DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Principal Stress Directions on the Atlantic Continental Shelf Inferred from the Orientations of Borehole Elongations

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Open-File Report 87-283

[1]Denver, Colorado [2]Menlo Park, California

1987

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ABSTRACT

Horizontal principal stress orientations inferred from wellbore elongations ("breakouts") in petroleum exploration wells on the Atlantic outer continental shelf yield the following results by area (from north to south): Georges Bank (9 wells, total depths between 4.30 and 6.66 km)-maximum horizontal compressive stress (S_{Hmax}) orientation approximately E-W; Baltimore Canyon (14 wells, total depths between 3.74 and 5.58 km)-S_{Hmax} orientation between N 50° E and N 70° E; and the southeast Georgia Embayment (3 wells, total depths between 1.83 and 2.13 km)-S_{Hmax} orientation between N 8°E and N 23°E. All wells lie within 70 km of the continental slope and the inferred least horizontal principal stress orientations are generally aligned perpendicular to the local trend of the slope. Focal mechanisms of earthquakes directly adjacent onshore indicate compressional deformation (thrust and strike-slip faulting) resulting from NE to ENE S_{Hmax} orientation. In addition, available unambiguous data on young faulting on the continental shelf suggest thrust and/or strike-slip faulting and in-situ stress magnitudes measured on the Scotian shelf, offshore Canada, indicate a strike-slip faulting stress regime with S_{Hmax} oriented about NE (Ervine and Bell, 1987). It appears that the state of stress on the continental margin is broadly consistent with the NE to ENE maximum horizontal compression characterizing most of mid-plate North America, however superimposed continental slope effects, including flexure due to sediment loading, may be locally large enough to rotate the principal stresses by as much as 40°.

INTRODUCTION

Knowledge of the in-situ stress field is invaluable for assessing seismic hazards in areas such as the eastern United States with a relatively low level of seismicity and where major active faults have not been identified. Results of previous studies (Zoback and Zoback, 1980; Yang and Aggarwal, 1981; and Wentworth and Mergner-Keefer, 1983) suggested that a zone of NW-oriented compression exists along the Atlantic seaboard of the U.S. in contrast to the NE- to ENE- oriented maximum horizontal compressive stresses found throughout much of the midcontinent region of North America (Sbar and Sykes, 1973; Zoback and Zoback, 1980; M. L. Zoback and others, 1986). The evidence for a distinct Atlantic coast stress province includes poorly constrained earthquake focal mechanisms (Yang and Aggarwal, 1981) and small (1-2 m) late Tertiary reverse fault offsets (Prowell, 1983).

However, new stress data suggests that the NE to ENE compressive stress state characterizing the midcontinent region may be continous into the mid-plate region of the Western Atlantic basin making the existence of a separate coastal stress province doubtful. These new stress data include: 1) better-constrained earthquake focal mechanisms in the Charleston, South Carolina area (Talwani, 1982) and in the Western Atlantic basin (Nishenko and Kafka, 1982), as well as new mechanisms and a re-analysis and error assessment (Quittmeyer and others, 1985, C.T. Statton, 1984, written communication) of earlier focal mechanisms in the New York-New Jersey area that suggested NW-compression (Yang and Aggarwal, 1981), 2) Analysis of well bore elongations in southeastern Canada and the northeastern U.S. (Plumb and Cox, 1987) and on the Scotian shelf (Prodrouzek and Bell, 1985), 3) in-situ stress (hydraulic fracturing) measurements in a 1 km-deep well in the New York-New Jersey area (Zoback and others, 1985) and in several holes near the Georgia-South Carolina border (M. D. Zoback and others, 1986).

To further evaluate the state of stress along the Atlantic coast area we analyzed high resolution four-arm dipmeter logs for stress-induced borehole elongations ("breakouts") in Continental Offshore Test wells (COST) and other petroleum industry exploration wells drilled on the outer continental shelf. Numerous studies using commercially available dipmeter data indicate that the average azimuth of these elongations is generally very consistent within a given well or oil field (Cox, 1970; Babcock, 1978; and Brown and others, 1980). Comparison with other types of data (Gough and Bell, 1981 and 1982; Hickman and others, 1985; Plumb and Hickman, 1985; Teufel, 1985) and theoretical analyses (Bell and Gough, 1979 and 1982; and M. D. Zoback and others, 1985) suggest that the consistent azimuth of the elongation is parallel to the minimum horizontal compressive stress orientation. We determined borehole elongation azimuths for wells from three fields on the eastern U.S. continental margin (Georges Bank, Baltimore Canyon, and Southeast Georgia Embayment) in order to evaluate stress orientations in this region.

