-relief features, such as canyons or basins, usually appear as a dark zone (the near wall is shadowed) followed by a bright zone (the far wall is facing the sonar beam). Not all bright regions are related to topographic relief; many are caused by sedimentation patterns. Dark regions also have a variety of causes, of which shadows and certain sediment facies are the most common. Contained within the sidescan imagery is a wealth of information on both the geology of the sea floor and the processes by which sediment is deposited.

Bathymetry

The bathymetric contours (in meters) are printed in blue directly onto each imagery sheet along with the geologic interpretation. A 400-m contour interval is used on mosaic sheets 1–6 and 9, and a 200-m interval

is used on sheets 7 and 8. Geographic names correspond to features identified on the airgun records in the seismic section of the atlas and are approved names from the Gazetteer of Undersea Features (Defense Mapping Agency, 1981). The bathymetry south of lat. 20° N. was digitized from Matthews and Holcombe (1976). North of lat. 20° N., NAVOCEANO contour sheet 704 (NA-9) was used (NAVOCEANO, 1973). The quality and accuracy of the bathymetric data vary from sheet to sheet, and under no circumstances should the bathymetric maps be used for navigation. In some areas the bathymetry may not be a good representation of the topography and may not align with the imagery. The bathymetry should be used as a guide for interpretation and not as a precise rendition of the topography.

The bathymetry shown in figure 14 (p. B7) was derived by mosaicking and reducing the bathymetry of the nine imagery sheets.

Seismic-Reflection Profile Data

Three seismic-reflection profile systems were used: a 10-kHz echo sounder, a 3.5-kHz high-resolution subbottom profiler, and an airgun system. Depth values were digitized from the 10-kHz echo sounder every 6 minutes (min) along with intermediate peak, trough, and inflection-point values. These values, in meters, were corrected for sound velocity, merged with the navigation data, and used in the image processing to geometrically correct the sonographs. They are shown as profiles plotted along the ship's track at the beginning of the seismic-reflection profile section of the atlas (p. B33) as a key to aid in correlating the seismic-reflection profile data with the imagery. The bathymetry data are also shown in the magnetics section of the atlas for comparison with the magnetic-anomaly data.

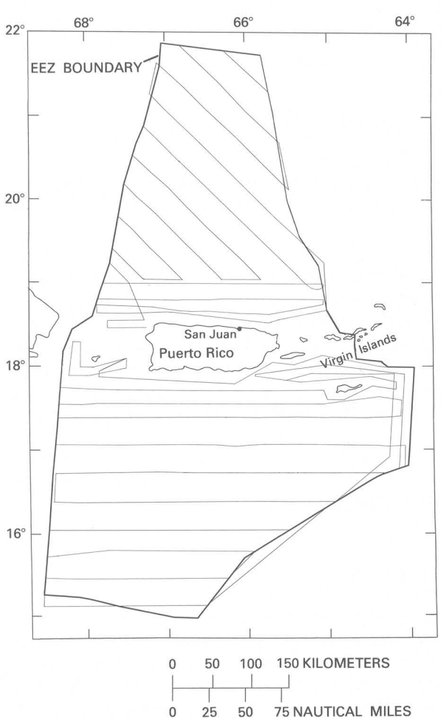

Figure 3—Limits of the GLORIA survey of the EEZ off Puerto Rico and the U.S. Virgin Islands. Ship tracklines are also shown.

The 3.5-kHz data provide high-resolution, shallow-penetration seismic-reflection information that was used to help interpret the sidescan-sonar data.

The airgun data were recorded on analog recorders at both 5-s and 10-s sweep rates and were filtered between 20 and 200 Hz. Shown in the seismic-reflection profile section are photographs of the analog records recorded at a sweep rate of 5 s. The photographs are printed so that the vertical depth scale is the same on all profiles. The vertical scale is annotated in two-way traveltime in seconds. As an approximation, each second of two-way traveltime equals 750 m of depth (assuming a sound velocity in sea water of 1500 m/s). Within the sediments, the velocity of sound is usually greater, which means that each second within the sediments represents more than 750 m (for example, 800 to 900 m).

The Julian day and time are annotated along the profiles, as are course and speed changes. The data are broken into segments to draw attention to major course changes and to facilitate correlation with the track map at the beginning of the seismic-profile section and with the imagery sheets. Occasional gaps occur in the records as a result of repairs being made to the airgun system; such gaps are identified with the words "No data". Handwritten annotations, visible on some of the records, are the shipboard remarks for post-cruise analysis.

Magnetic-Anomaly Data

Total Earth's magnetic field values were collected continuously along the ship's track. These data were logged by computer and merged with the navigation and bathymetry information. Residual magnetic anomaly values were calculated by subtracting the International Geomagnetic Reference Field updated to 1985 (IAGA, Division 1, Working Group I, 1986) from the total Earth's magnetic field values measured. These residual anomaly values are displayed in the magnetic anomaly profile section of the atlas as continuous profiles plotted with bathymetric data for each Julian day. The anomaly data are plotted in gammas (one gamma represents one nanotesla) against time. Ship's heading and speed information can be obtained from the trackline map at the beginning of the section (p. B49).

DIGITAL PROCESSING TECHNIQUES

Introduction

The imagery in this atlas is made from computer-processed, digitally collected sidescan sonographs. In order to process the digital sonar data, computer software had to be designed that would correct for both geometric and radiometric distortions that exist in the original "raw" data. This section describes the techniques developed by the USGS to correct and enhance GLORIA digital sonar images. A more detailed explanation of the digital processing is given by Chavez (1986).

Sonographs are a record of the acoustic backscattering properties of the sea floor. The strength of the acoustic backscatter is a convolution of several functions, the four major ones being: (1) the slope angle of a feature relative to the incident sonar signal; (2) the sea-floor roughness factor, the minimum being 4 cm of

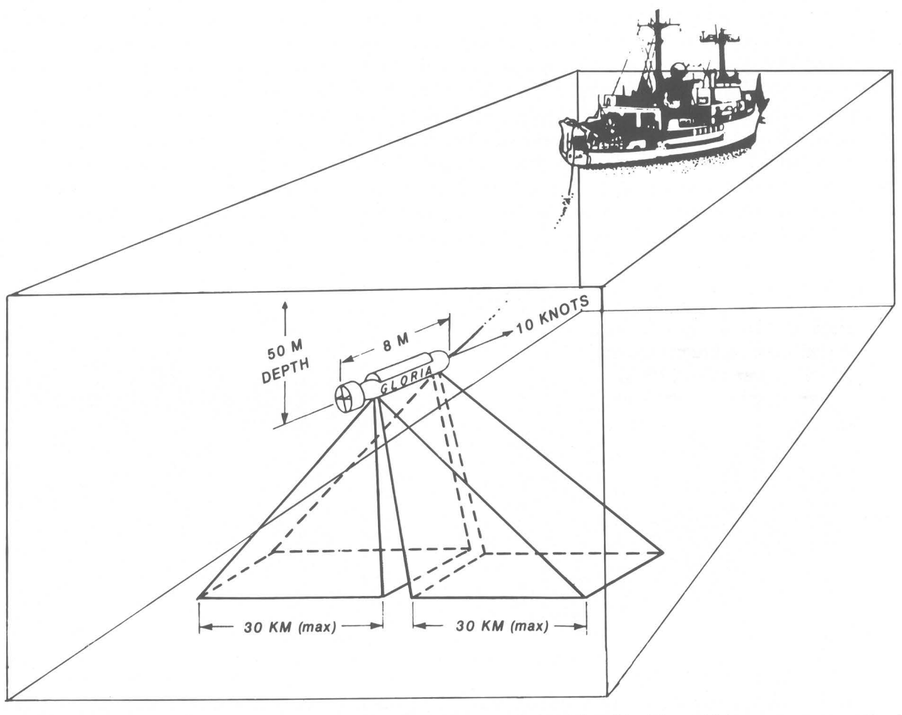

Figure 4—The GLORIA sidescan vehicle, or "fish", being towed behind the ship. The vehicle can map a swath of sea floor up to 60 km wide.

relief for the GLORIA system (determined by the wavelength of the signal and the grazing angle of the sonar ray to the sea floor; Sabins, 1978); (3) the variation in physical properties of the upper few tens of centimeters of the sea floor; and (4) the water column—the distance of the vehicle above the sea floor—which attenuates the strength of the sonar signal and produces background noise. The backscatter was recorded as a digital number (DN) with a range of 0 to 255 discrete values. The reflected sound waves were recorded on a time basis so that the data are in a slant-range rather than a ground-range (true geographic) geometry. Also, variations in the ship's speed generated variations in the size of the footprint (the area on the sea floor) of each pixel in the along-track direction. These distortions, as well as others discussed below, were corrected so that the sonograph images in this atlas represent orthorectified and true plan views (assuming a flat sea floor) of acoustic backscatter patterns on the sea floor.

Geometric Corrections

The major sources of geometric distortions in the sidescan-sonar data are: (1) water-depth offset; (2) slant-range geometry; (3) aspect- or anamorphic-ratio distortion; and (4) changes in the ship's speed. Each of these major distortions was eliminated from the data presented in this atlas. Below is a brief explanation of the procedures used to correct for these geometric distortions.

Because the GLORIA system starts recording data as soon as the transmitted acoustical wave is terminated, the original images include pixels to both sides of the nadir (the projection directly beneath the ship) that contain water-column data. The number of these pixels varies along the trackline as a function of the water depth directly beneath the ship. The processing software merges the navigational and bathymetric data, recorded every four sonar scan lines, with the image data. The water-depth offset is then calculated in pixels and these non-image pixels are removed.

The slant-range distortion is a consequence of the range to features being measured relative to the vehicle, not to the projected location of the trackline on the sea floor below the vehicle. In trigonometric terms, GLORIA measures the length of the hypotenuse of a triangle (the distance a feature is from the vehicle). Since the vertical side of the triangle is known (from the 10-kHz echo-sounder record), the horizontal side of the triangle can be determined to properly locate pixels in the across-track direction. For example, before the

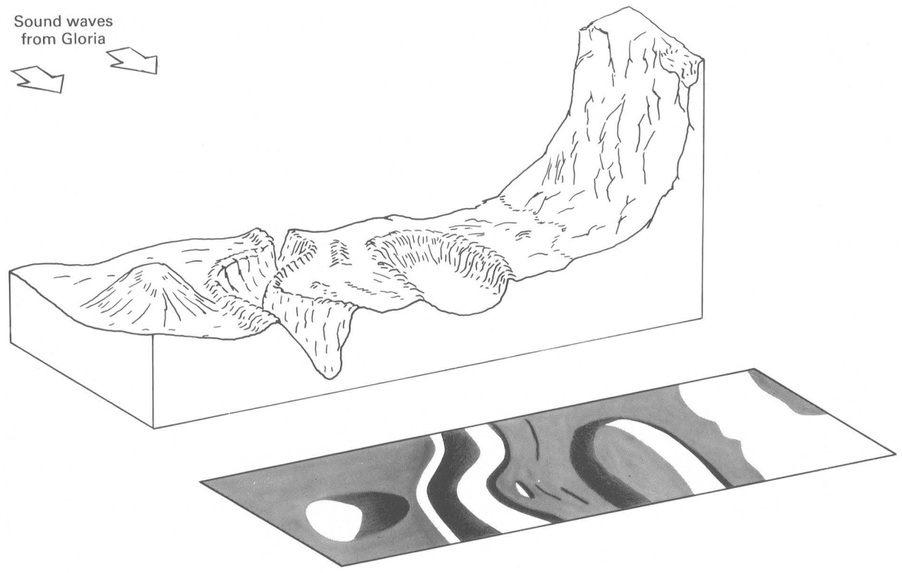

Figure 5—Block diagram showing a composite of sea-floor features typically observed in the EEZ off Puerto Rico and the U.S. Virgin Islands, and sketch of this morphology as it appears on a sidescan-sonar image.

slant-range correction is made, data from the nadir is offset from the centerline of the image, on both the port and starboard sides, by a distance proportional to the height of the vehicle above the sea floor. The water-depth and slant-range corrections remove the water column, thus drawing the nadir into its proper position directly beneath the ship. In the same way these corrections properly locate other features in the across-track direction.

The third major geometric distortion present in GLORIA images is the aspect ratio, or anamorphic ratio, that exists between the along- and across-track directions. The sampling interval in the across-track direction for the 30-s pulse-repetition rate generates pixels with an approximate resolution of 45 m. The computer program that corrects for the water-depth and slant-range distortions generates 50-m-resolution pixels in the across-track direction. However, the resolution in the along-track direction is dependent not only on the 30-s pulse-repetition rate but also on the ship's speed. The average resolution in the along-track direction is approximately 125 m at a speed of 8 kts (15 km/hr). This generates a raw image that is distorted or stretched by a factor of about 2.5 in the along-track direction. The fourth, and related, source of geometric distortion is introduced by any change that occurs in the ship's speed while it is collecting the image data. The ship's speed can be influenced by the direction and strength of currents and wind relative to the ship's course and by whether the ship is heading in a straight line or is turning. During the surveys the speeds varied from about 7 to 10 kts (13 to 18 km/hr), which caused the pixel resolution in the along-track direction to vary from approximately 110 to 140 m. This introduced an "accordion" effect into the geometry of the image in the along-track direction (Chavez, 1986).

The aspect-ratio distortions discussed above were removed by using the latitude and longitude values extracted from the header of each record to compute the distance traveled by the ship every 30 min (unless a turn is detected, in which case the program used a 10-min interval). Given the distance traveled and the desired pixel size, the number of pixels required for the particular 30-min segment was calculated. Pixels were then duplicated the appropriate number of times to achieve a 1:1 ratio between along-track and across-track distances. To simultaneously correct for the aspect-ratio distortion, a 50-m-resolution pixel size was generated on the output image in the along-track direction. This pixel size was selected so that information in the across-track direction would not have to be omitted. This procedure corrects the image data for aspect-ratio distortions and for any distortion introduced by changes in the ship's speed.

Radiometric Corrections

Radiometric corrections change the DN value of a pixel rather than its spatial location, as is the case with geometric corrections. Four different corrections were used for the GLORIA data in this atlas: (l) a shading correction to correct for the attenuation of the sonar energy in water as a function of range; (2) a power correction for very-near-nadir data because of slow buildup; (3) a speckle-noise correction; and (4) removal of striping noise. The value of making these corrections is that, in the case of noise, the corrections remove artifacts associated with the data acquisition, and in the case of attenuation, they normalize all data so that pixel values from the across-track direction can be compared directly with each other.

The loss of power due to attenuation and the power buildup problems were both corrected by using a two-pass algorithm. During the first pass through the data, the average DN value was computed for each column of pixels of the digital image in the along-track direction. These values were then normalized by the average of all the column averages (the overall average of the image) to generate correction coefficients for each column. The correction coefficients were then applied to each pixel during the second pass through the data. The coefficients are nonlinear and are a function of range, so they effectively removed attenuation in the across-track direction. This technique has the characteristics of a spatial filter that removes large horizontal low-frequency patterns that are present because of the radiometric problems introduced by the imaging system (Chavez, 1986). By normalizing to the average of the image rather than to a set DN value, backscatter comparisons could be made between different areas or different images. The correction also allowed areas within the image with lower or higher backscatter characteristics to be properly identified and mapped. This was not possible before the correction because the DN values were strongly modified as a function of their range position. Profiles of different areas in the across-track direction could then be used for backscatter comparison.

Speckle noise was removed by applying a small smoothing filter (2 samples by 2 lines) to the entire image. This approach was found best with GLORIA data, because in addition to removing speckle noise, it helped smooth the blocky appearance that the image otherwise would have had—caused by the stretching (by a factor of 2.5) in the along-track direction by pixel duplication—that was introduced when correcting for the aspect-ratio distortion.

Another radiometric or noise problem commonly present in data collected by scanning devices is striping in the scan direction. A combination of high- and low-pass spatial filtering was used to remove the striping. Two separate images were generated from the input data; one composed of the high-frequency components minus the noise frequency, and the other composed of the low-frequency components minus the noise. The two resultant images were then combined to produce an image similar to the original but without the noise (Chavez and Soderblom, 1974). The filter shapes used to remove the striping noise from the GLORIA data were a 1-line by 71-sample high-pass filter and a 9-line by 71-sample low-pass filter.

Digital Mosaicking

After the sidescan-sonar data underwent the initial geometric and radiometric corrections, they were ready for the digital mosaicking steps that result in the imagery sheets shown in the sonar mosaic section of the atlas. The processed segments of data, approximately 6 hr in length, were spliced end-to-end to make continuous line segments for portions of the tracklines where the ship's heading remained generally constant. The segments were tone matched by adjusting the contrast stretch of each to minimize the seam where they were joined.

Latitude, longitude, and heading were determined along the center line of each continuous segment of data at the start, end, and two intermediate points. These four control points, with eight additional points located along the edges of the image, were used to position the continuous line segment within the imagery sheet. After the map projection and latitude and longitude boundaries for the sheet were selected, a transformation file was created to position the 12 control points and then the complete image within the sheet.

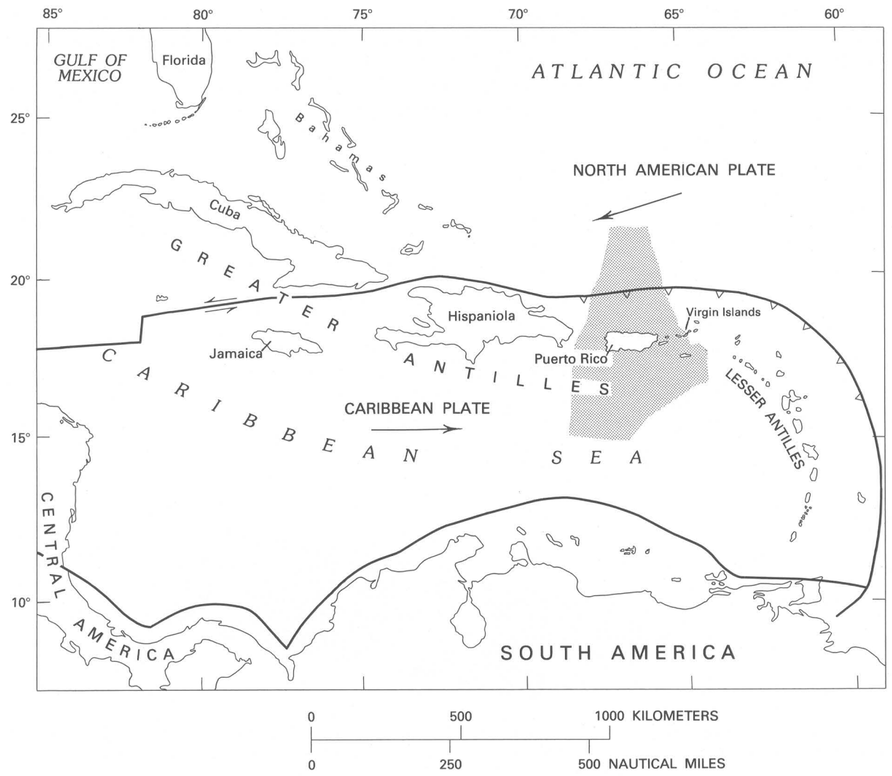

Figure 6—Major tectonic features of the Caribbean region. Arrows under plate names show direction of plate movement; paired arrows indicate relative movement of plates. Sawteeth represent approximate location of Puerto Rico Trench. Shaded area shows the EEZ off Puerto Rico and the U.S. Virgin Islands.

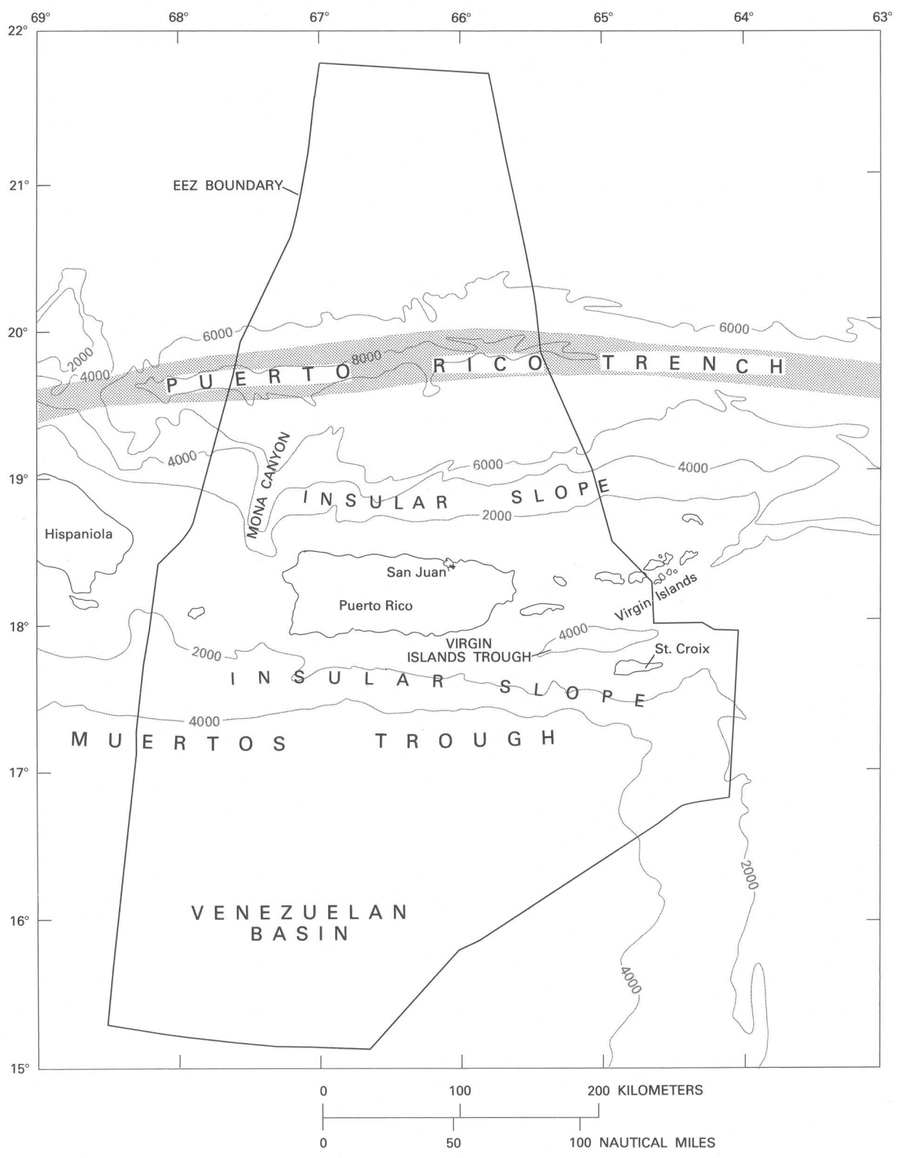

Figure 7—Map of the EEZ off Puerto Rico and the U.S. Virgin Islands showing location of features discussed in the text. Bathymetric contours are in meters. Screen pattern indicates boundary between the North American and Caribbean plates (also see figure 6).

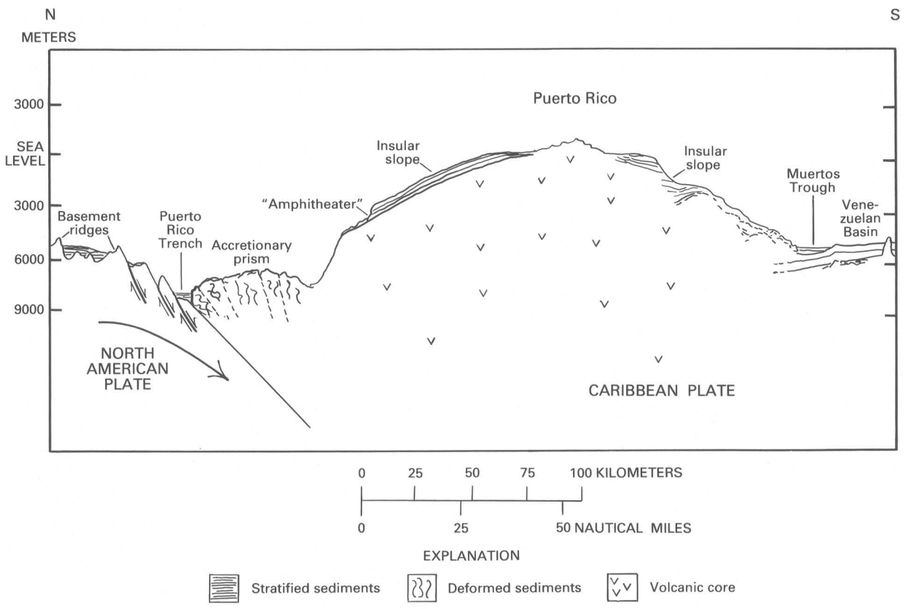

Figure 8—Schematic north-south cross section of the EEZ through Puerto Rico. Large arrow indicates subduction of North American plate under Caribbean plate. Paired arrows show relative movement along fault planes.

The next step was to stencil adjacent line segments together, providing a continuous mosaic covering the imagery sheet. Interactively a line was drawn on a video display outlining the portion of each image to be retained. This line was smoothed and then converted from vector to raster format. The rasterized mask was superimposed on the sidescan image and all pixels outside the area of the mask were converted to zero values, thereby retaining only that portion of the image desired. After this process of stenciling, each line segment was mosaicked to adjacent segments, sequentially building the composite map. In this way a digital file for each of the imagery sheets was created with the desired map projection. Film negatives were output from the Scitex scanner at the desired scale.

GEOLOGIC INTERPRETATION

Regional Perspective

The Earth's crust is broken into a number of pieces, or plates, which move relative to one another at a rate of several centimeters per year. The boundaries between plates have different characteristics depending on how the plates are moving relative to each other. If the plates are sliding past each other (as they are at the San Andreas fault in California), the boundary is referred to as strike-slip and is characterized by earthquakes. Where one plate is being thrust, or subducted, under an overriding plate, the boundary is termed convergent and is marked by a deep trench, an arc of volcanoes, and deep earthquake activity. The volcanic island arcs in the South Pacific and the Lesser Antilles of the Caribbean are examples of this type of plate boundary. If two plates are moving apart, the boundary is defined as a spreading ridge, along which new sea floor is created. Plate boundaries are particularly interesting areas for several reasons. They contain key information for understanding geologic processes within the Earth's crust. Moreover, because they are generally characterized by earthquakes, volcanoes, and steep slopes, they are a source of concern to human inhabitants. Also they commonly are areas of high potential for energy and mineral resources.

The EEZ of Puerto Rico and the U.S. Virgin Islands contains the boundary between the Caribbean and North American plates, which is marked by the Puerto Rico Trench (figs. 6,7). Today the motion between the two plates is mainly strike-slip, but that has not always been the case. Between Early Cretaceous time (120 million years ago) and Eocene time (40 million years ago) the two plates were converging and the North American plate was being thrust beneath the Caribbean plate. The Puerto Rico Trench was formed during this period, as was a parallel arc of volcanoes south of the trench. These volcanic rocks have been faulted and metamorphosed and now form the core of Puerto Rico and the Virgin Islands (Donnelly, 1966). Oligocene-age and younger shallow-water limestone platforms flank the volcanic and metamorphic core (Mattson, 1966). Because the present-day motion between the Caribbean and North American plates is mainly strike-slip, there are no active volcanoes in Puerto Rico or the Virgin Islands. A small component of convergence still exists between the two plates, however, and accounts for the continued presence of the Puerto Rico Trench and the associated occurrence of deep earthquakes (Mann and Burke, 1984; Sykes and others, 1982; Mattson, 1977; and Westbrook and McCann, 1986). Although the boundary between the two plates lies north of Puerto Rico along the Puerto Rico Trench, deformation resulting from the relative motion of the two plates occurs in a broad zone that extends southward from the trench to the Muertos Trough south of Puerto Rico (fig. 7).

Geology of the EEZ

North of Puerto Rico and the Virgin Islands, the GLORIA sidescan-sonar mosaic and the seismic profiles reveal numerous north-northeast-trending basement ridges that in some places crop out through the flat-lying abyssal sediments (fig. 8). These ridges are oriented parallel to the magnetic anomaly pattern in the region (Klitgord and Schouten, 1986) and are presumably related to the formation of oceanic crust by sea-floor spreading at the Mid-Atlantic Ridge. South of about lat. 20°30′ N., the sea floor slopes downward to the floor of the Puerto Rico Trench. With a depth of over 8,000 m, the Puerto Rico Trench is the deepest part of the Atlantic Ocean. Although the major component of motion is strike-slip, earthquake studies (Sykes and Ewing; 1965, Frankel and others, 1980) indicate that the North American plate is being thrust beneath the thicker and more buoyant Caribbean plate. The floor of the Puerto Rico Trench is a flat sedimentary surface or abyssal plain formed by sediments flowing periodically into the trench. It can be seen in the GLORIA mosaic as a dark east-west band at approximately lat. 19°50′ N. The north wall of the trench is broken into ridges and scarps, which are parallel to the trench axis and which may be caused by the fracturing of the North American plate as it is bent into the Puerto Rico Trench (figs. 8,9). South of the trench axis, between the trench floor and the base of the insular slope, lies a 50-km-wide zone of ridges and sediment-filled basins (fig. 8). The ridges are subparallel to the trench axis and show no internal structure in our airgun profiles. We

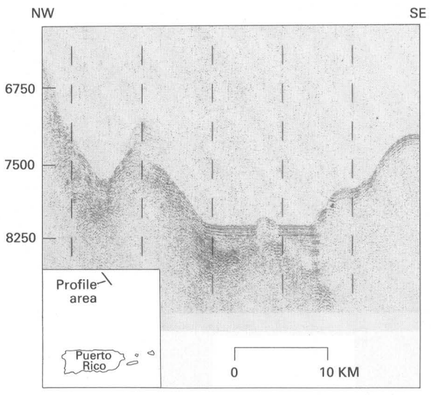

Figure 9—Seismic-reflection profile across the sediment-filled floor of the Puerto Rico Trench. Vertical scale shows depth, in meters.

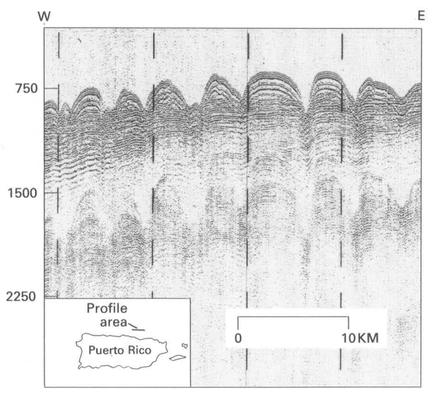

Figure 10—Seismic-reflection profile across the upper insular slope north of Puerto Rico, showing erosional channels. Vertical scale shows depth, in meters.

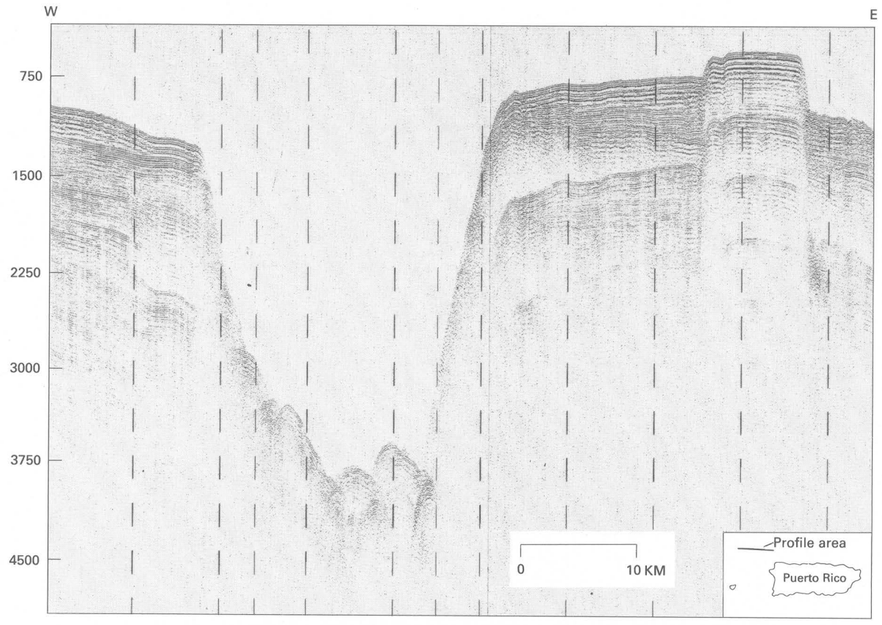

Figure 11—Seismic-reflection profile across Mona Canyon. Vertical scale shows depth, in meters.

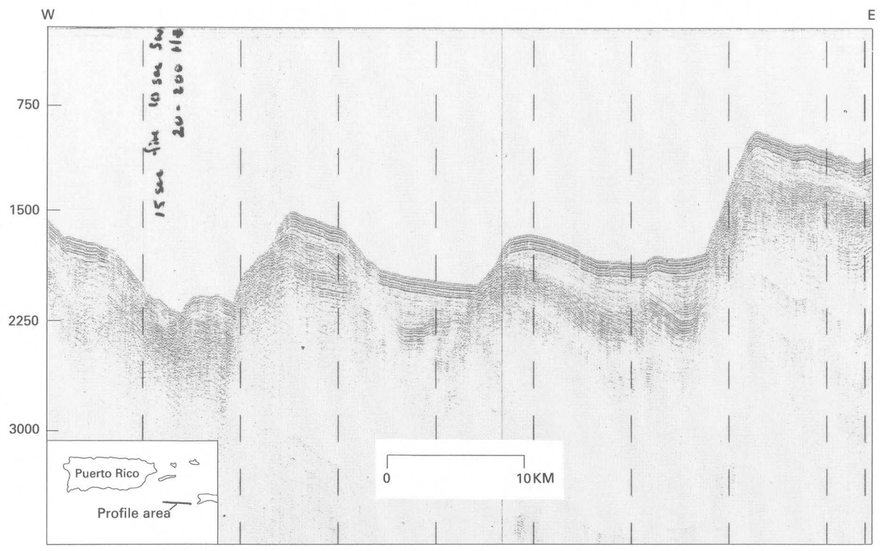

Figure 12—Seismic-reflection profile across northeast-trending normal faults west of St. Croix. Vertical scale shows depth, in meters.

believe that the ridges form an accretionary prism (in the terminology of Karig and Sharman, 1975) of deformed sediments scraped from the subducting North American plate.

Numerous channels are cut into the sedimentary rocks on the insular slope north of Puerto Rico. On the upper part of the slope the channels are between 1 and 3 km wide (fig. 10) and have been cut as much as 400 m into the surrounding sea floor. Submarine dives in the upper parts of some of these channels have revealed step-like outcrops of Tertiary limestone (Gardner and others, 1980). We suspect that similar outcrops are present on the floors and walls throughout the channels. These outcrops are too small to be seen individually in the GLORIA images, but collectively they could cause the brightly reflective character of the channels. Downslope, many channels merge, broaden, and become less-deeply incised, creating areas dominated by eroded, irregular sea floor rather than by discrete channels. In these areas the surficial sediments have been eroded, exposing a hard and irregular rock surface. This surface reflects more of the sonar signal than the surrounding sediment-covered areas, producing the bright areas mapped as eroded sea floor on the GLORIA images (overprinted with a red screen tint). South of Puerto Rico, similar channels and areas of eroded sea floor exist, but the channels are fewer, shorter, and less deeply incised. This may be a result of the larger sediment input and the strong wave and current action that characterize the northern side of the island.

A large amphitheater-shaped scarp, representing the removal of more than 1,500 cubic kilometers of sediment (fig. 8), is present on the insular slope north of Puerto Rico near long. 66°45′ W. The head of the scarp is about 3,000 m deep. The removal of the sedimentary rocks has exposed the basement core of Puerto Rico on the lower part of the insular slope (fig. 8). It is not known if this feature was formed by a single catastrophic event or by slower erosion and dissolution processes. Farther east along the slope (near long. 66° W.), a smaller but similar amphitheater scar occurs, as well as numerous smaller scarps that may represent incipient slumps. Nothing similar is seen on the insular slope south of Puerto Rico.

Mona Canyon (fig. 11) is a submarine canyon cutting the northern insular slope about 20 km west of the western end of Puerto Rico. It differs from the channels described above in several important ways. Its width of 15–25 km makes it an order of magnitude wider than the channels. The floor of Mona Canyon is dark on the GLORIA images, which implies that it is sediment covered, rather than eroded as are the bright channel floors. Also, the location and orientation of Mona Canyon are controlled by faults in the underlying bedrock. There are no other features similar to Mona Canyon in the survey area.

The Muertos Trough lies at the base of the insular slope south of Puerto Rico (fig. 7). The northern wall of the trough is formed by a zone of deformed sediments. The lobate front of this deformation zone has been outlined on the GLORIA imagery and represents the northern boundary of the Muertos Trough. This deformation is related to compression resulting from the convergence of the Caribbean and North American plates. A north-facing scarp defines part of the southern wall of the trough. The Muertos Trough dies out to the east, south of the island of St. Croix.

St. Croix is separated from Puerto Rico and the other Virgin Islands by the more than 4,000-m deep Virgin Islands Trough. Northeast-trending normal faults can be seen clearly on the GLORIA mosaic and in the seismic profiles of the western end of the basin (fig. 12). South of the Muertos Trough the survey covers a large part of the relatively flat and featureless Venezuelan Basin. The mosaic of this area reveals subtle variations in the reflectivity of the sea floor, which are probably caused by variations in the sediment type or by small-scale bedforms.

GLORIA sidescan-sonar imagery furnishes a new perspective of one of the Earth's dynamic plate boundaries. The data collected from the EEZ corridor cutting across the Greater Antilles island arc will increase geologists' understanding of sea-floor processes and potential resources.

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The computer-processed mosaics displayed in this atlas are possible because of the image processing and mosaicking software developed by Pat Chavez and staff of the USGS in Flagstaff, Ariz. Their effort and support is greatly appreciated. Very special thanks are extended to Valerie Paskevich, who kept the hardware and software operational in the USGS office in Woods Hole, Mass., and who was always willing to lend a hand. Gratitude is also expressed to Wayne Huffman, USGS, Reston, Va., who devoted much effort in trying to solve monumental hardware problems.

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It is recommended that reference to this atlas be made in the following form:
EEZ-SCAN 85 Scientific Staff, 1987, Atlas of the U.S. Exclusive Economic Zone, Eastern Caribbean : U.S. Geological Survey Miscellaneous Investigations Series I-1864-B, 58 p., scale 1:500,000.

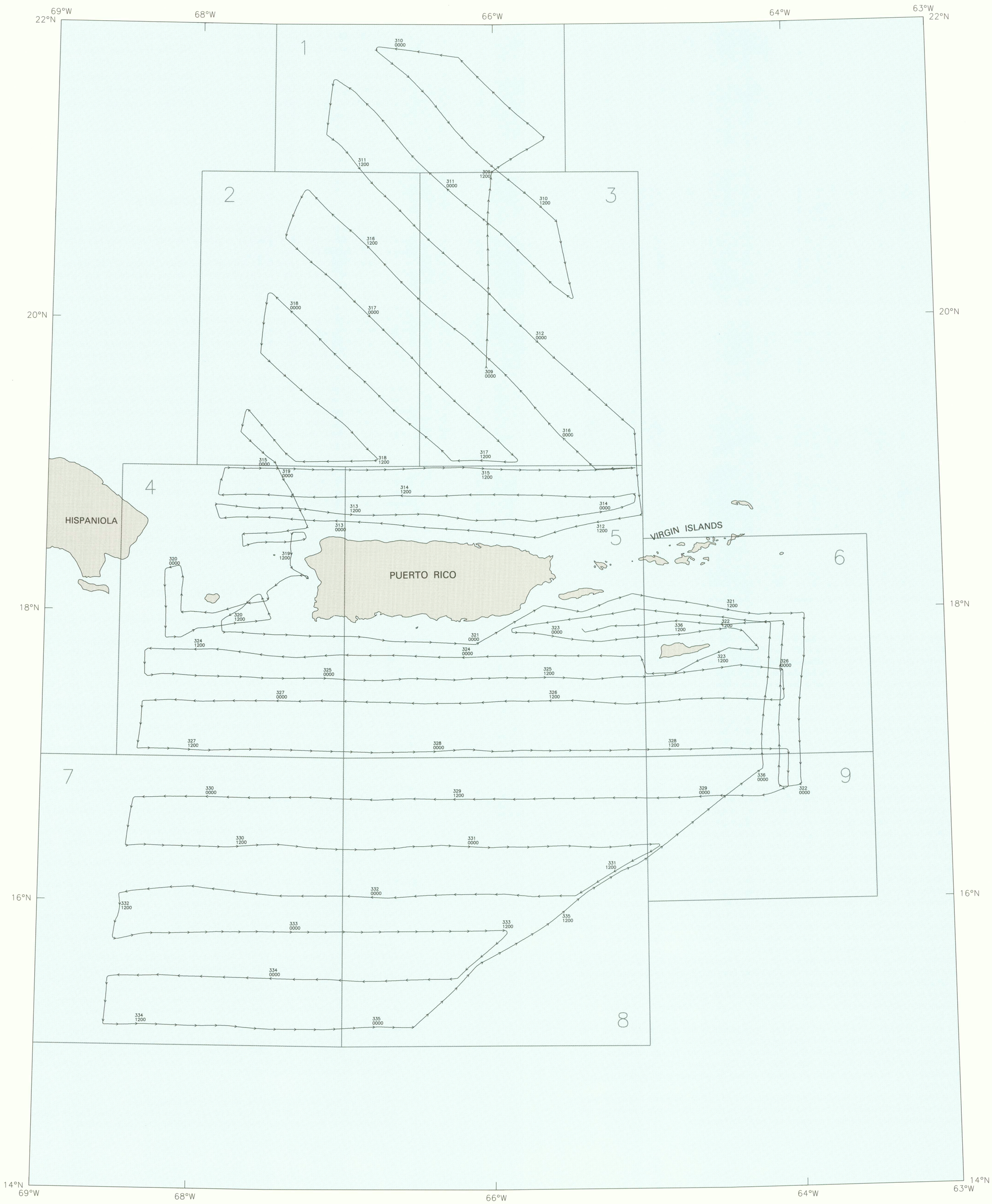

Figure 13—Tracklines of the GLORIA survey in the EEZ around Puerto Rico and the U.S. Virgin Islands. Julian day and time (Greenwich Mean Time) are annotated on the tracklines at 12-hour intervals, and every hour is marked by an arrowhead showing direction of travel. Outlines of imagery sheets 1–9 are also indicated.

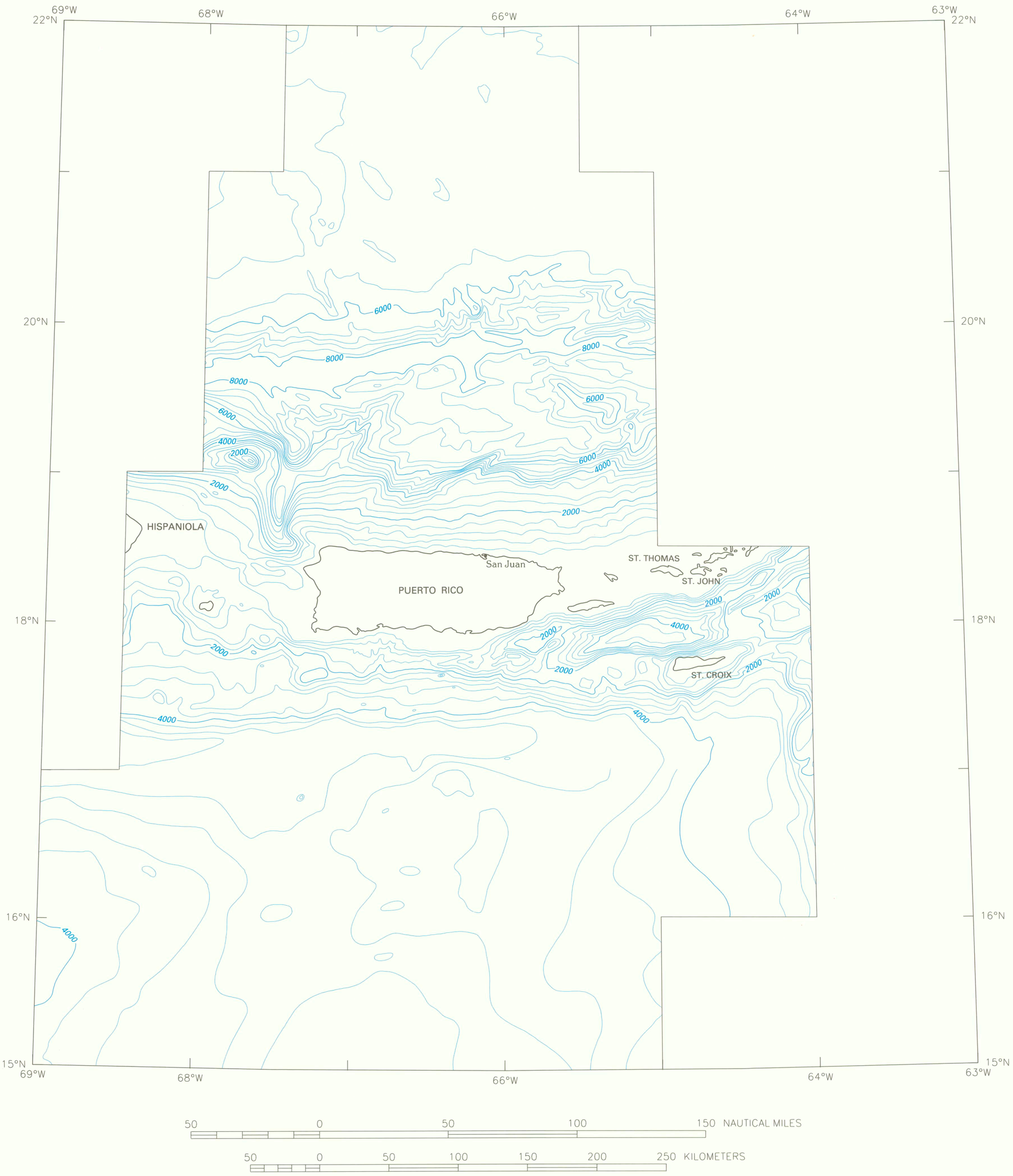

Figure 14—Bathymetry of the survey area in the eastern Caribbean. Contour interval 400 m, supplemented by 200-m contours south of lat. 17° N. Derived from the bathymetry shown on imagery sheets 1–9.

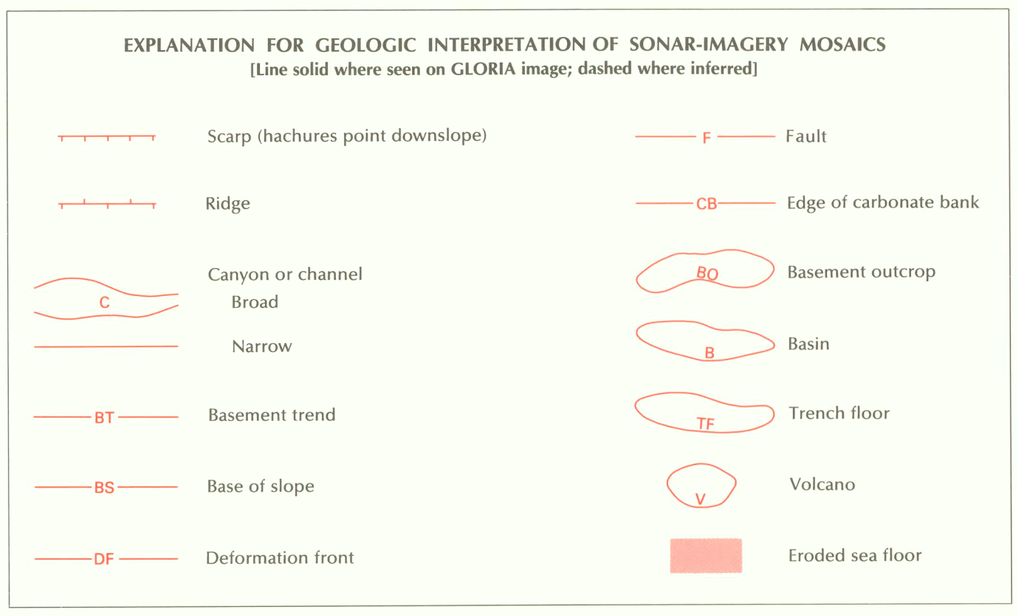

Figure 15—Explanation for geologic interpretation of sonar-imagery mosaics (sheets 1–9, p. B12–B29).

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SONAR-IMAGERY MOSAICS WITH GEOLOGIC INTERPRETATIONS AND BATHYMETRY (SHEETS 1–9)

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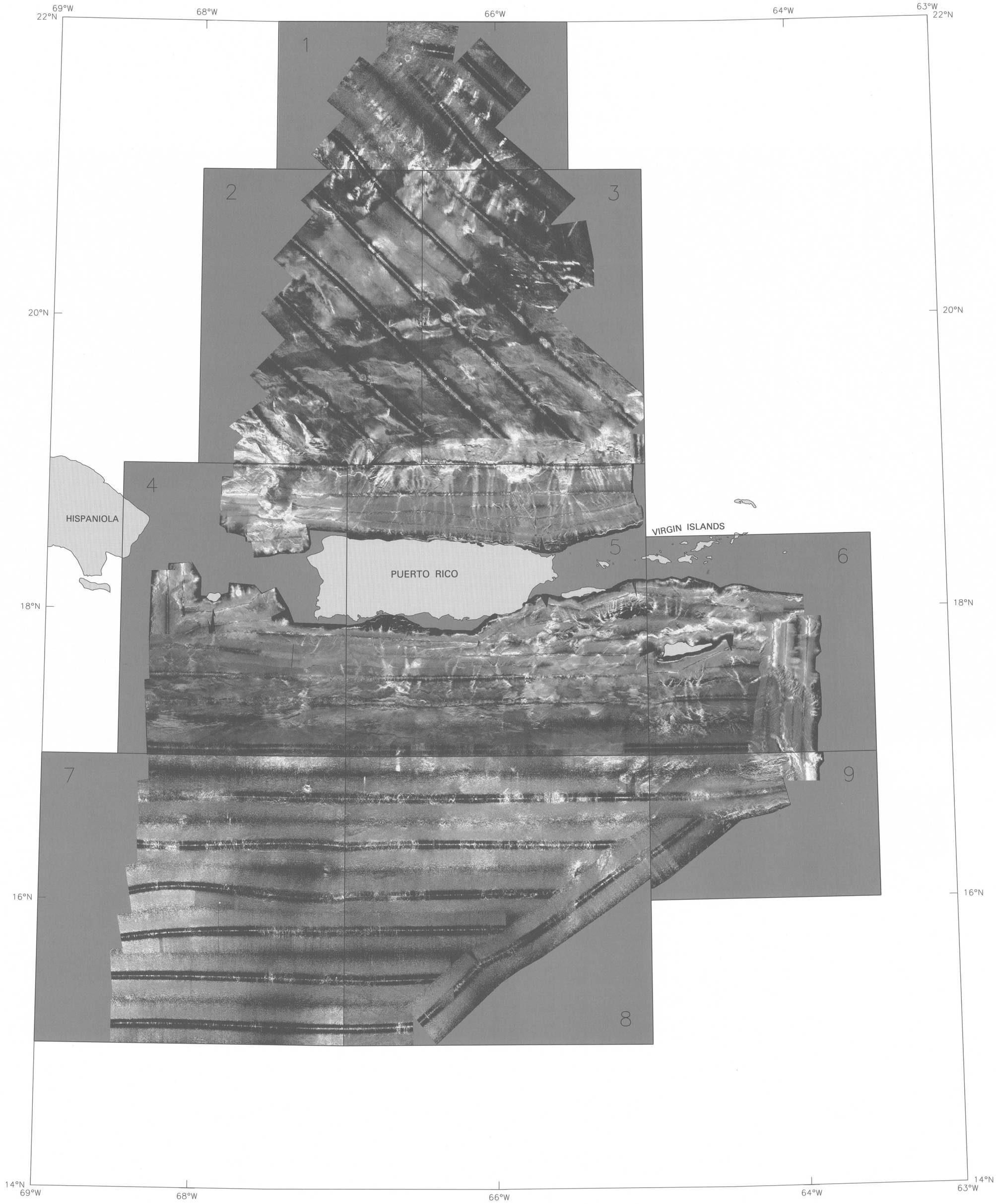

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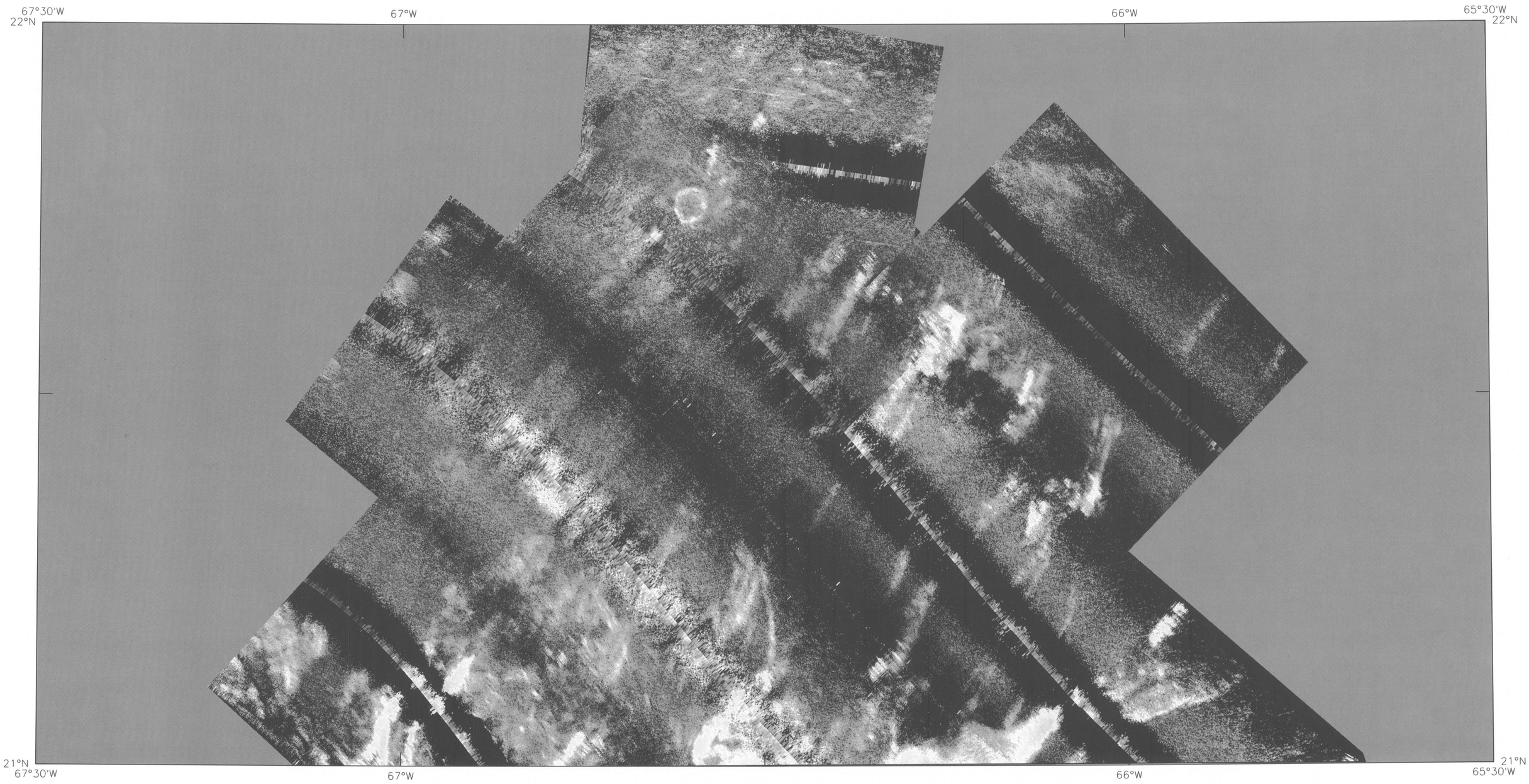
50 0 50 100 150 200 250 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

Mosaic of the sidescan-sonar imagery in the EEZ survey area around Puerto Rico and the U.S. Virgin Islands. Each pixel of data represents 200 m on the sea floor. Outlines of imagery sheets 1–9 are indicated.

SONAR MOSAIC—SHEET 1



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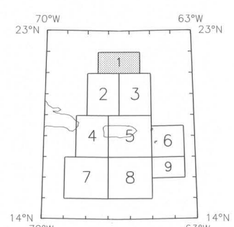
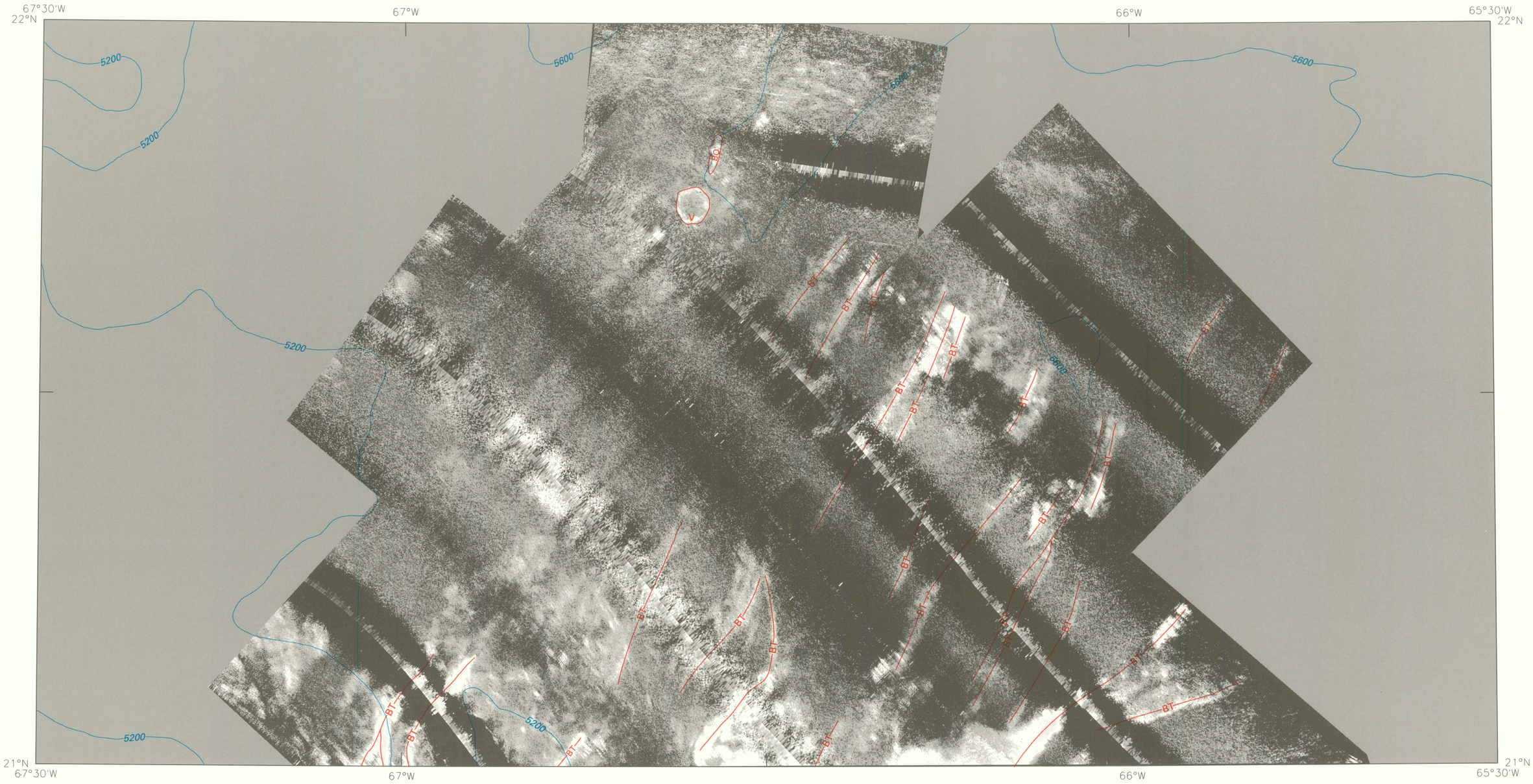
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 1
GEOLOGIC INTERPRETATION
BATHYMETRY



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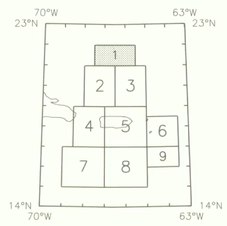
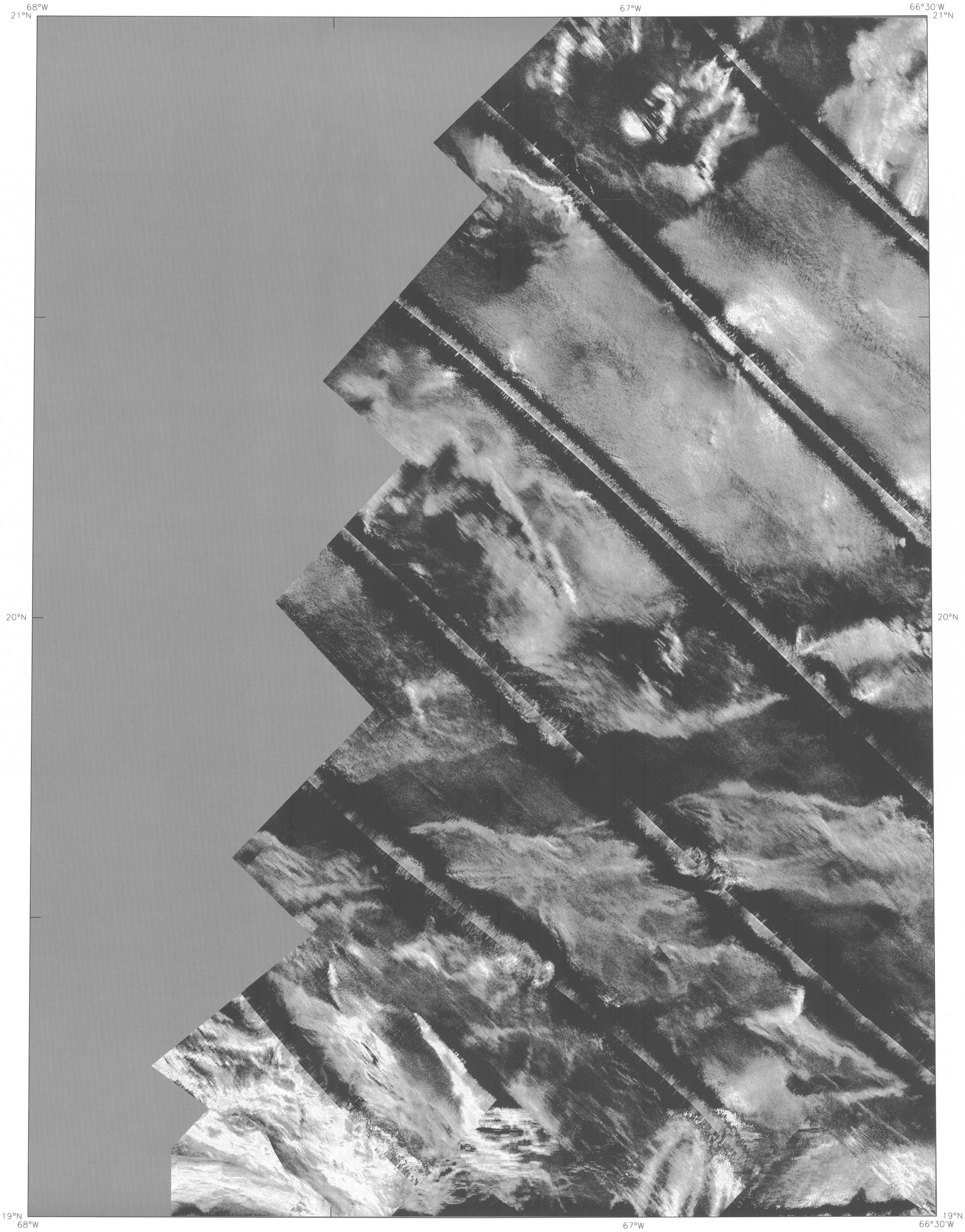
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 400 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 2



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ALBERS EQUAL-AREA PROJECTION
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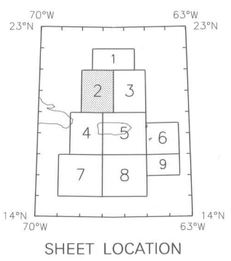
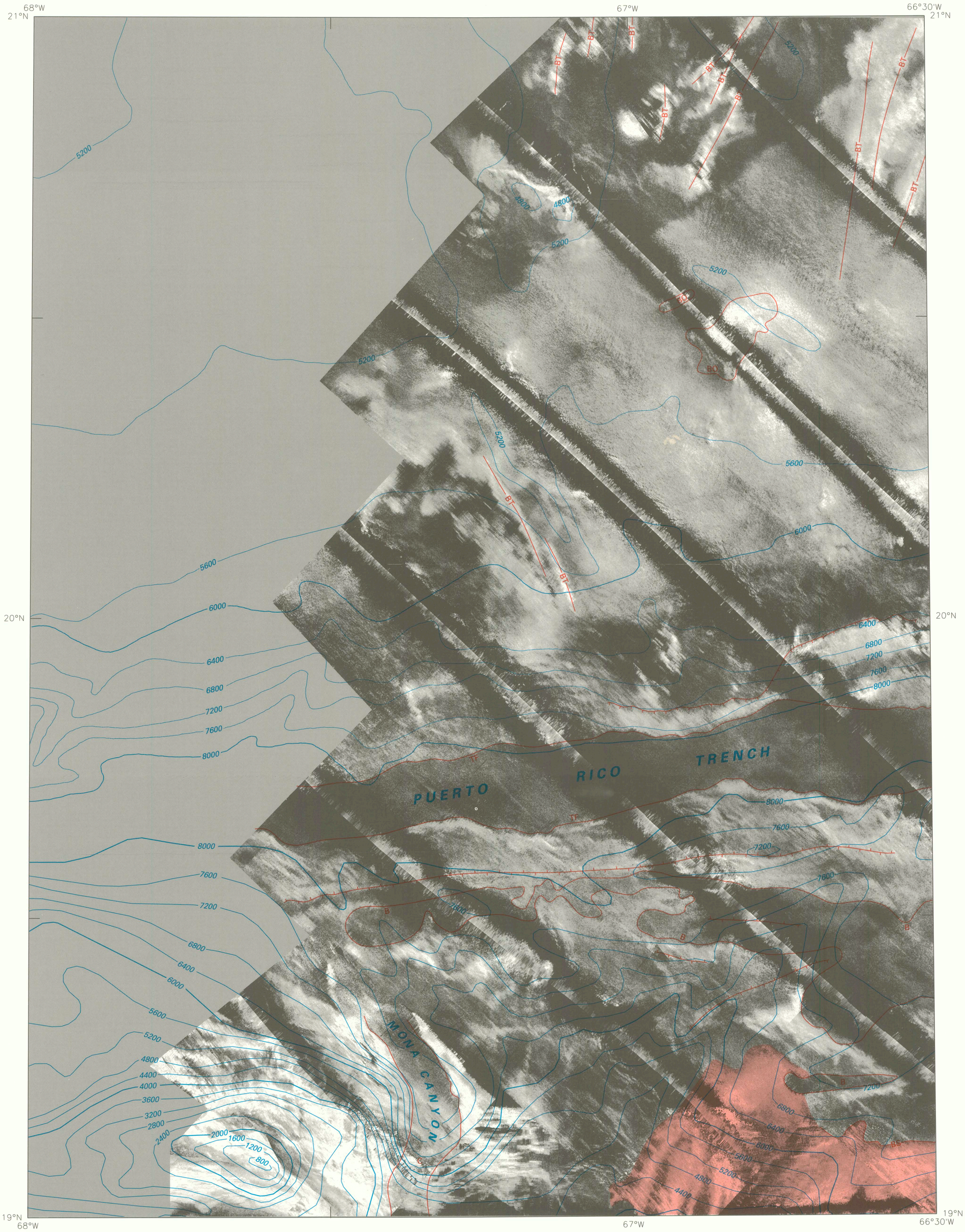


SHEET LOCATION

SONAR MOSAIC—SHEET 2
GEOLOGIC INTERPRETATION
BATHYMETRY



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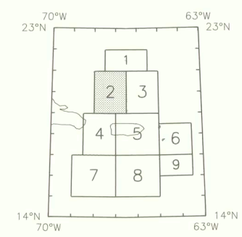
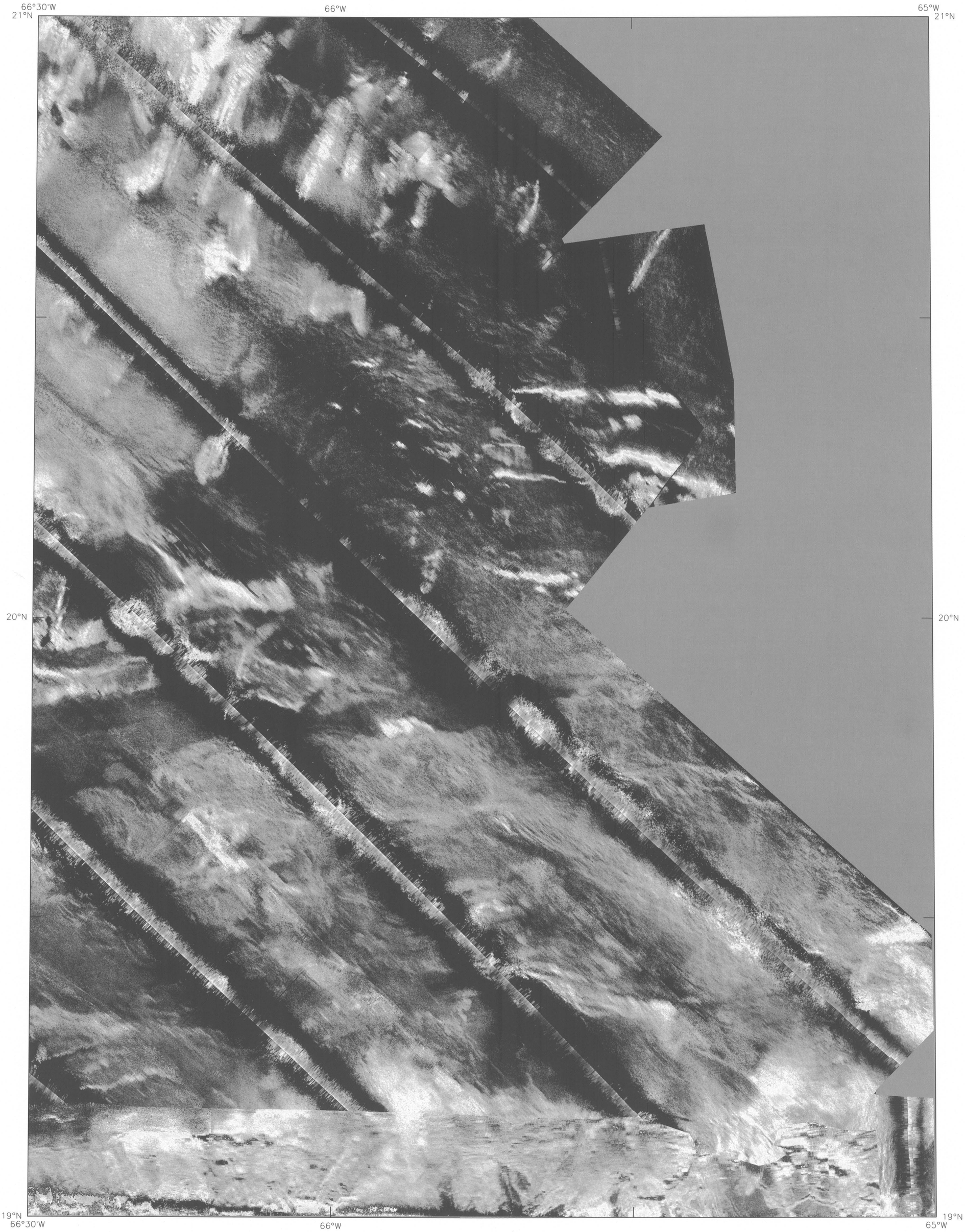
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 400 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 3



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ALBERS EQUAL-AREA PROJECTION
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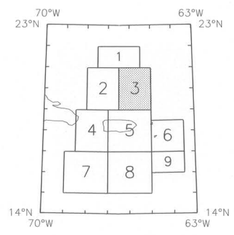
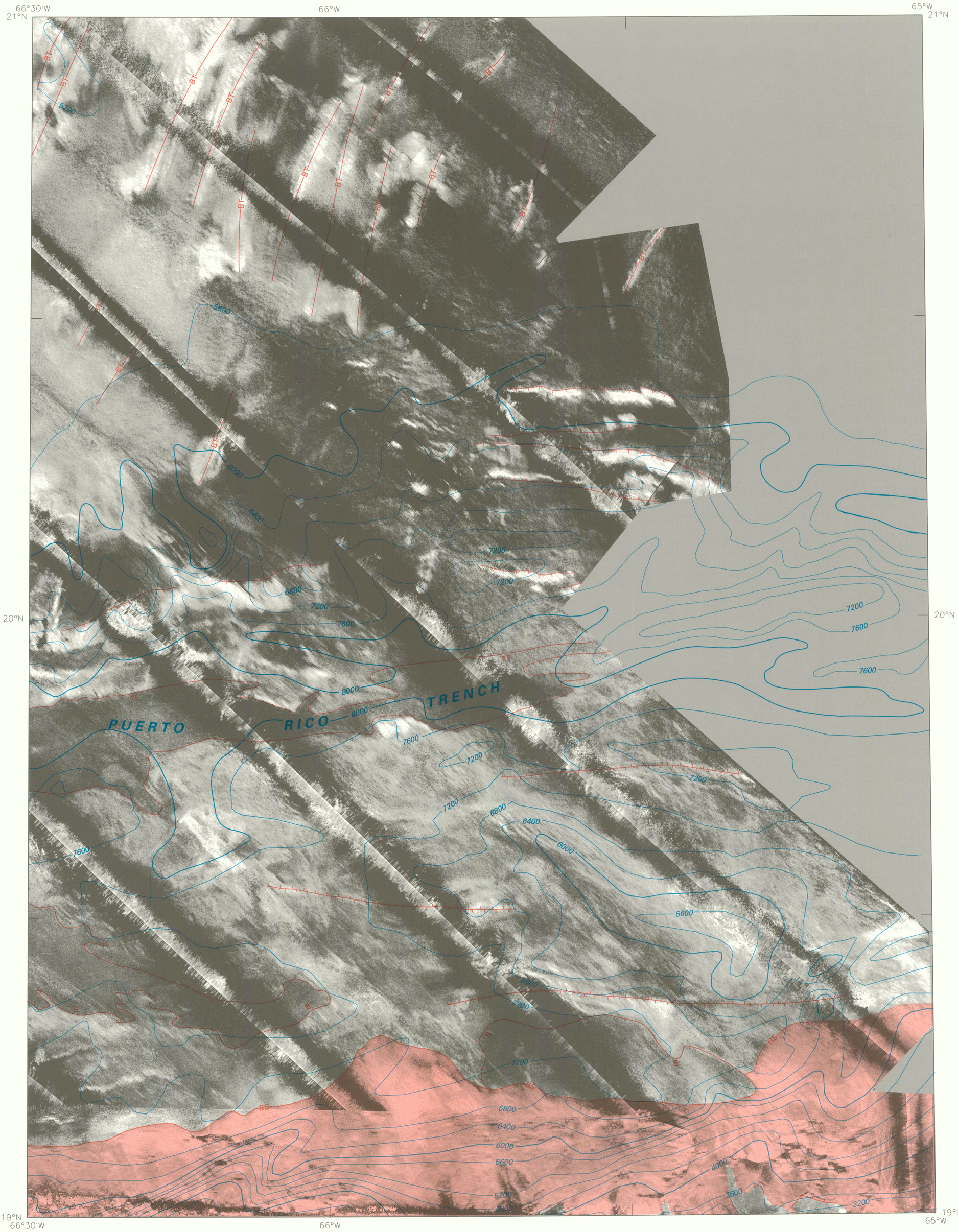


SHEET LOCATION

SONAR MOSAIC—SHEET 3
GEOLOGIC INTERPRETATION
BATHYMETRY



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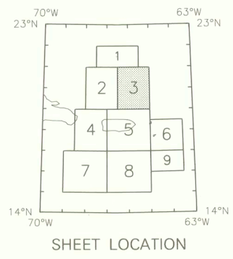
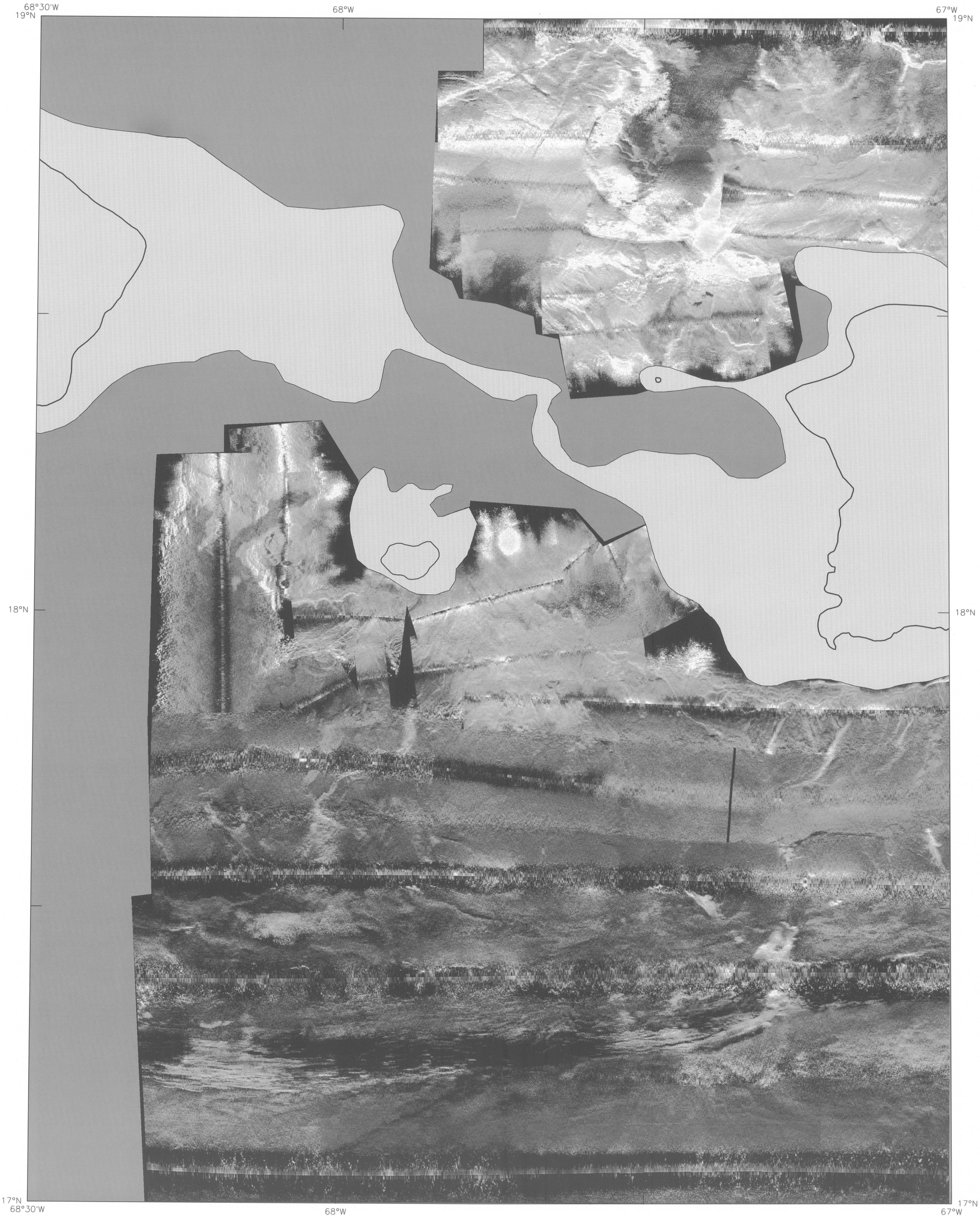
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 400 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 4



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ALBERS EQUAL-AREA PROJECTION
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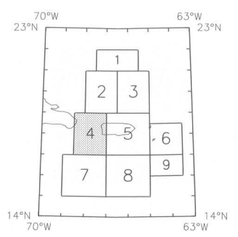
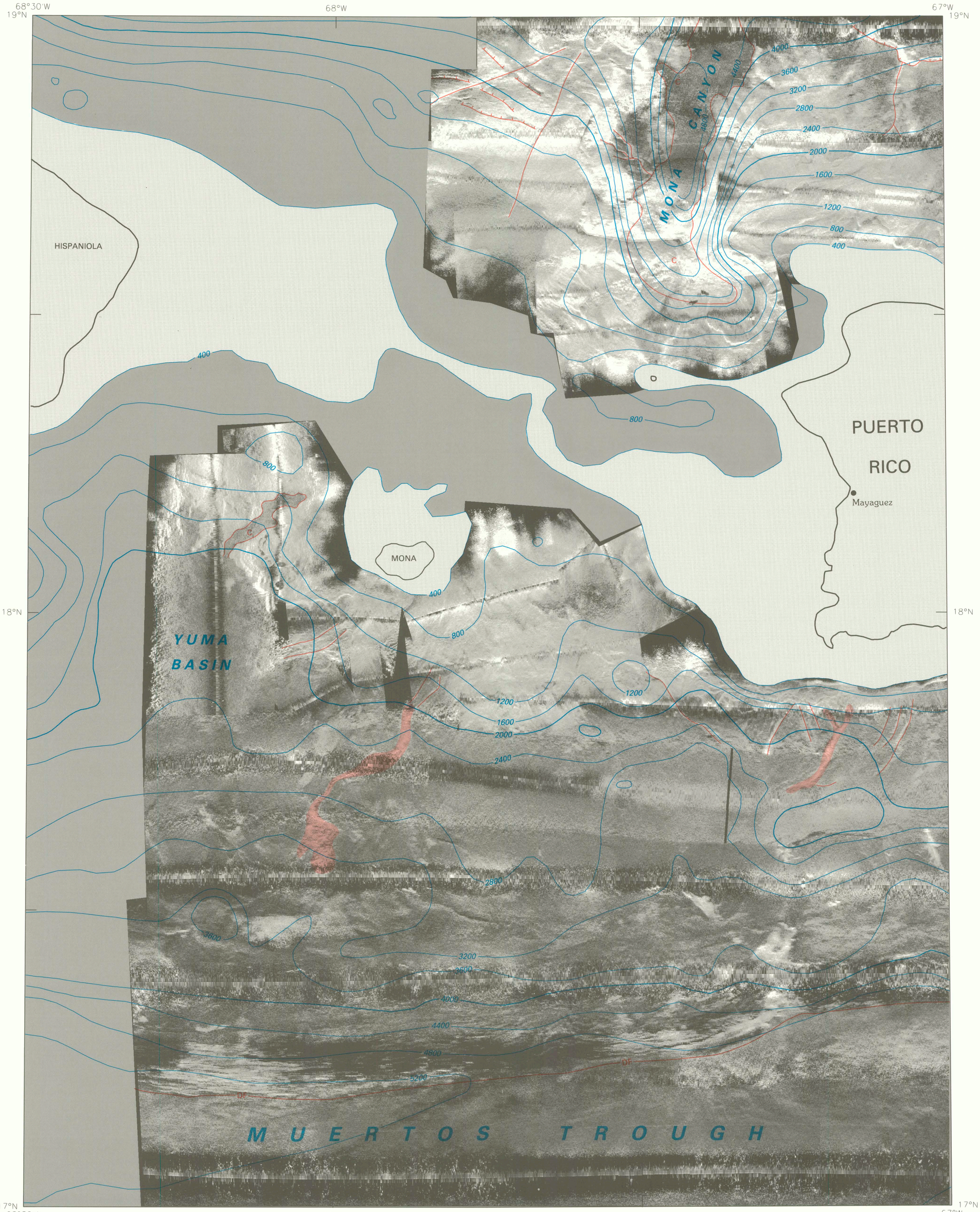


SHEET LOCATION

SONAR MOSAIC—SHEET 4
GEOLOGIC INTERPRETATION
BATHYMETRY



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ALBERS EQUAL-AREA PROJECTION
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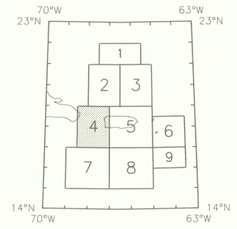
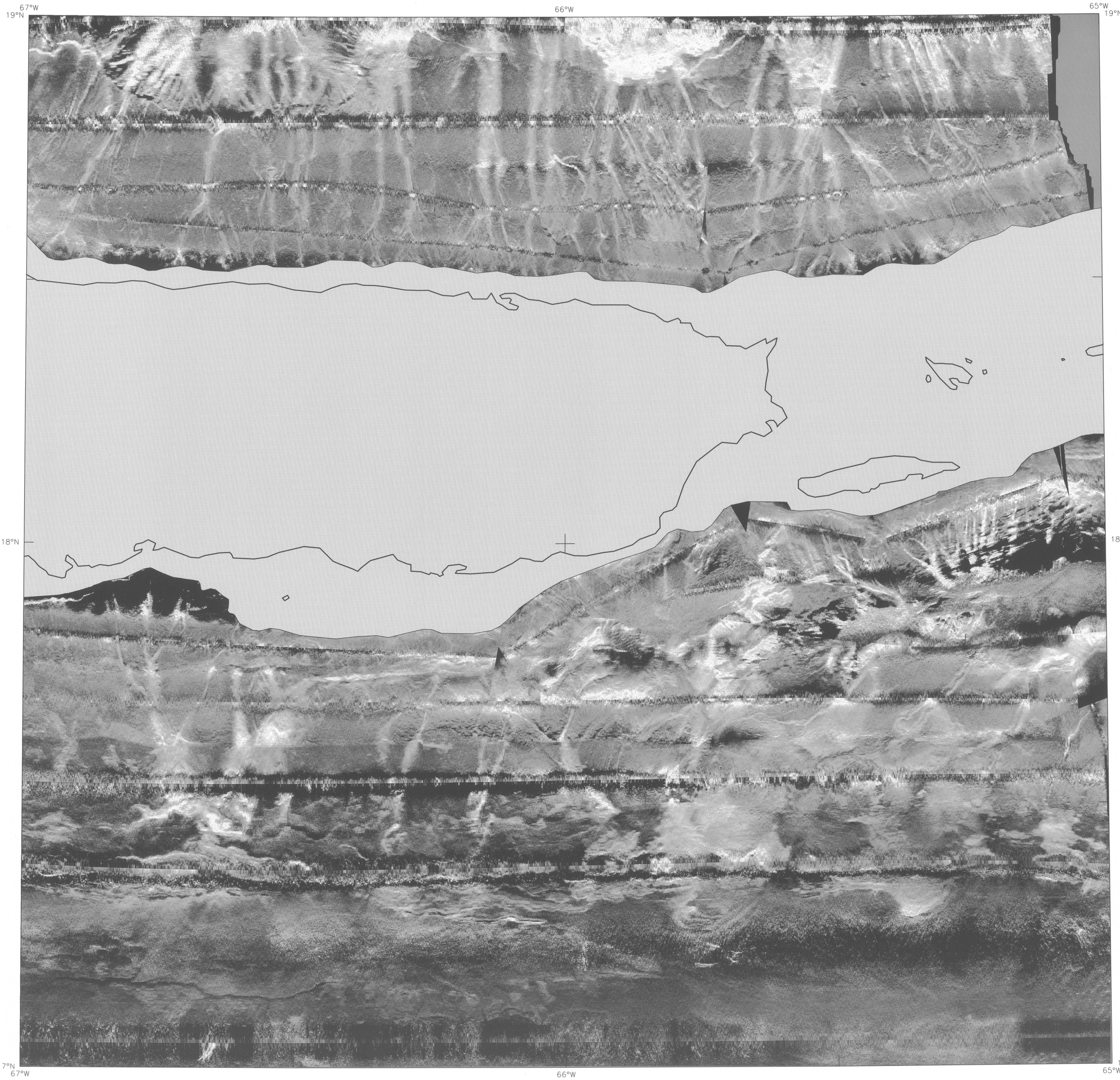
BATHYMETRIC CONTOUR INTERVAL 400 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 5



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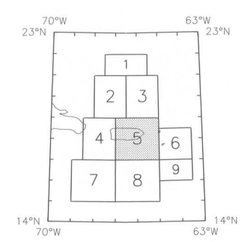
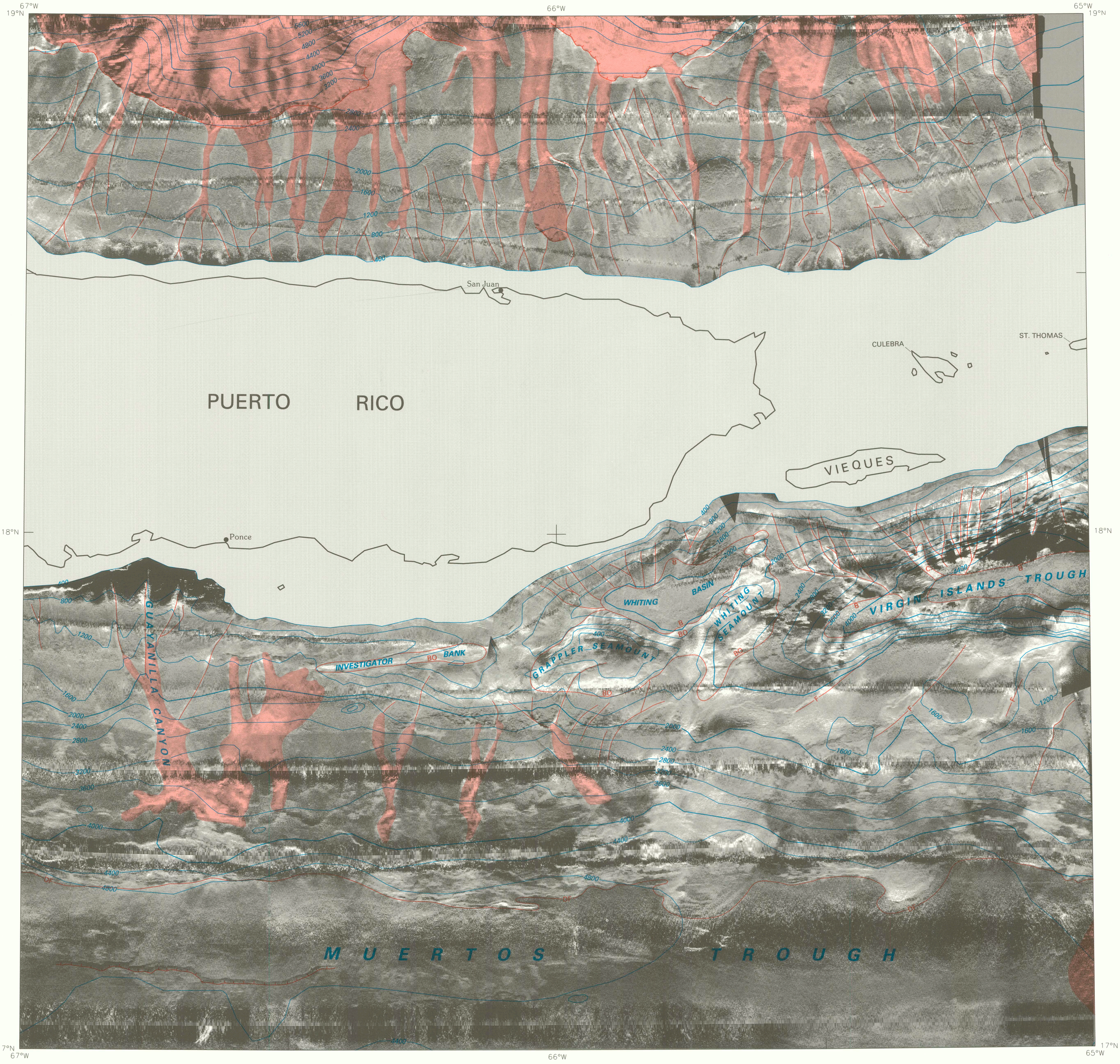


SHEET LOCATION

SONAR MOSAIC—SHEET 5
GEOLOGIC INTERPRETATION
BATHYMETRY



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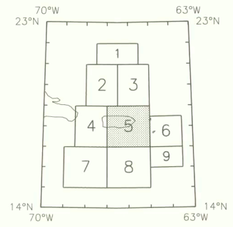
BATHYMETRIC CONTOUR INTERVAL 400 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 6

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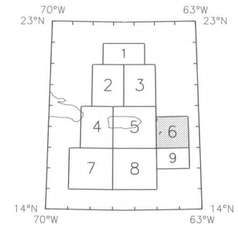
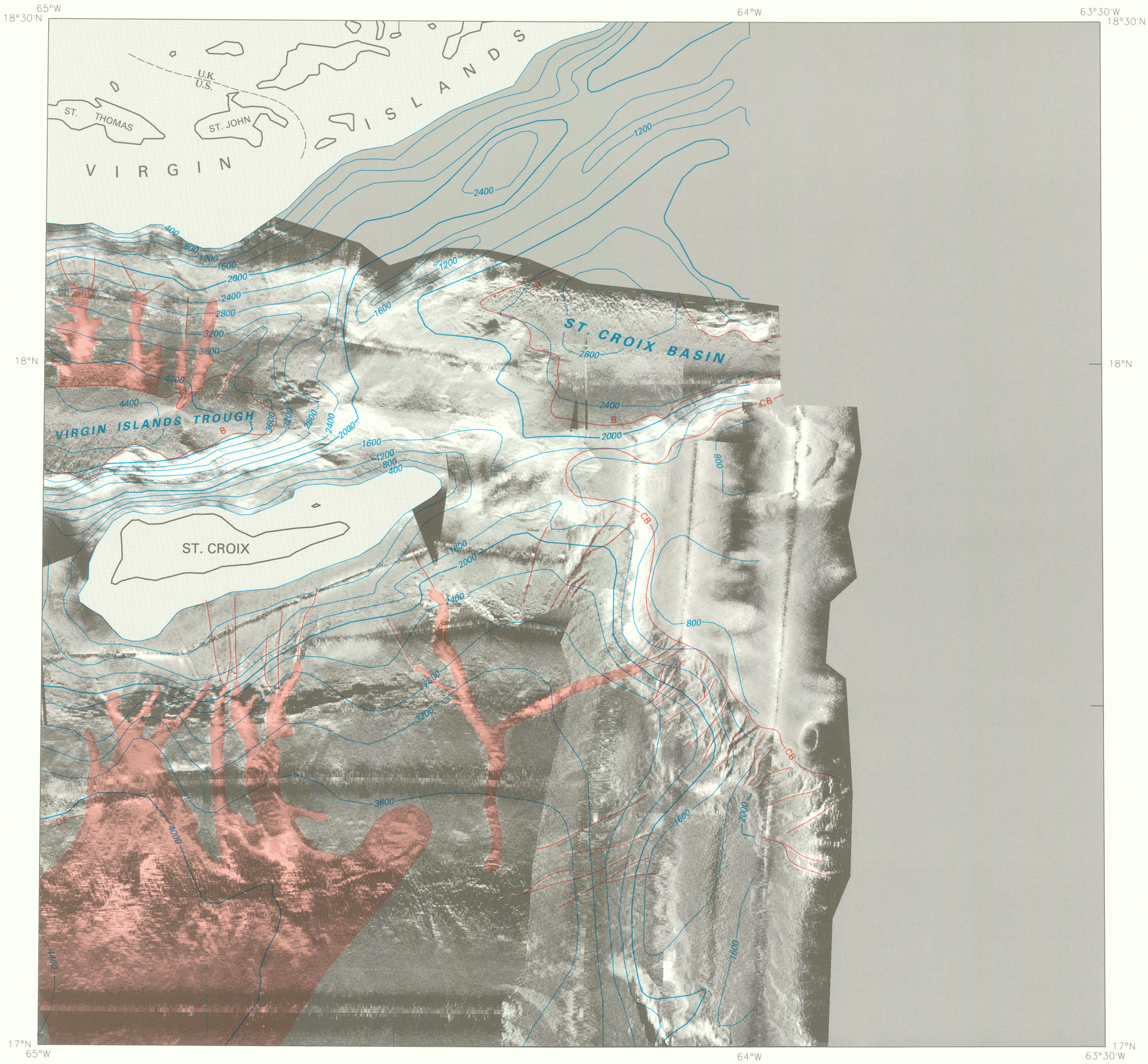


SHEET LOCATION

SONAR MOSAIC—SHEET 6
GEOLOGIC INTERPRETATION
BATHYMETRY



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ALBERS EQUAL-AREA PROJECTION
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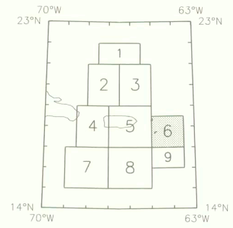
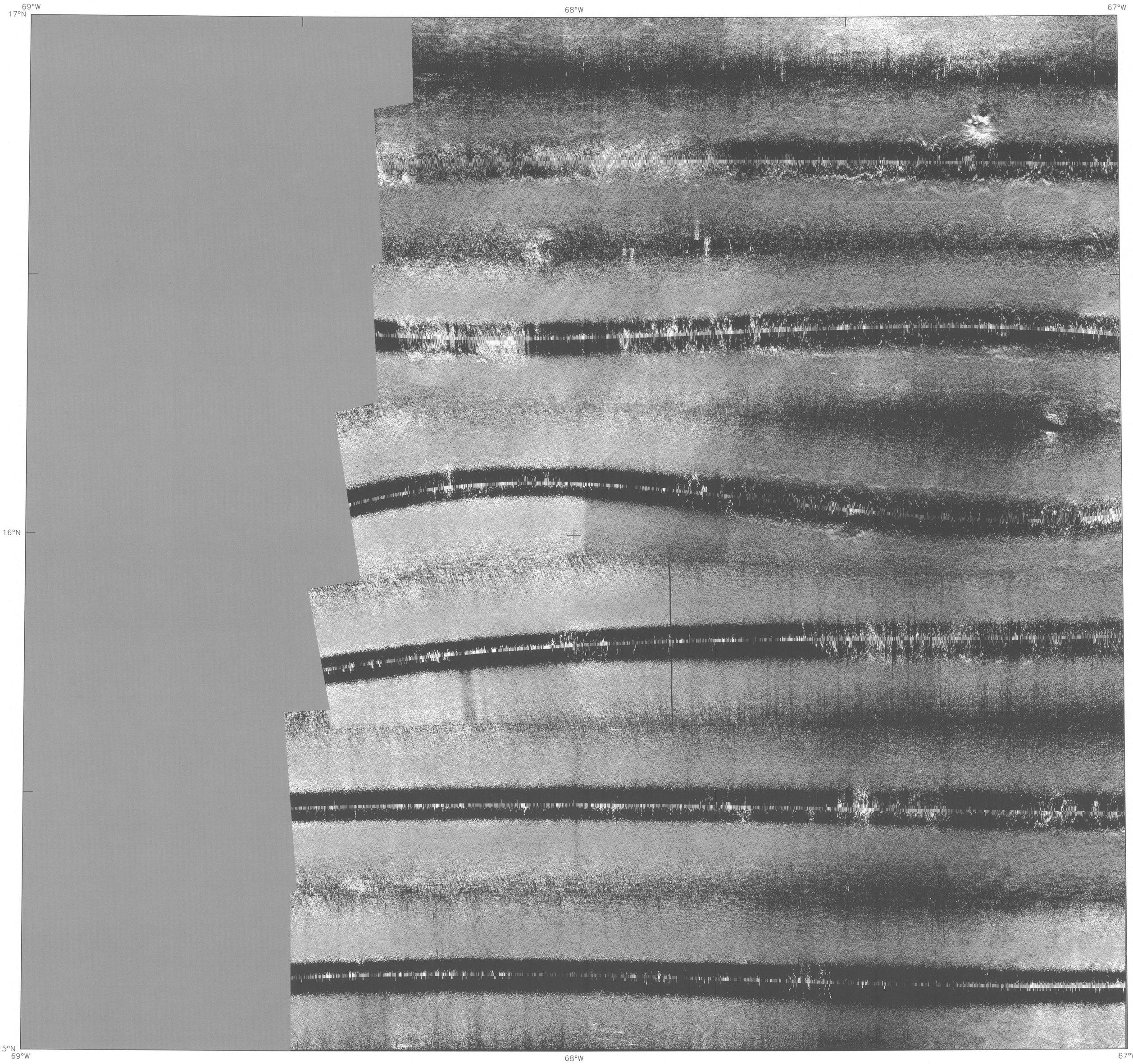
BATHYMETRIC CONTOUR INTERVAL 400 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 7



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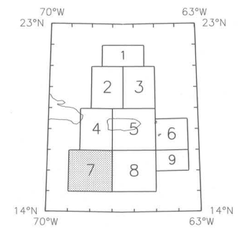

SHEET LOCATION

SONAR MOSAIC—SHEET 7
GEOLOGIC INTERPRETATION
BATHYMETRY

NO DATA

SCALE 1:500,000

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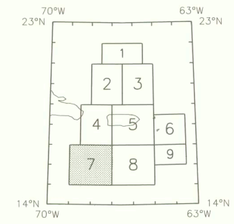
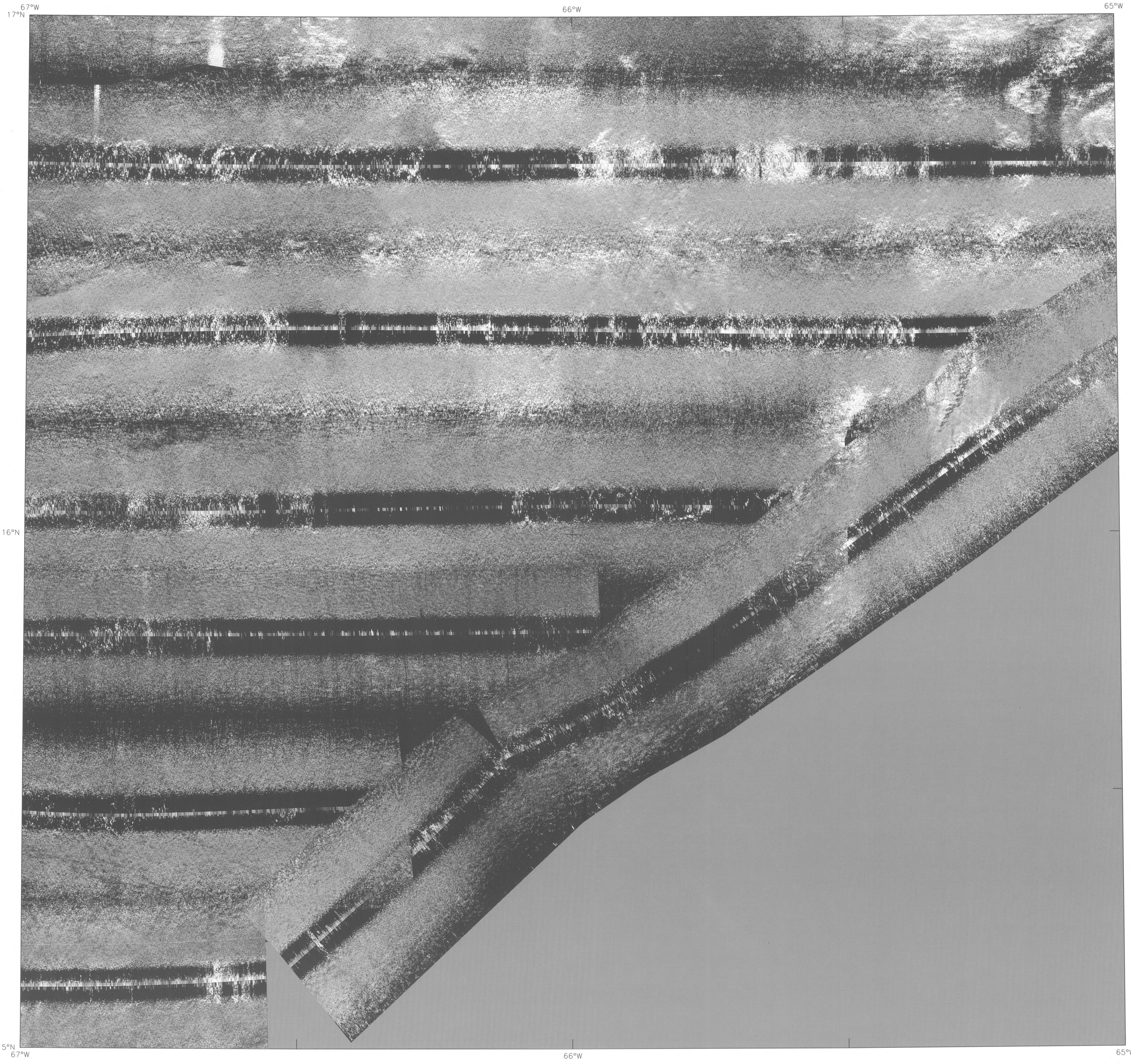
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 200 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 8



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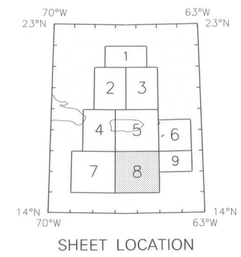
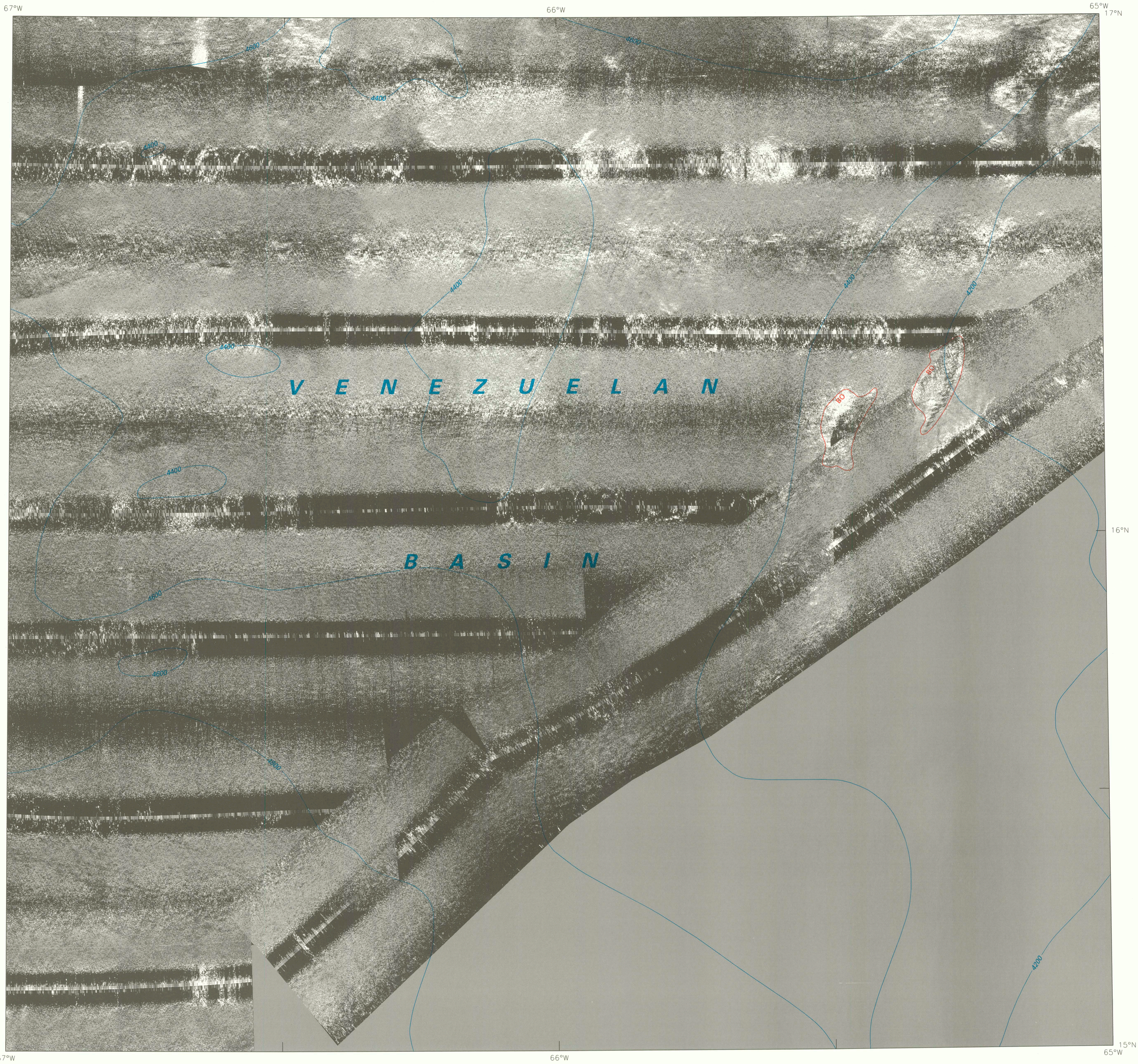


SHEET LOCATION

DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

SONAR MOSAIC—SHEET 8
GEOLOGIC INTERPRETATION
BATHYMETRY

ATLAS OF THE U.S. EXCLUSIVE ECONOMIC ZONE
EASTERN CARIBBEAN
I-1864-B



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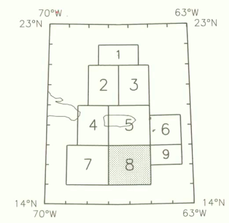
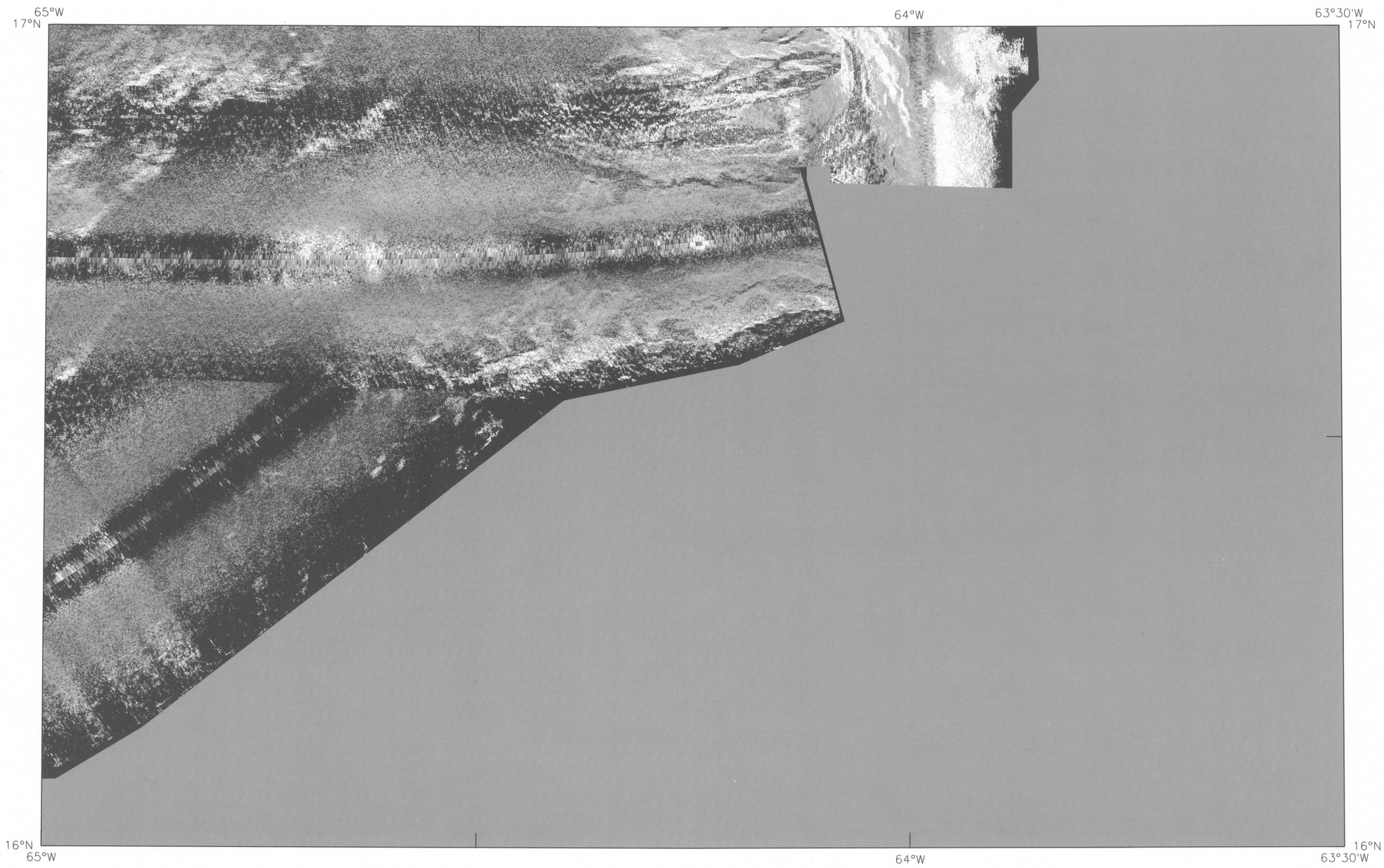
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 200 METERS



SHEET LOCATION

SONAR MOSAIC—SHEET 9



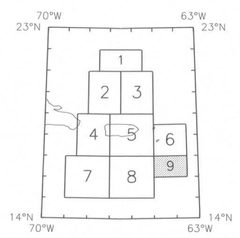
NO DATA

SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

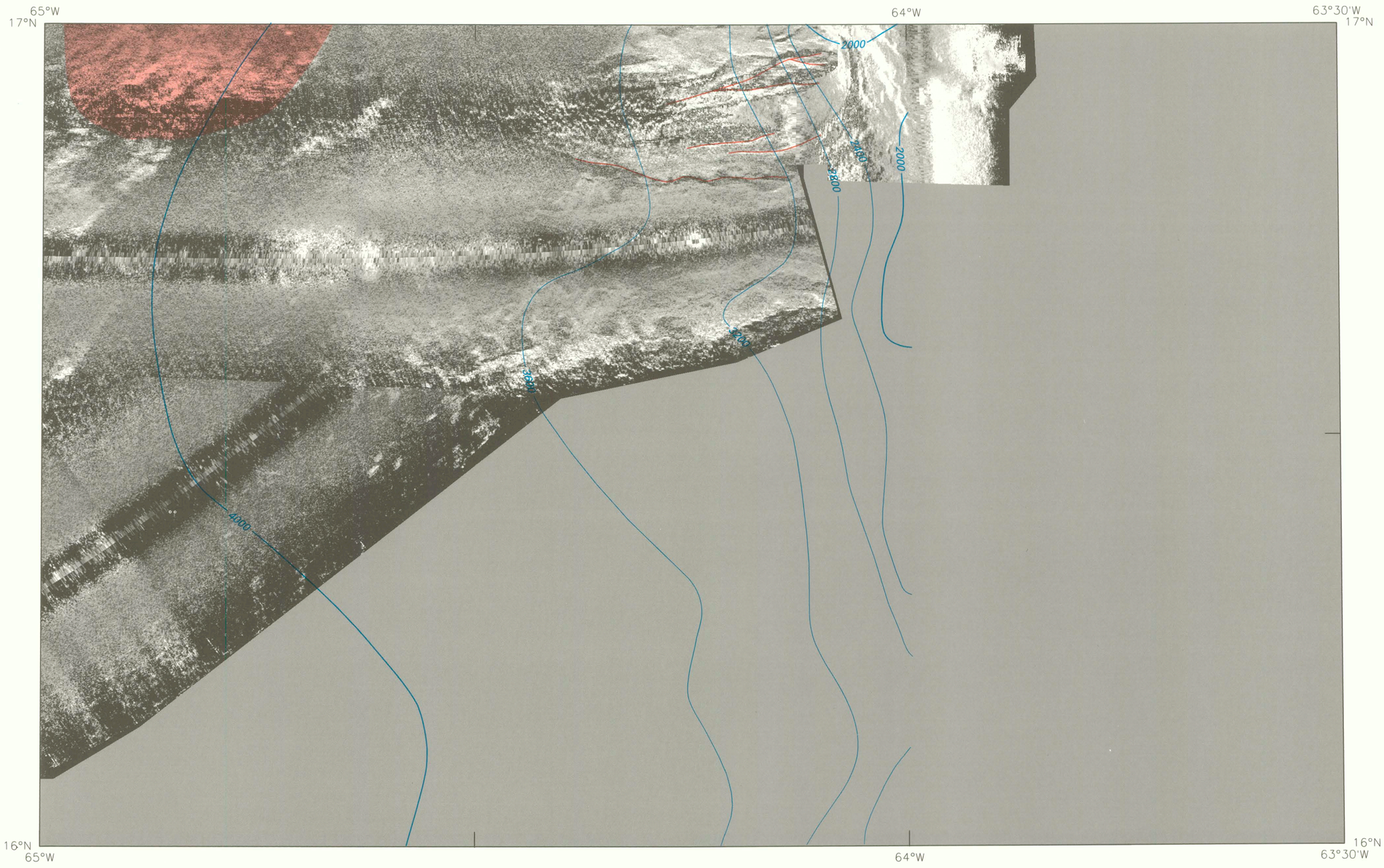
10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N



SHEET LOCATION

SONAR MOSAIC—SHEET 9
GEOLOGIC INTERPRETATION
BATHYMETRY



NO DATA

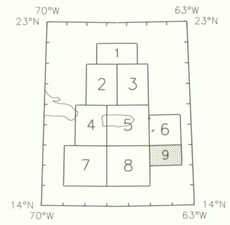
SCALE 1:500,000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 40 50 KILOMETERS

ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

BATHYMETRIC CONTOUR INTERVAL 400 METERS



SHEET LOCATION

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SEISMIC-REFLECTION PROFILES

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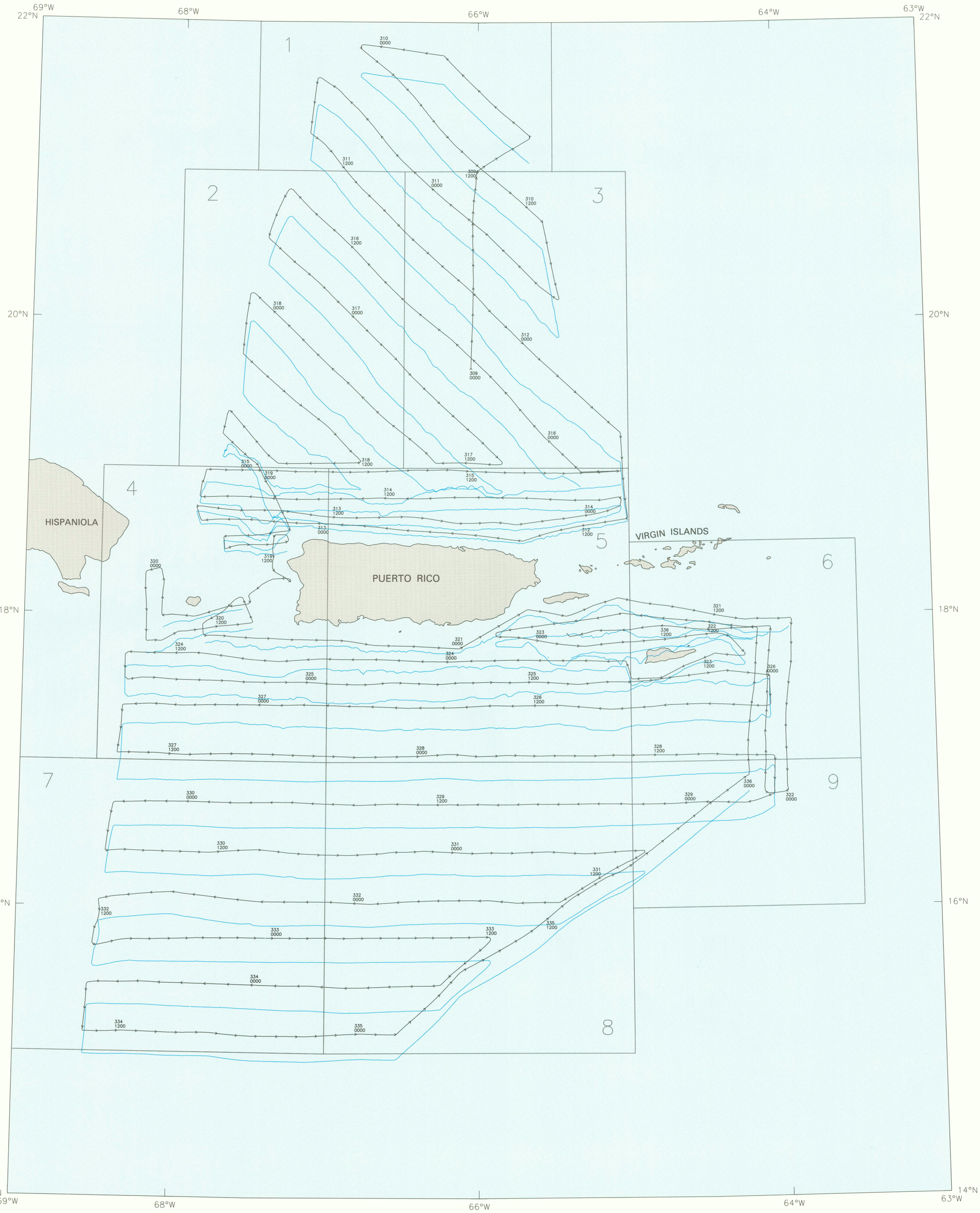


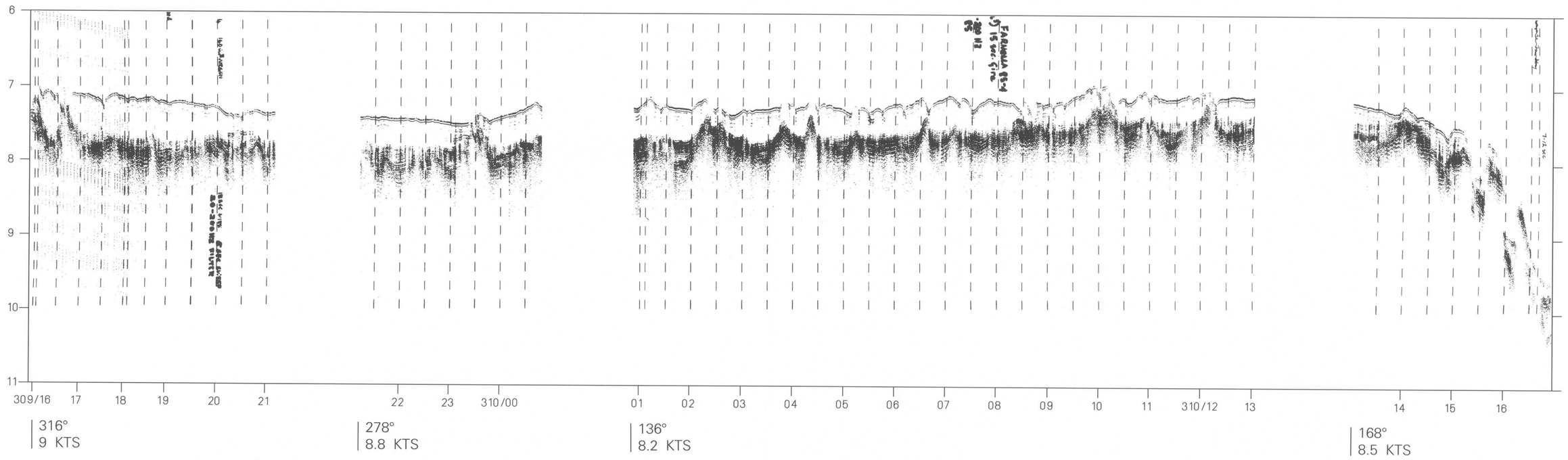
SCALE 1:2 000 000

50 0 50 100 150 NAUTICAL MILES

50 0 50 100 150 200 250 KILOMETERS

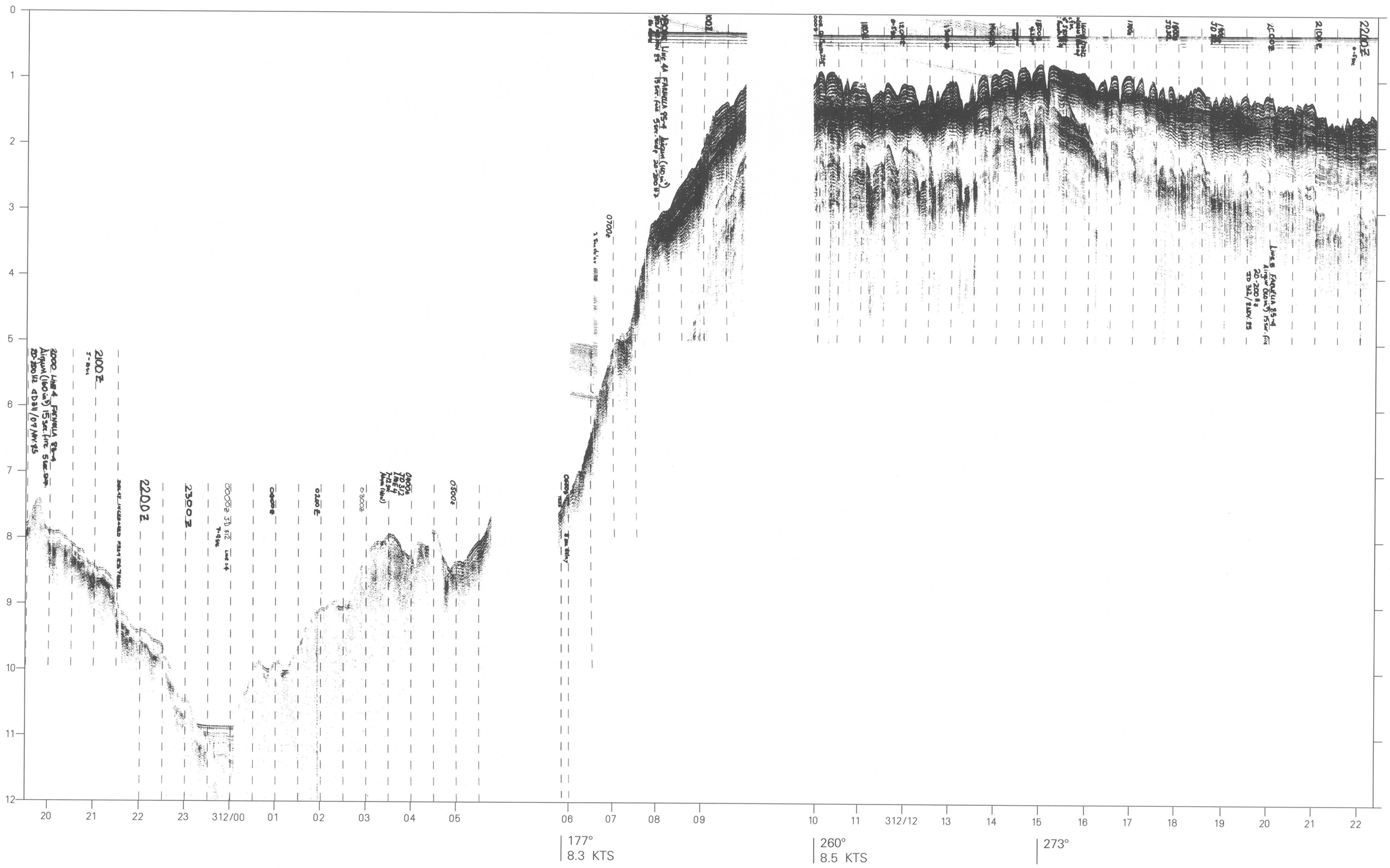
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

Map showing generalized bathymetric profiles (in blue) along tracklines in the EEZ survey area around Puerto Rico and the U.S. Virgin Islands. Sea-floor depth at any point along a trackline can be determined by measuring the distance from that point to the profile. Profiles are scaled so that a 1–cm offset from the trackline (sea level) represents a water depth of 5,300 m.

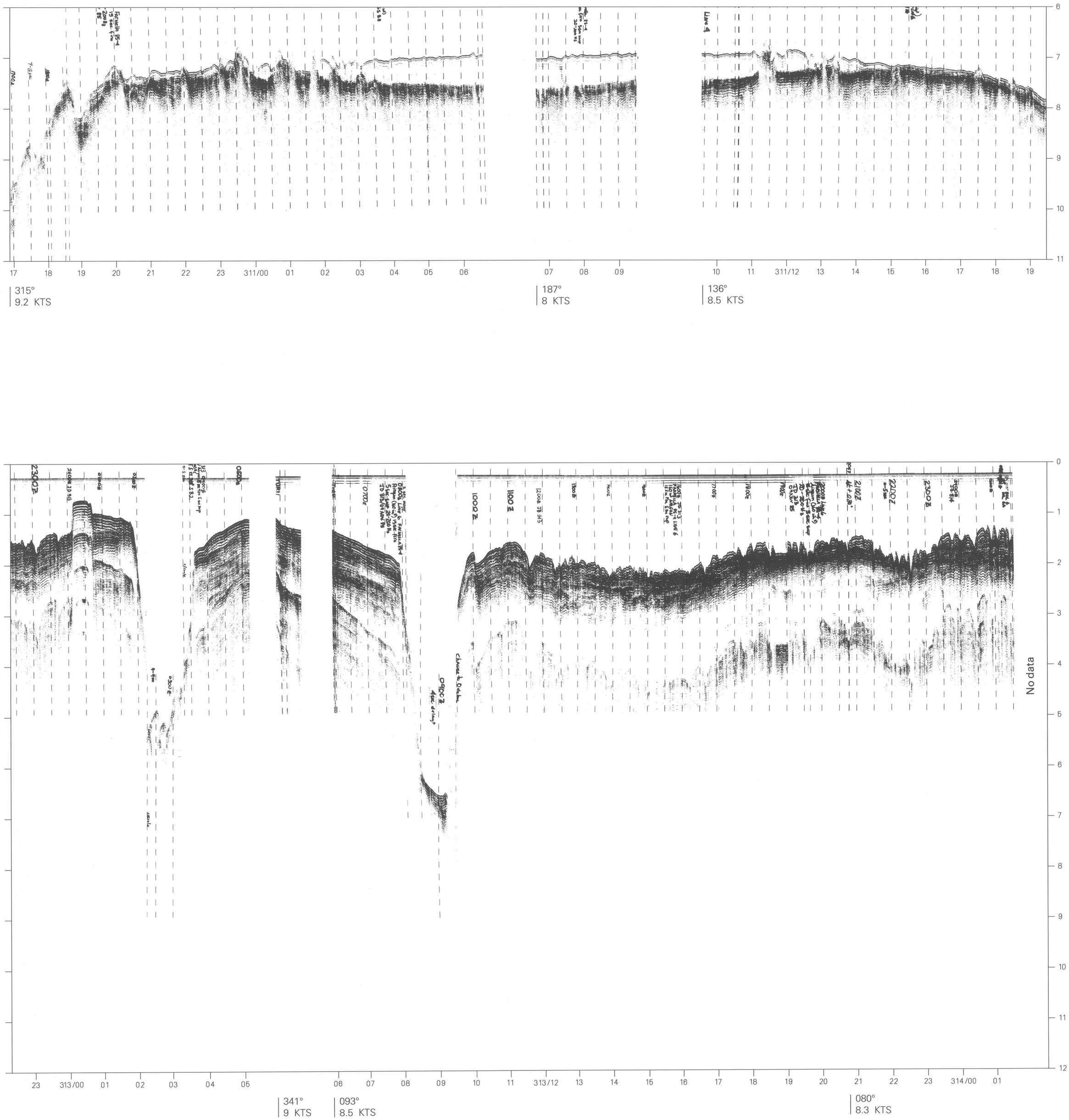


TWO-WAY TRAVELTIME, IN SECONDS

PUERTO RICO TRENCH

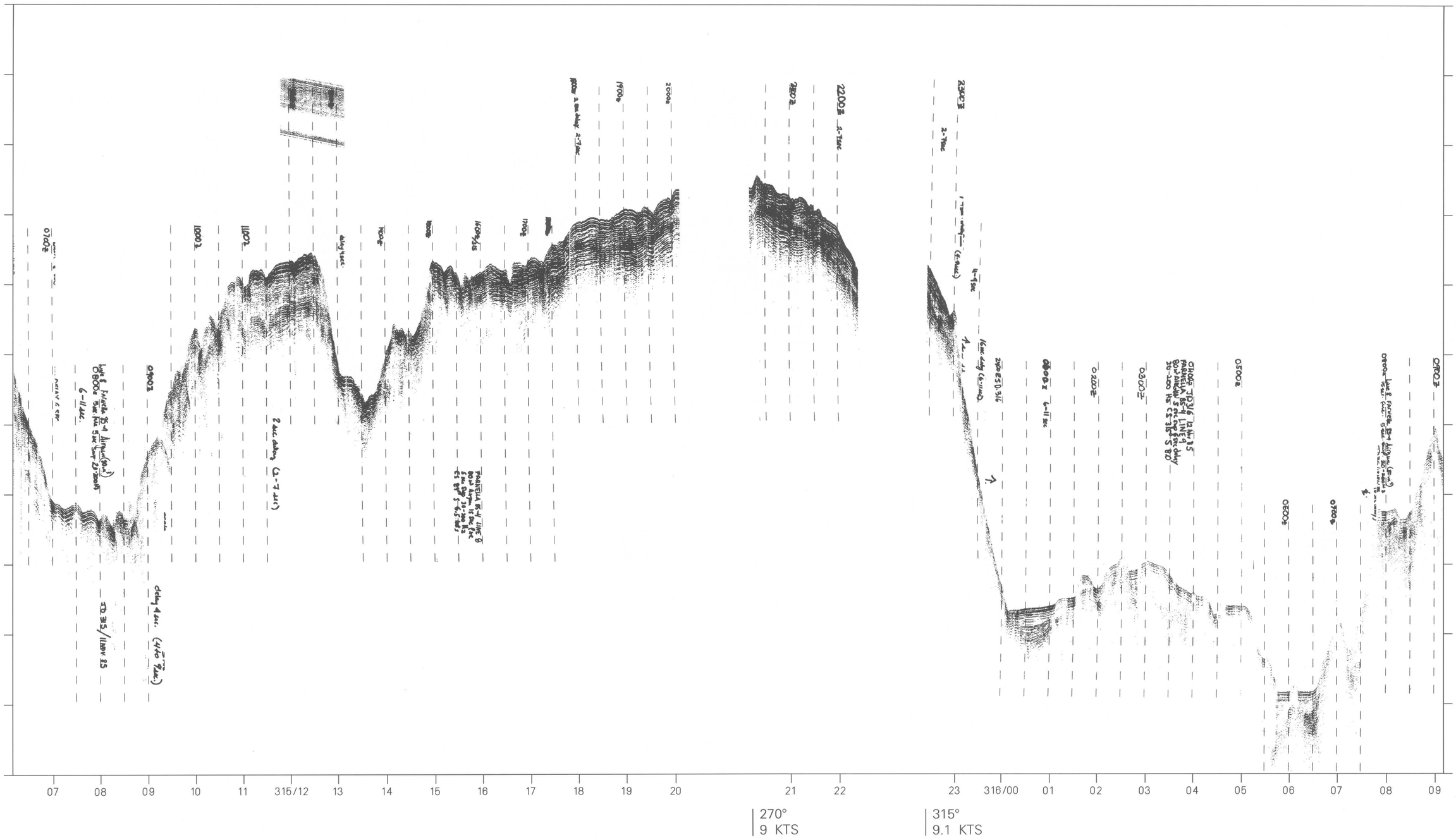


HOURS


TWO-WAY TRAVELTIME, IN SECONDS
0
1
2
3
4
5
6
7
8
9
10
11
12
No data
17 18 19 20 21 22 23 311/00 01 02 03 04 05 06 07 08 09 10 11 311/12 13 14 15 16 17 18 19
315° 9.2 KTS
187° 8 KTS
136° 8.5 KTS
23 313/00 01 02 03 04 05 06 07 08 09 10 11 313/12 13 14 15 16 17 18 19 20 21 22 23 314/00 01
341° 9 KTS
093° 8.5 KTS
080° 8.3 KTS
HOURS

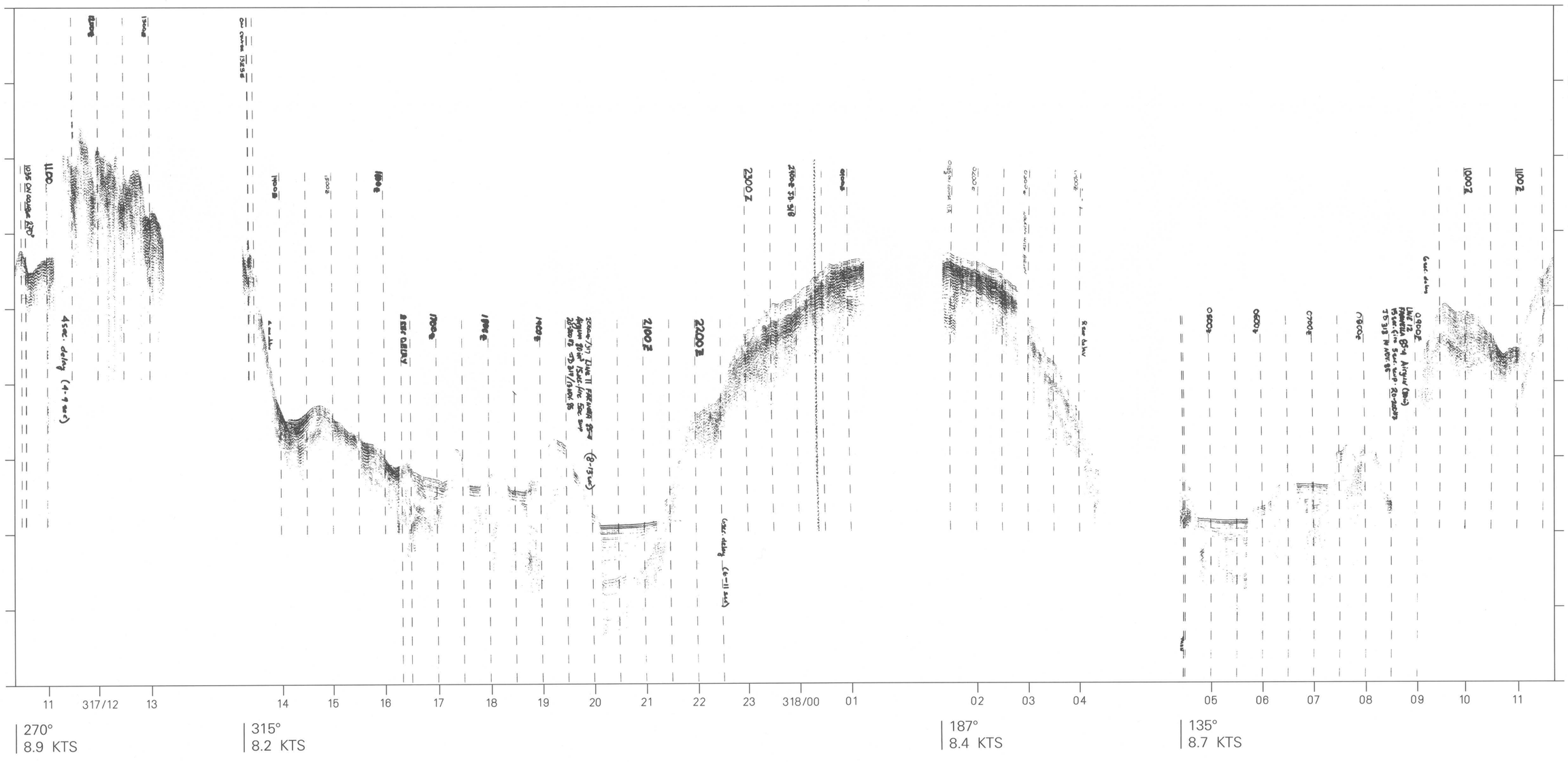
MONA CANYON
MONA CANYON
PUERTO RICO TRENCH
TWO-WAY TRAVELTIME, IN SECONDS
1
2
3
4
5
6
7
8
9
10
11
12
03 04 05 06 07 08 09 10 11 314/12 13 14 15 16 17 18 19 20 21 22 23 315/00 01 02 03 04 05 06
270°
8.8 KTS
012°
5.5 KTS
090°
7.1 KTS
4
5
6
7
8
9
10
11
12
13
10 11 316/12 13 14 15 16 17 18 19 20 21 22 23 317/00 01 02 03 04 05 06 07 08 09 10
200°
8.5 KTS
135°
7.9 KTS
HOURS

PUERTO RICO TRENCH



PUERTO RICO TRENCH

PUERTO RICO TRENCH



HOURS

MONA CANYON

MONA CANYON

MONA CANYON

TWO-WAY TRAVELTIME, IN SECONDS

0 1 2 3 4 5 6 7 8 9 10 11

No data

318/12 13 14 15 16 17 18 19 20 21 22 23 319/00 01 02 03 04 05 06 07

269° 9 KTS | 318° 7.7 KTS | 193° 7.5 KTS | 133° 7 KTS | 154° 7.3 KTS | 265° 8.0 KTS | 177° 7.5 KTS | 083° 7.2 KTS

GUAYANILLA CANYON

VIRGIN ISLANDS TROUGH

SAINT CROIX BASIN

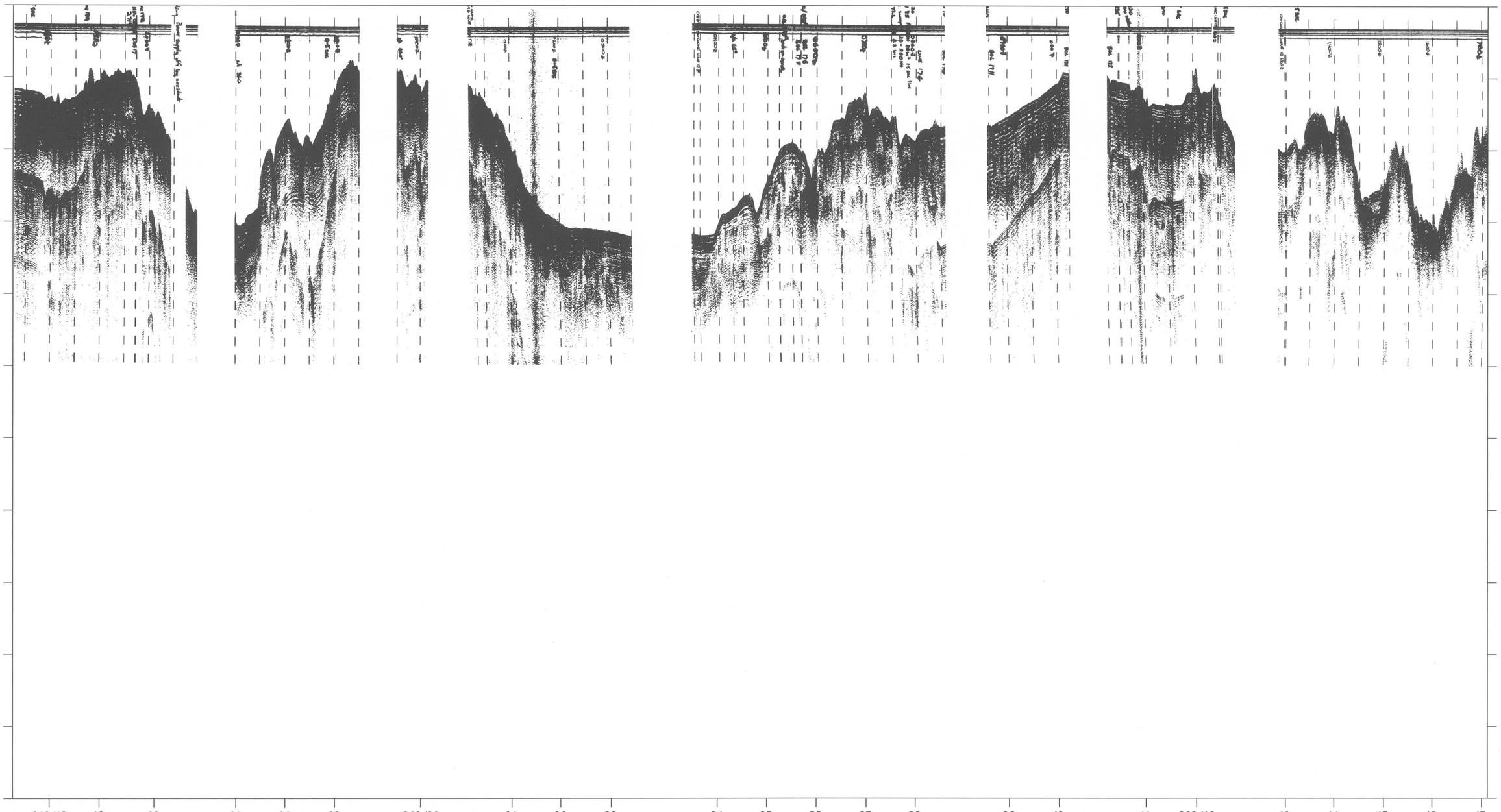
0 1 2 3 4 5 6 7

18 19 20 21 22 23 321/00 01 02 03 04 05 06 07 08 09 10 11 321/12 13 14 15 16 17 18 19 20 21

058° 8.5 KTS | 100° | 069° | 098° 8.3 KTS | 183° 8.5 KTS

HOURS

YUMA BASIN

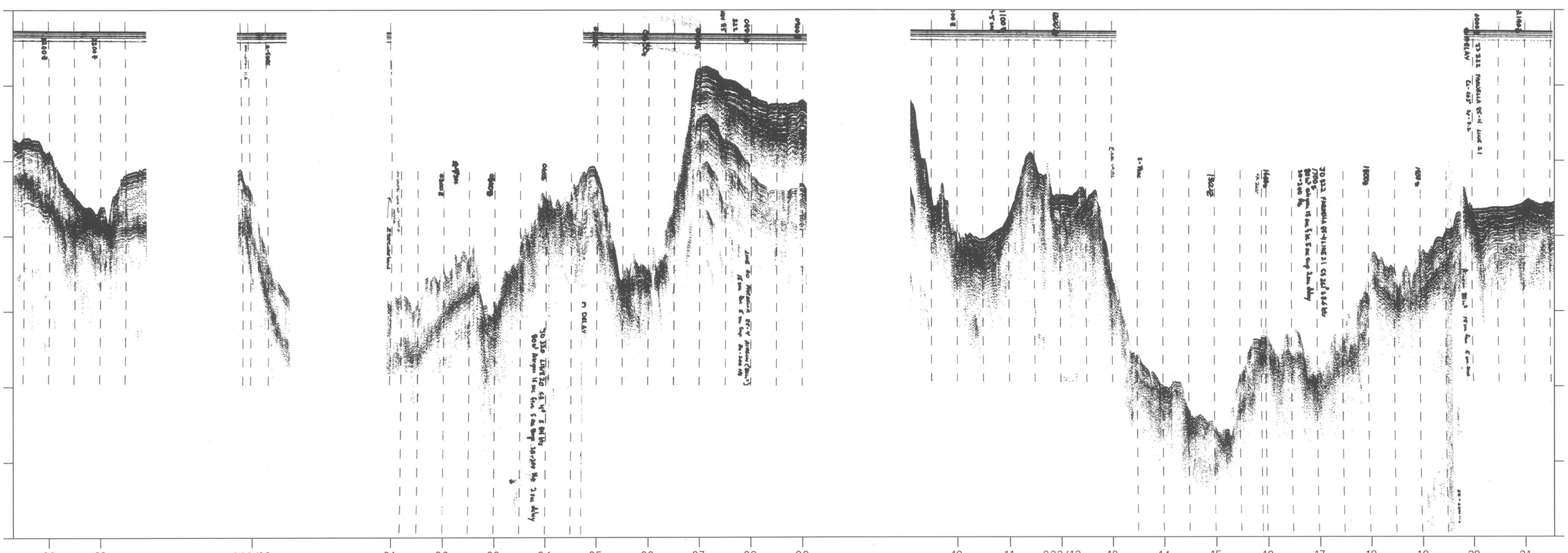


TWO-WAY TRAVELTIME, IN SECONDS

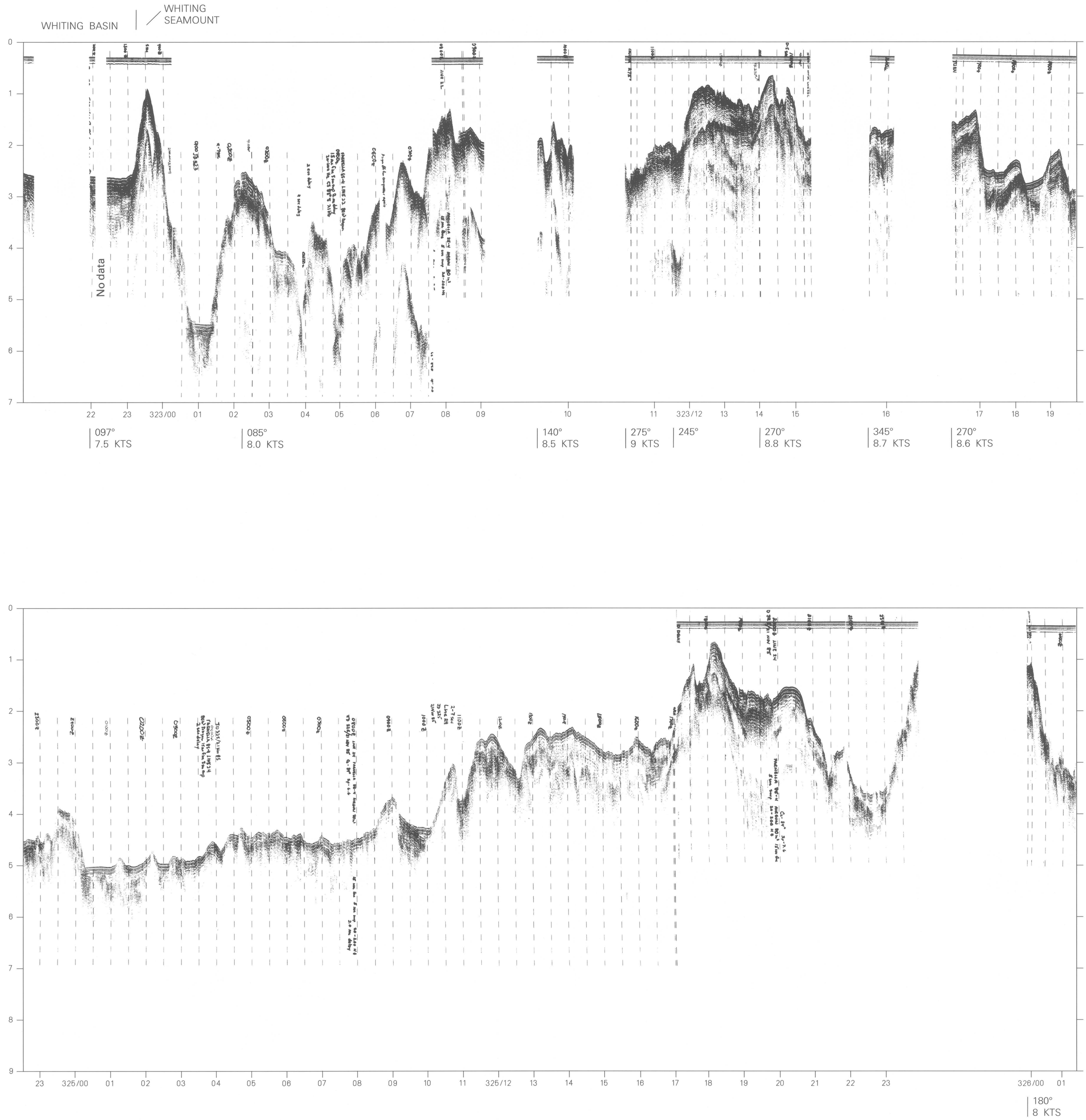
SAINT CROIX BASIN

VIRGIN ISLANDS TROUGH

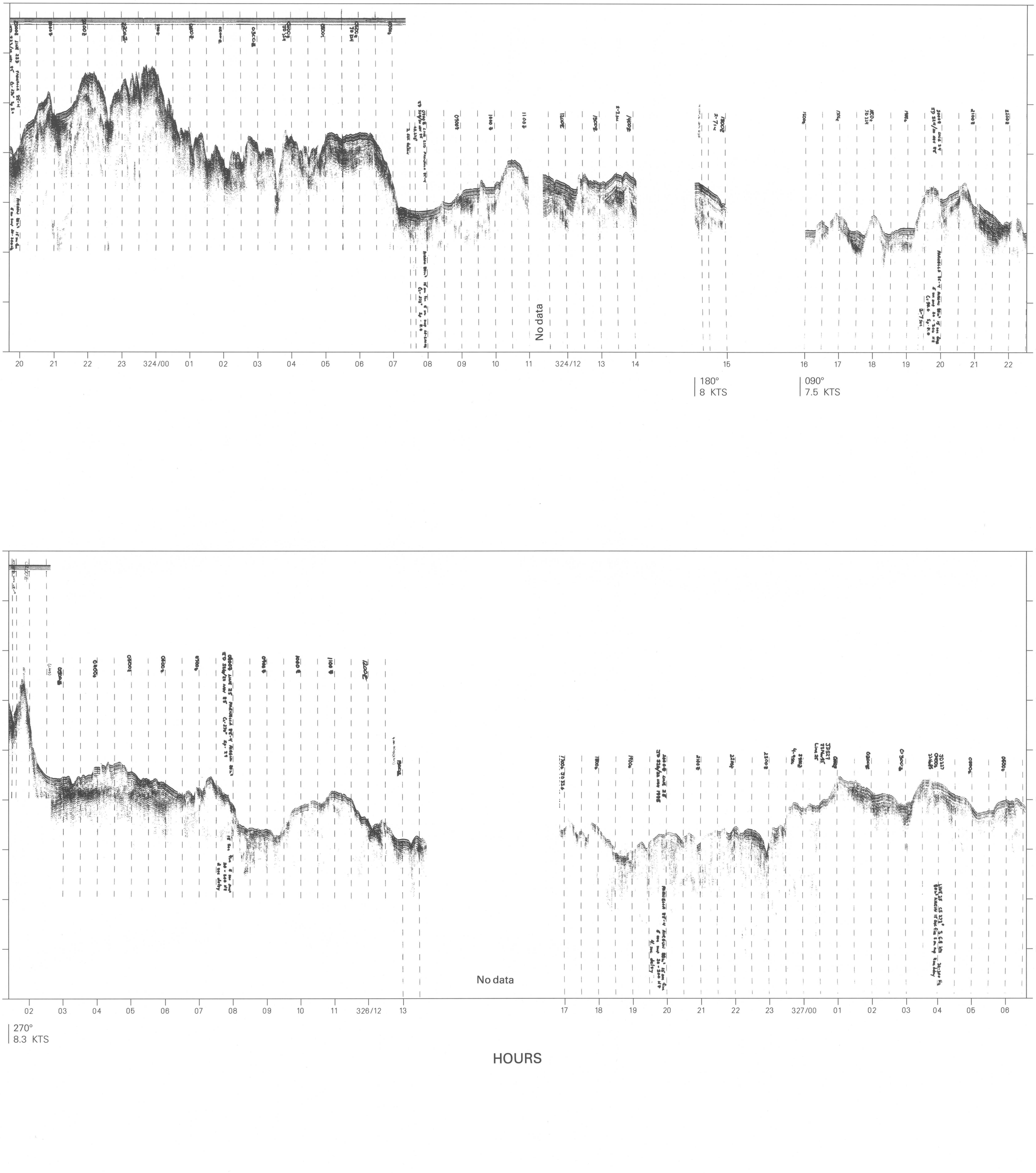
WHITING BASIN



HOURS

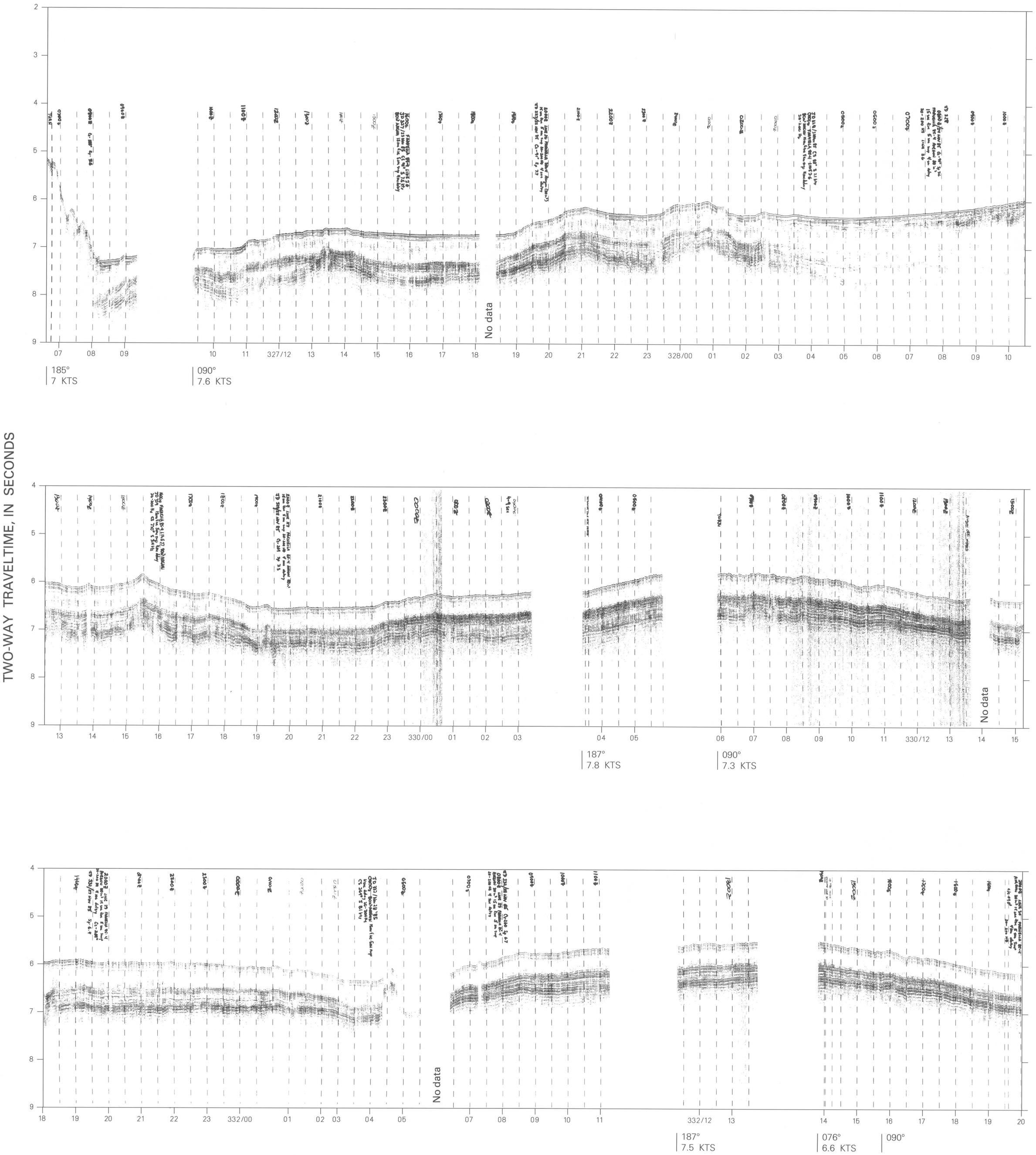

WHITING BASIN
WHITING SEAMOUNT
No data
TWO-WAY TRAVELTIME, IN SECONDS
0
1
2
3
4
5
6
7
8
9
22 23 323/00 01 02 03 04 05 06 07 08 09 10 11 323/12 13 14 15 16 17 18 19
097° 7.5 KTS
085° 8.0 KTS
140° 8.5 KTS
275° 9 KTS
245°
270° 8.8 KTS
345° 8.7 KTS
270° 8.6 KTS
23 326/00 01 02 03 04 05 06 07 08 09 10 11 325/12 13 14 15 16 17 18 19 20 21 22 23 326/00 01
180° 8 KTS
HOURS

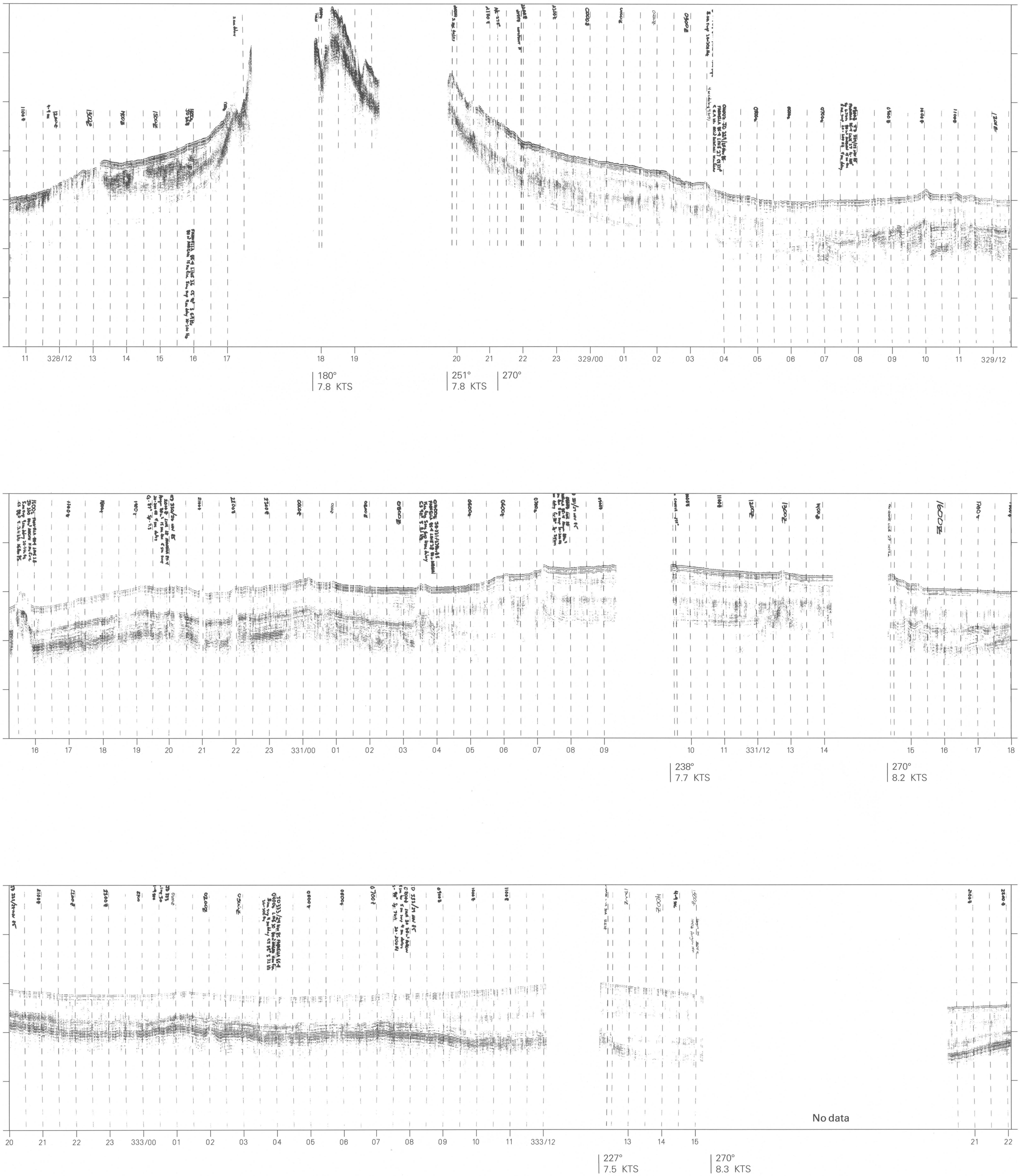
GUAYANILLA
CANYON



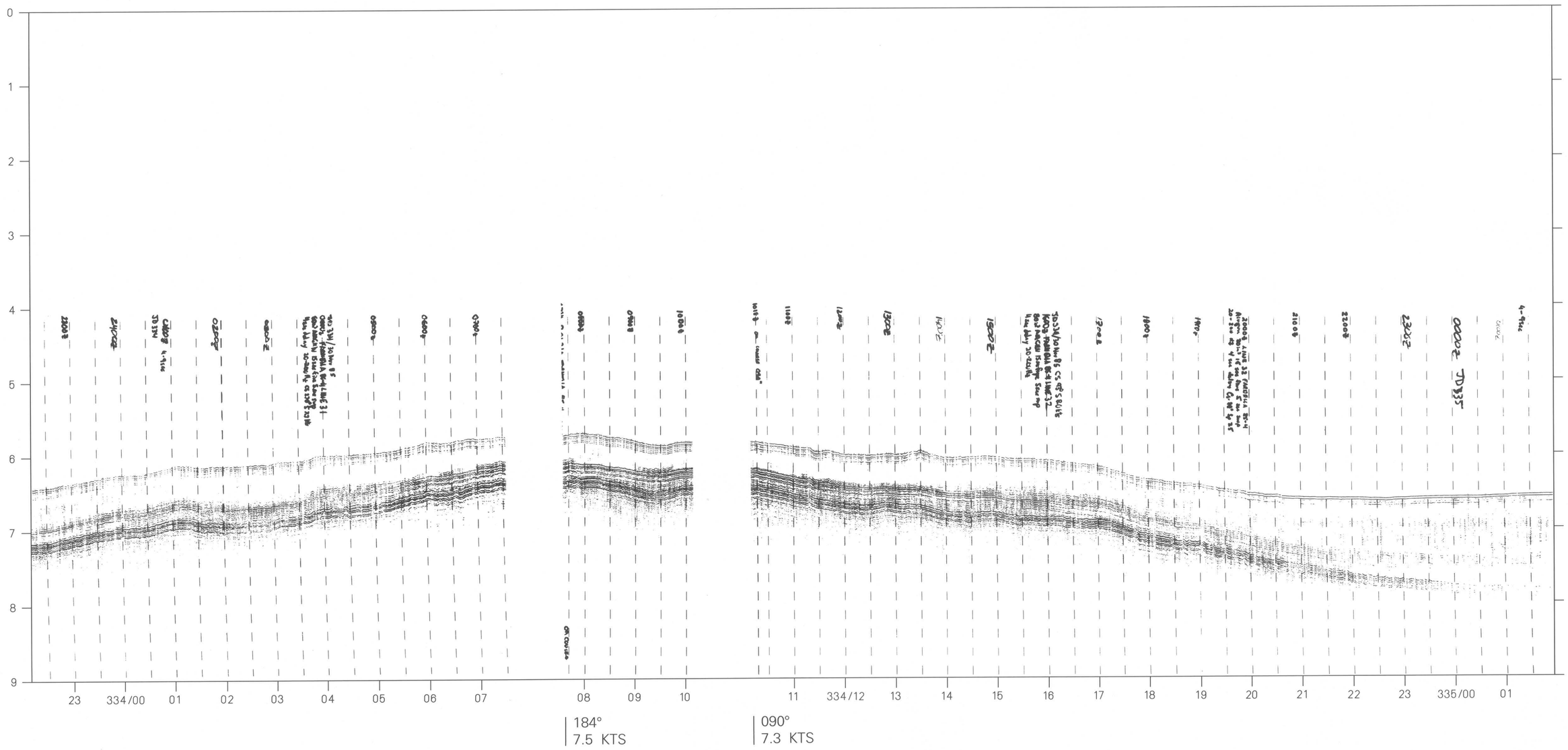
TWO-WAY TRAVELTIME, IN SECONDS

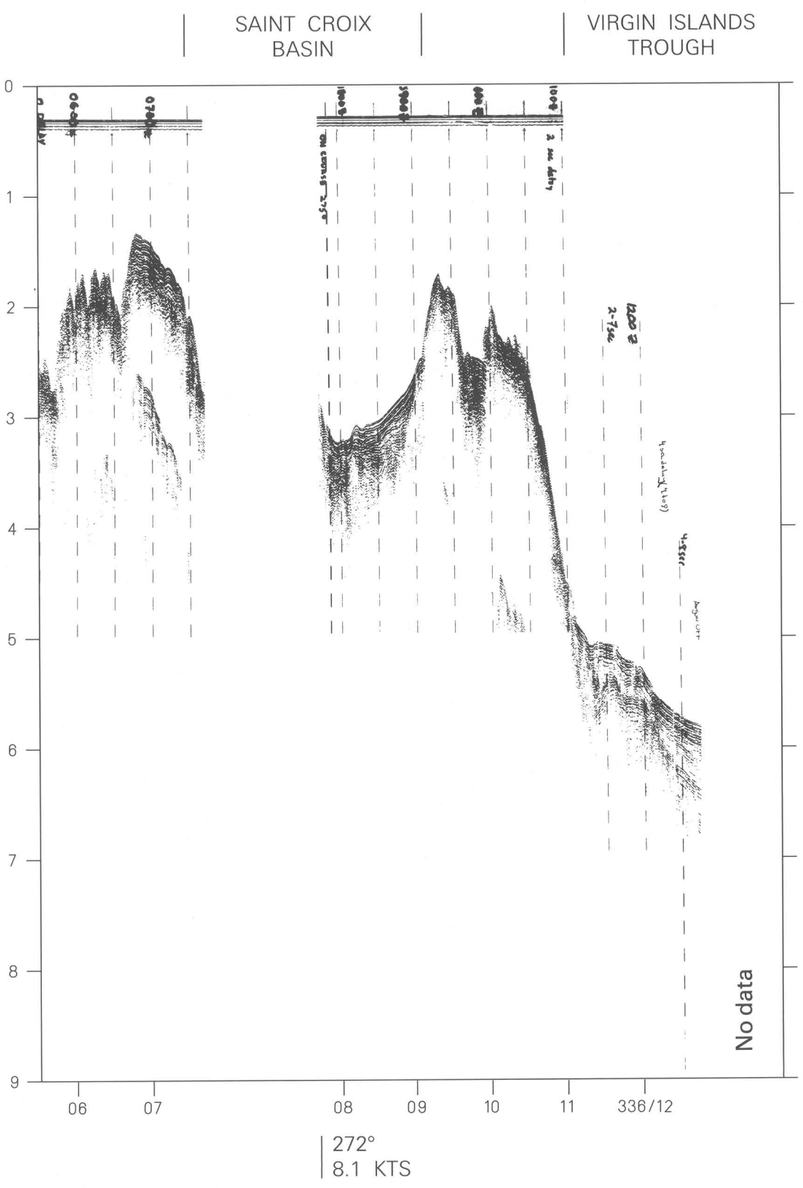
HOURS


TWO-WAY TRAVELTIME, IN SECONDS
2
3
4
5
6
7
8
9
07 08 09 10 11 327/12 13 14 15 16 17 18 19 20 21 22 23 328/00 01 02 03 04 05 06 07 08 09 10
No data
185°
7 KTS
090°
7.6 KTS
13 14 15 16 17 18 19 20 21 22 23 330/00 01 02 03 04 05 06 07 08 09 10 11 330/12 13 14 15
No data
187°
7.8 KTS
090°
7.3 KTS
18 19 20 21 22 23 332/00 01 02 03 04 05 07 08 09 10 11 332/12 13 14 15 16 17 18 19 20
No data
187°
7.5 KTS
076°
6.6 KTS
090°
HOURS

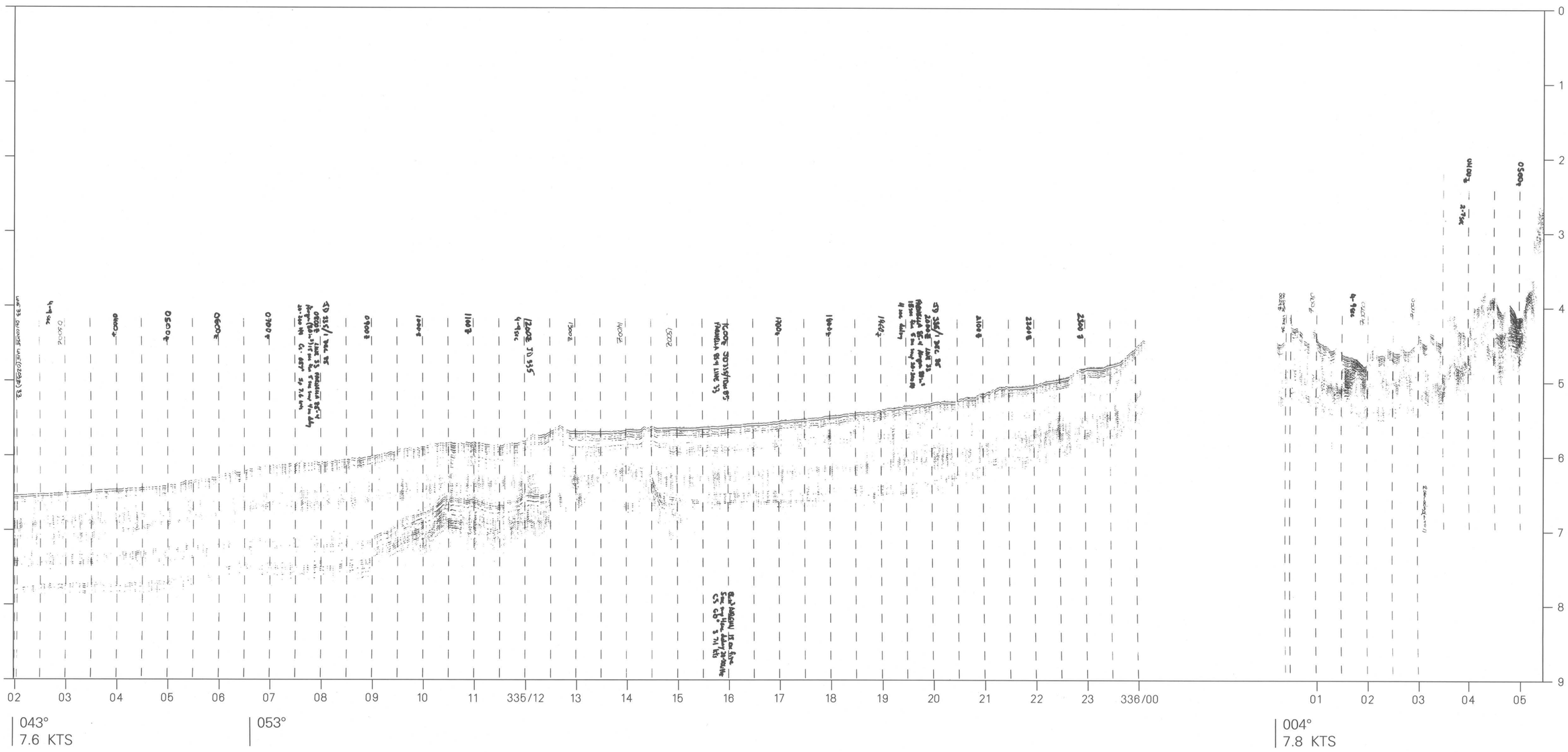

TWO-WAY TRAVELTIME, IN SECONDS
HOURS
180°
7.8 KTS
251°
7.8 KTS
270°
238°
7.7 KTS
270°
8.2 KTS
227°
7.5 KTS
270°
8.3 KTS
No data

TWO-WAY TRAVELTIME, IN SECONDS





HOURS


TWO-WAY TRAVELTIME, IN SECONDS
0
1
2
3
4
5
6
7
8
9
02
03
04
05
06
07
08
09
10
11
335/12
13
14
15
16
17
18
19
20
21
22
23
336/00
01
02
03
04
05
043°
7.6 KTS
053°
004°
7.8 KTS
HOURS

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MAGNETIC-ANOMALY AND BATHYMETRY PROFILES

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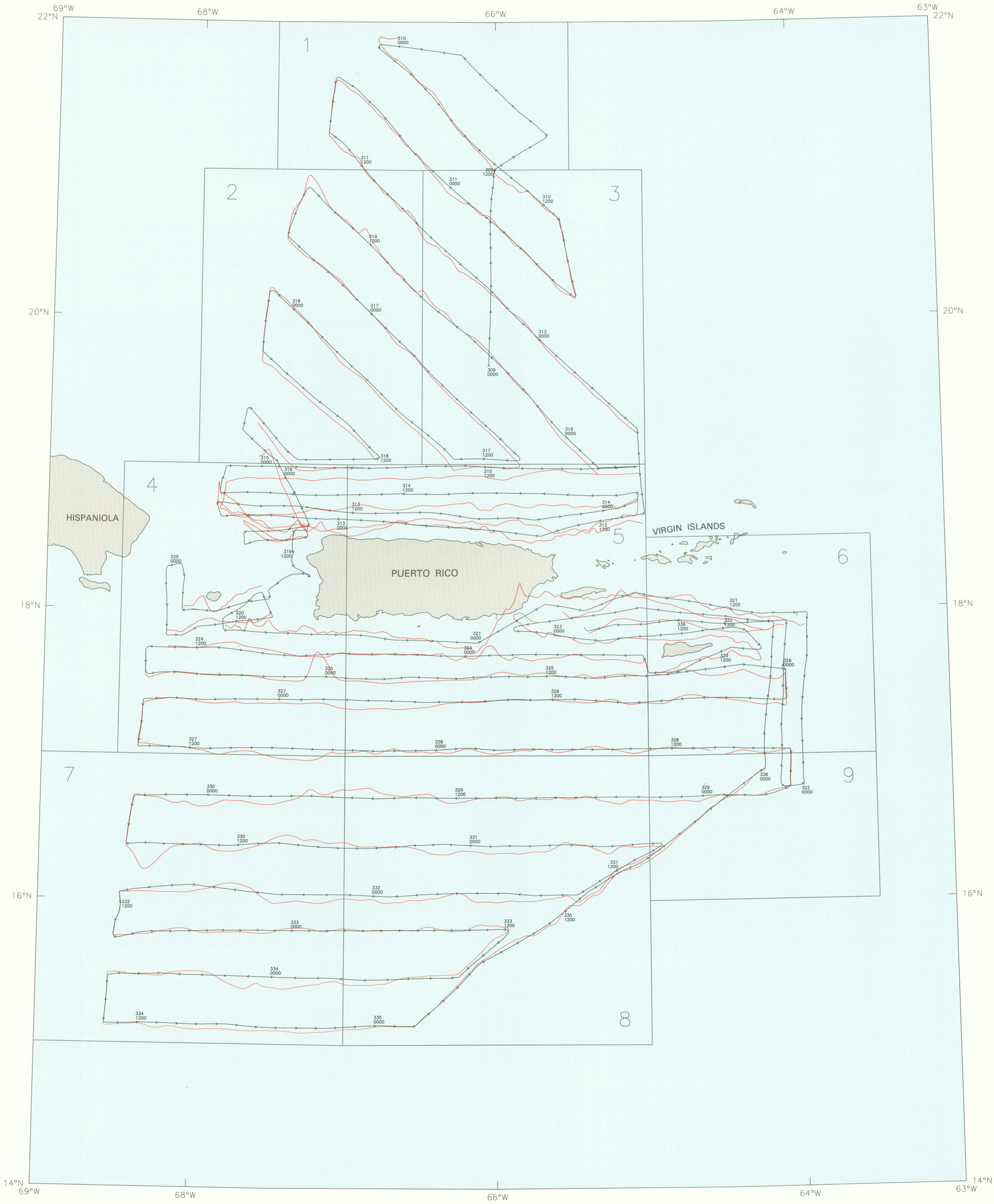


SCALE 1:2 000 000

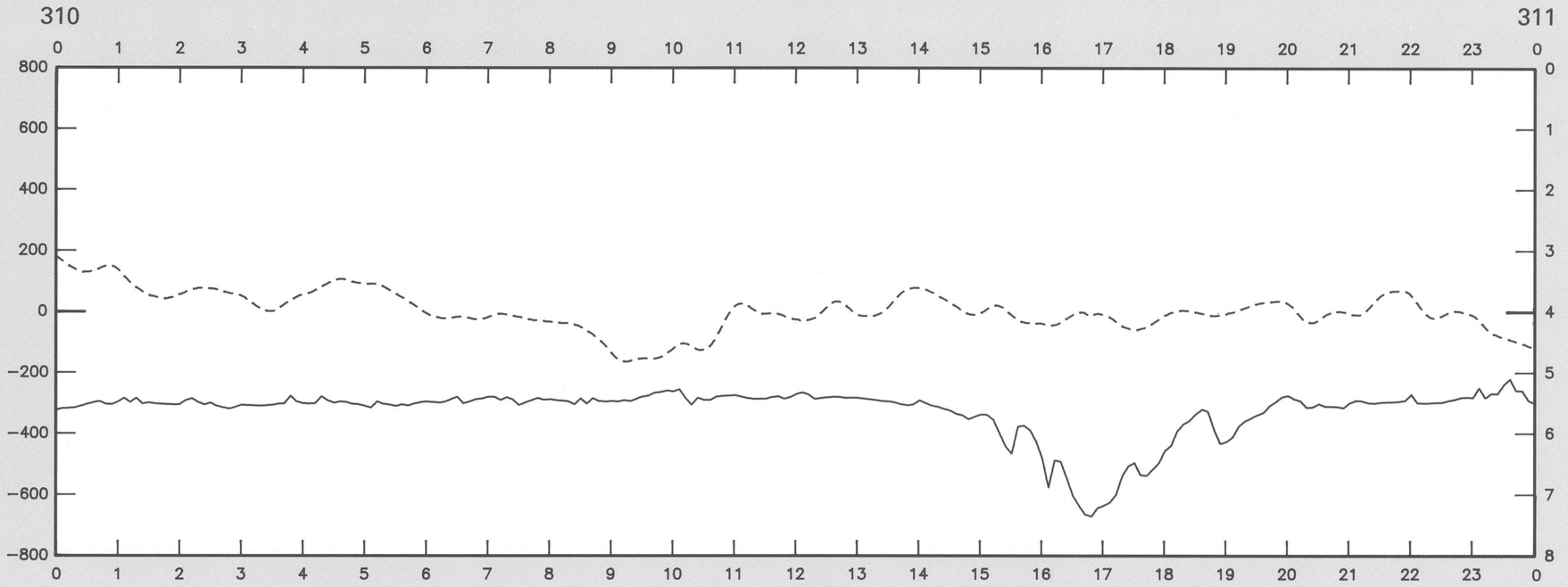
50 0 50 100 150 NAUTICAL MILES

50 0 50 100 150 200 250 KILOMETERS

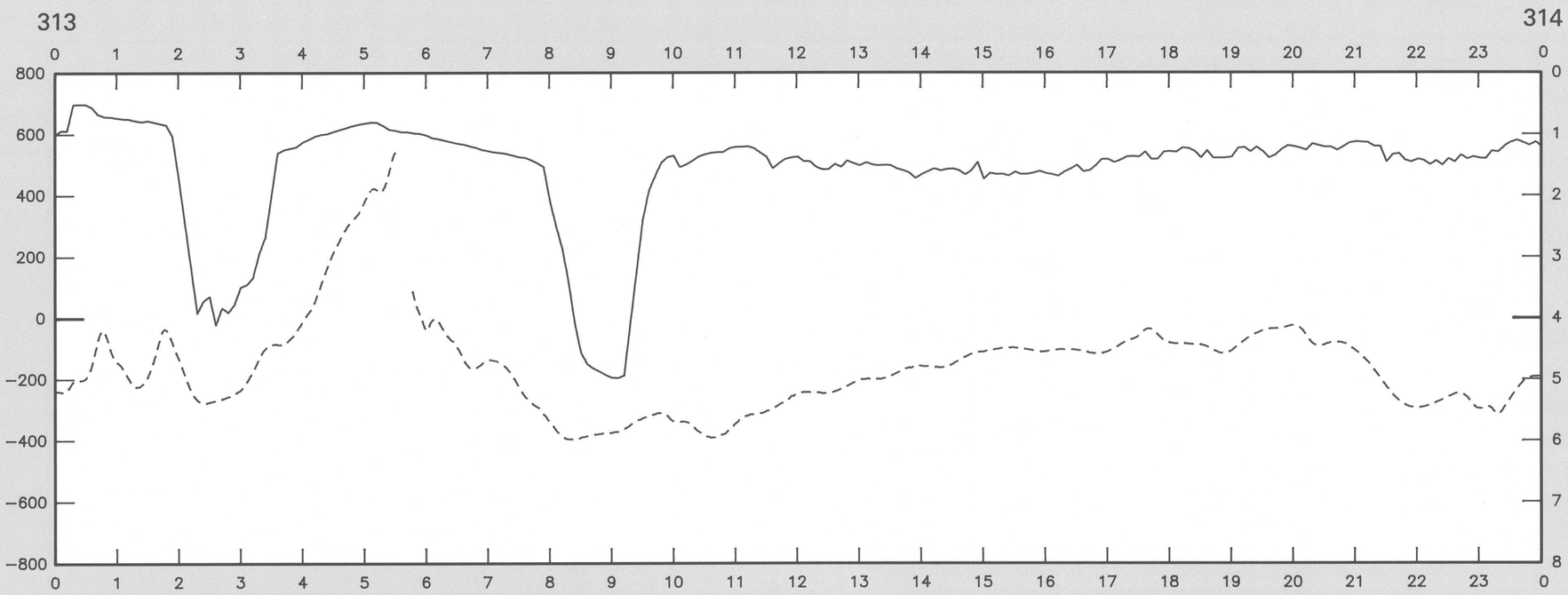
ALBERS EQUAL-AREA PROJECTION
Standard parallels 29.5° N and 45.5° N

Map showing generalized magnetic-anomaly profiles (in red) along tracklines in the EEZ survey area around Puerto Rico and the U.S. Virgin Islands. The profiles are scaled so that a 1–cm offset from the trackline (0 gammas) represents 500 gammas.

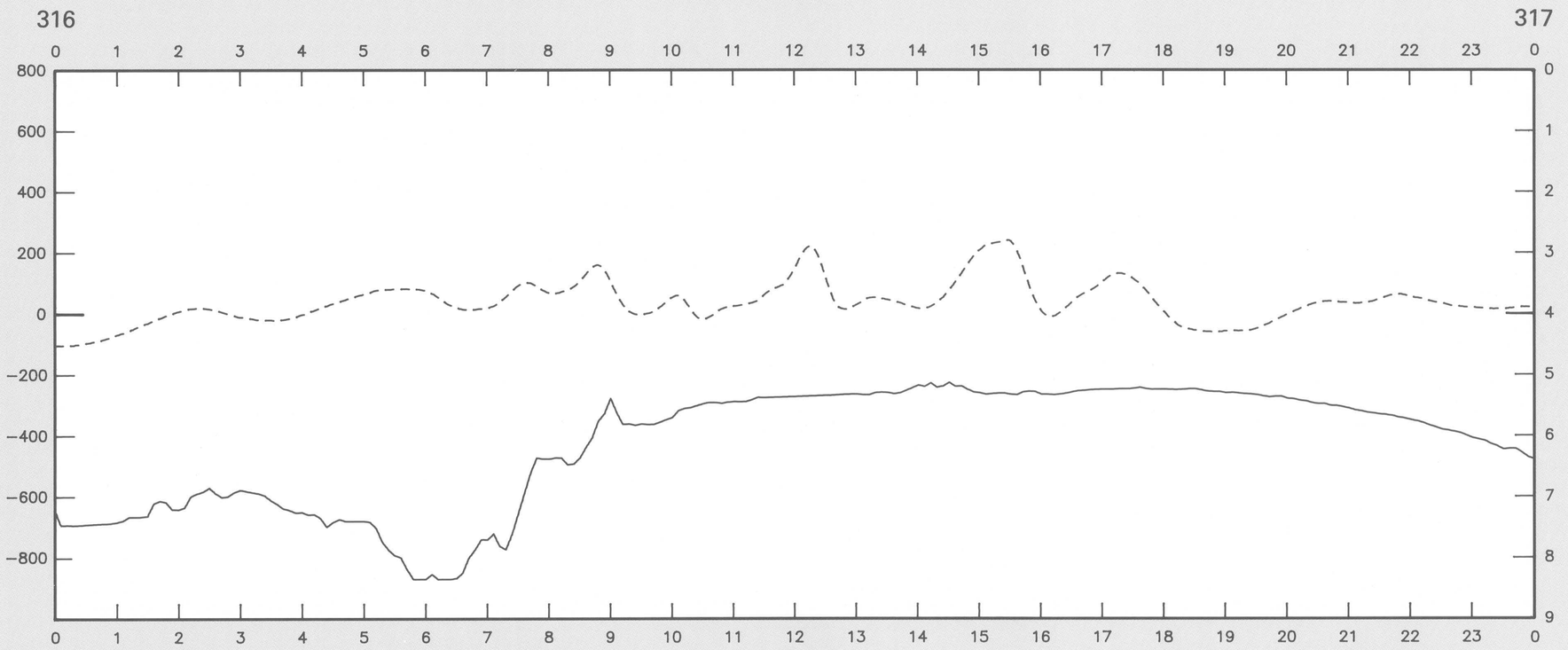
DAY 310–313


310
311
312
313
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0 1 2 3 4 5 6 7 8 9
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
HOURS
EXPLANATION
Bathymetry
Magnetics

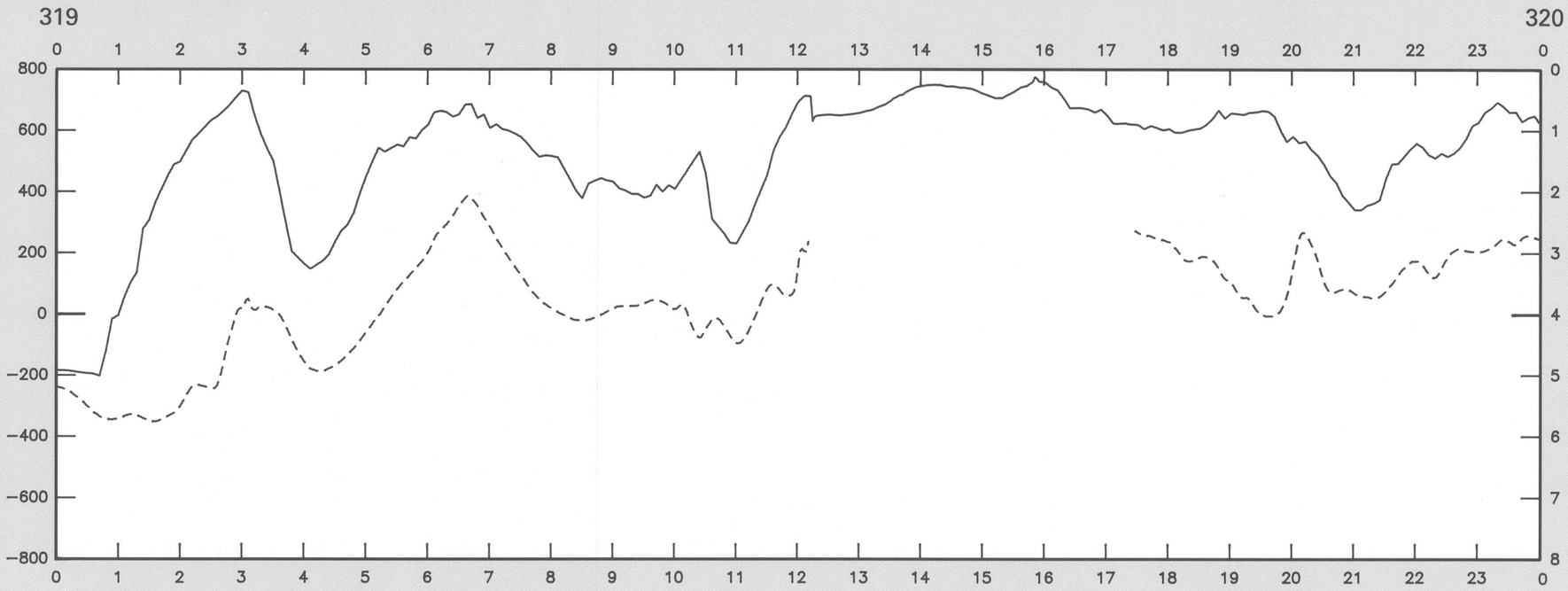
DAY 313–316


313
314
315
316
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
0 1 2 3 4 5 6 7 8
EXPLANATION
Bathymetry
Magnetics
HOURS

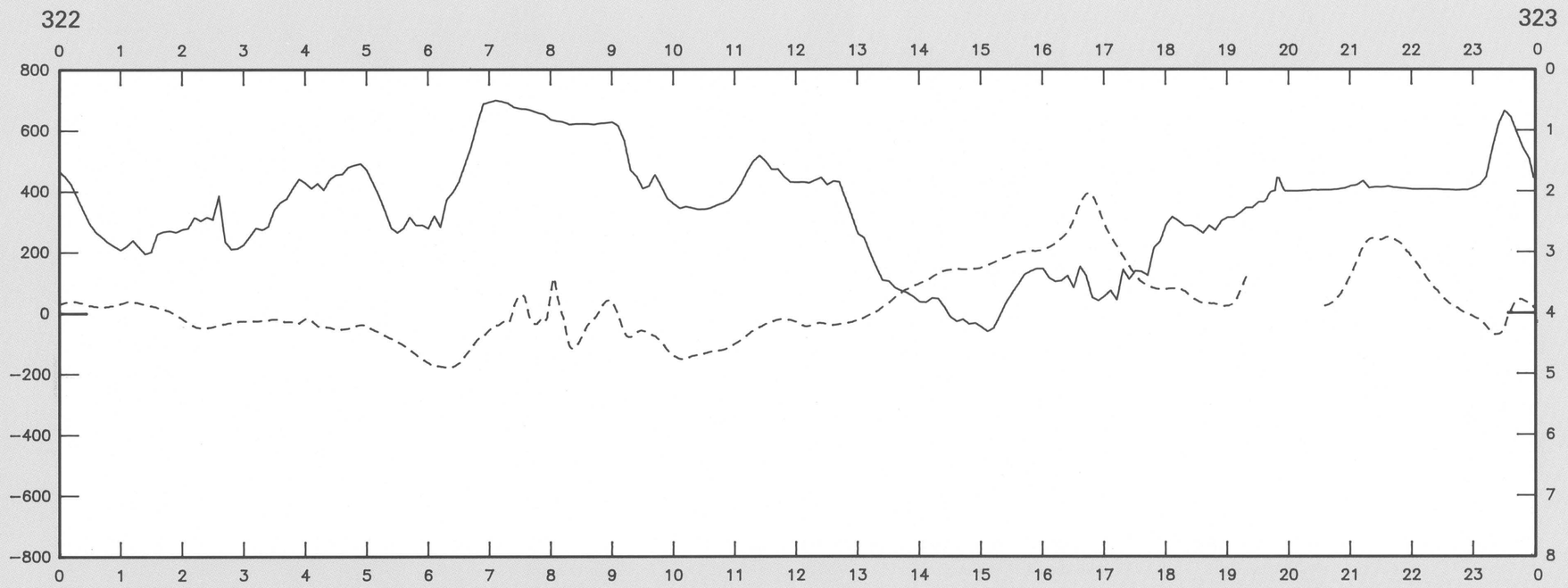
DAY 316–319

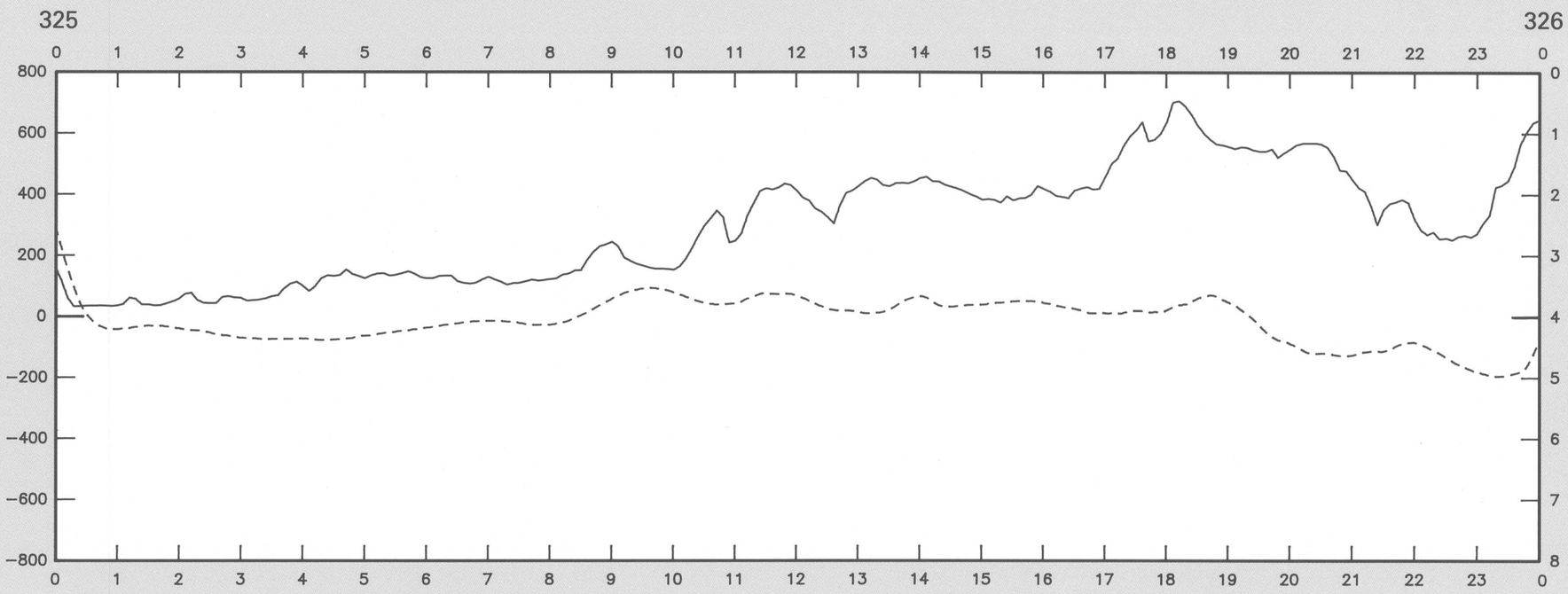

316
317
318
319
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0
1
2
3
4
5
6
7
8
9
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
HOURS
EXPLANATION
Bathymetry
Magnetics

DAY 319–322

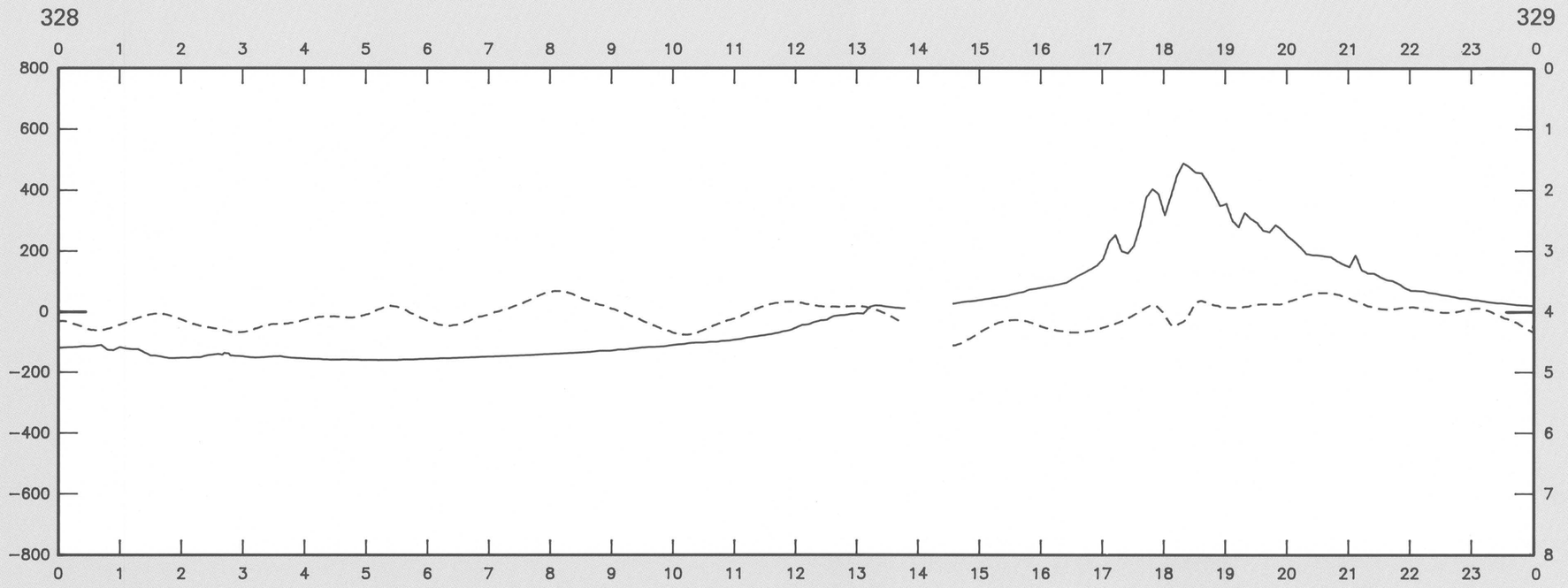

319
320
321
322
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0 1 2 3 4 5 6 7 8
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
EXPLANATION
Bathymetry
Magnetics
HOURS

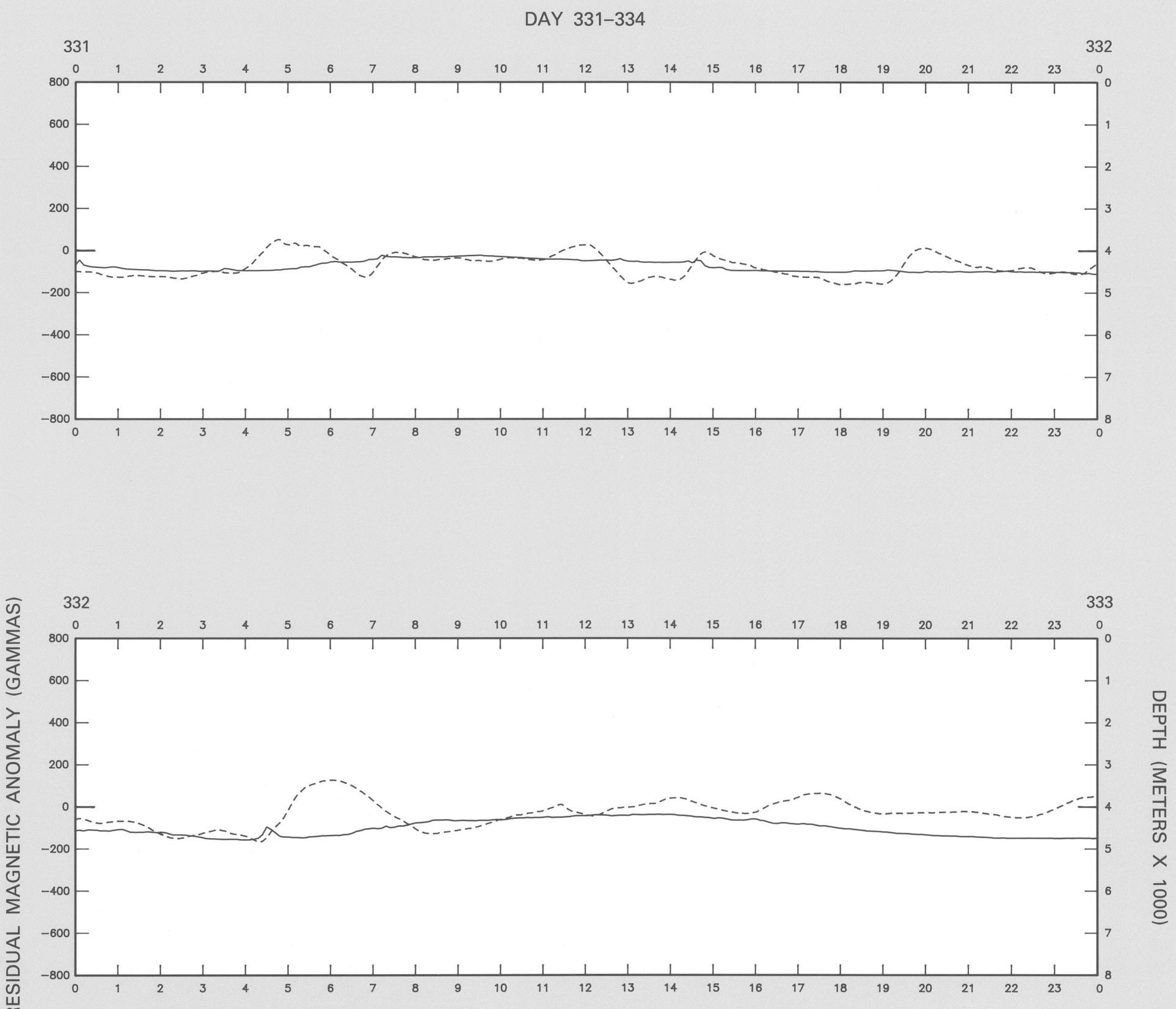
DAY 322–325

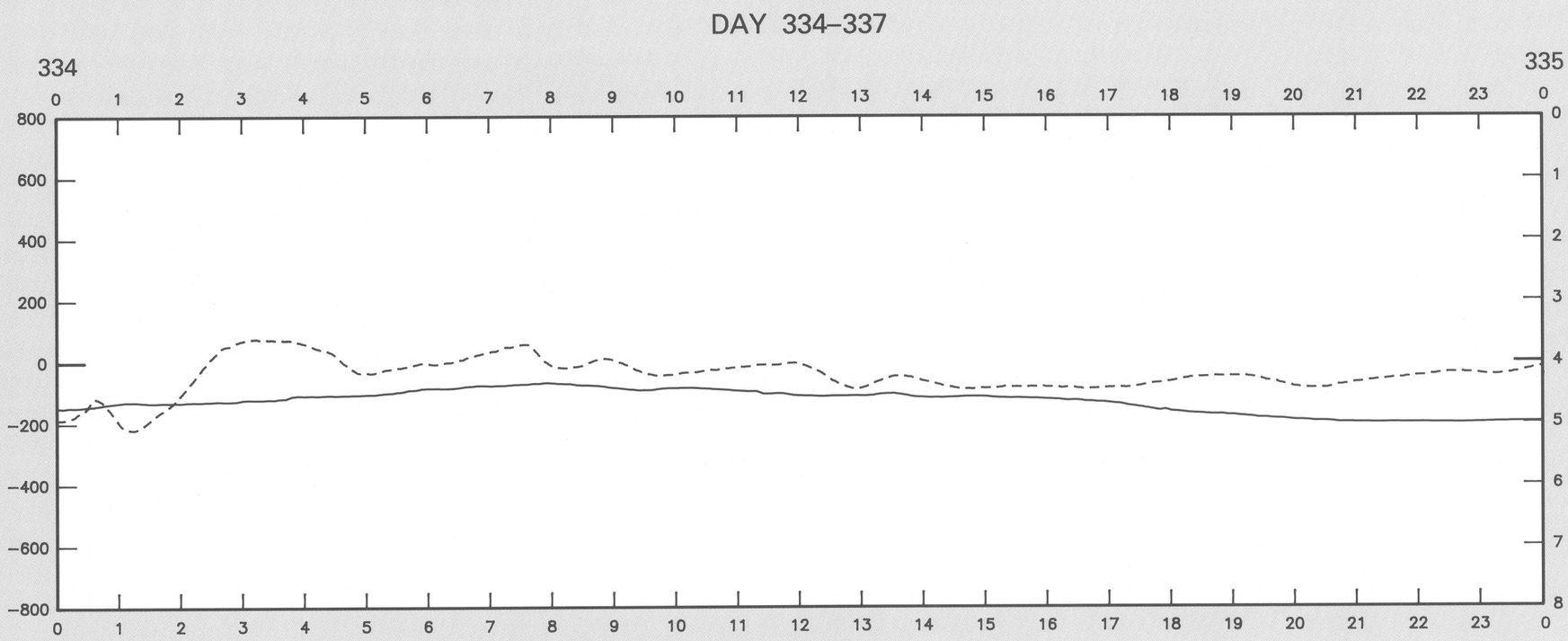

322
323
323
324
324
325
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0 1 2 3 4 5 6 7 8
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
EXPLANATION
Bathymetry
Magnetics
HOURS


DAY 325–328
325
326
327
328
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0 1 2 3 4 5 6 7 8
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
EXPLANATION
Bathymetry
Magnetics
HOURS

DAY 328–331


328
329
329
330
330
331
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0 1 2 3 4 5 6 7 8
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
EXPLANATION
Bathymetry
Magnetics
HOURS


DAY 331–334
331
332
333
334
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0 1 2 3 4 5 6 7 8
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
HOURS
EXPLANATION
Bathymetry
Magnetics


DAY 334–337
334
335
336
337
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 0
800
600
400
200
0
−200
−400
−600
−800
0 1 2 3 4 5 6 7 8
RESIDUAL MAGNETIC ANOMALY (GAMMAS)
DEPTH (METERS X 1000)
HOURS
EXPLANATION
Bathymetry
Magnetics