ANALYSIS OF LOG DATA TO DETERMINE ELONGATION DIRECTIONS

The elongation directions reported here were measured from field dipmeter logs obtained from the U.S. Minerals Management Service and also directly from the private companies who drilled the holes (see the Acknowledgments for a complete list of companies who provided logs). Dipmeter logs utilize an oriented-four arm caliper tool which records hole geometry in two orthogonal directions (for a complete description of this tool see Schlumberger, Limited, 1981). Torque in standard logging cable results in a clockwise rotation of the tool under normal operating conditions when the wellbore is approximately circular. In zones of wellbore elongation this rotation may temporarily be interupted when one set of caliper arms expands and locks into the elongated axis of the hole. Babcock (1978), Bell and Gough (1982), Cox (1983), and Dart (1985) give a detailed discussion of identification and discrimination of elongation ("breakout") zones from dipmeter logs and also provide numerous examples.

The primary criteria used in this study to distinguish elongation or breakout zones from other forms of wellbore enlargment and non-symmetrical caving are essentially identical to those reported in Dart (1985) and are repeated below:

1. The logging tool must exhibit normal rotation in circular parts of the hole.
2. Normal tool rotation is interrupted in elongation zones.
3. One of the caliper pairs must exceed the borehole diameter relative to the bit size.
4. The direction of elongation and azimuth of hole drift in cases where there is a vertical deviation of the hole must not coincide. Such non-verticality of the well bore may induce drill-pipe wear in the form of asymmetric borehole elongation (Plumb and Hickman, 1985).

GEOLOGY OF THE STUDY AREAS

The United States Atlantic continental margin extends from the Georges Bank southward to southern Florida, between the coastal plain and the outer continental rise (Figure 1). The physiography of the continental margin consists of a gently sloping shelf to depths of approximately 200 m, a continental slope on which bathymetric depths increase rapidly to about 2,000 m, and the broad continental rise that extends seaward to the abyssal plain (Emery and Uchupi, 1972). The continental margin is underlain by a series of structural platforms and basement depressions that trend parallel to the coastal plain (Maher, 1971; Klitgord and Behrendt, 1979). These platforms and basins are syn-rift and post-rift, fault-controlled structural features associated with the separation of the North American and African continental landmasses (Klitgord and Behrendt, 1979; Ziegler, 1983). Basin subsidence occurred in conjunction with the extensional thinning and cooling of the rifted crust and the thick accumulation of terrigenous and marine sediments (Hallam, 1971; Falvey, 1974; Bott, 1979; Steckler and Watts, 1985).

On the basis of the available geologic and geophysical data it appears that the entire Atlantic continental margin, from the Scotian shelf off the Canadian Maritime Provinces to the Southeast Georgia Embayment-Blake Plateau Basin, has undergone a similar tectonic and depositional evolution. References to apparent similarites in structure and lithology among the three areas studied and the Scotian shelf are made by Adinolfi and Jacobson (1979), Judkins and others (1980); Grow (1980); Scholle and Wenkam (1982); Poag and Valentine (1985); Libby-French (1983); Maher (1971); Emery and Uchaupi (1972); and Ziegler (1983).

COST wells and petroleum exploration wells used in this study were drilled in three of the major structural basins in the Atlantic continental margin: The Georges Bank basin offshore from Massachusetts, the Baltimore Canyon Trough offshore from New Jersey and the Southeast Georgia Embayment offshore from Georgia and northern Florida. These wells were generally located on the outer continental shelf, within 70 km of the shelf-slope break, but in a few cases the wells were drilled on the continental slope itself (see Figure 4). Wells in all three basins penetrated sedimentary strata consisting of unconsolidated to poorly consolidated Tertiary coarse sands, gravels and soft clay overlying poorly consolidated to well indurated Cretaceous and Jurassic interbedded siltstone, sandstone, and shale, limestone, dolomite and evaporite deposits (Scholle and Wenkam, 1982; Scholle, 1977, 1979 and 1980). Table A-2 correlates lithology with type of well-bore elongation for selected wells in each of the three basins.

Basement rock was drilled in two of the basins, Paleozoic rocks in the Georges Bank Basin and igneous intrusives and metamorphic rock in the southeast Georgian Embayment. Paleozoic basement was not reached in the Baltimore Canyon Trough (Scholle, 1979, 1977, 1980; and Scholle and Wenkam, 1982). Depositional environments of the rocks drilled in these three basins varied from nonmarine and restricted marine inner shelf to outer shelf open marine, slope and deep water pelagic (Poag and Valentine, 1985). The identification and correlation of certain stratigraphic units and

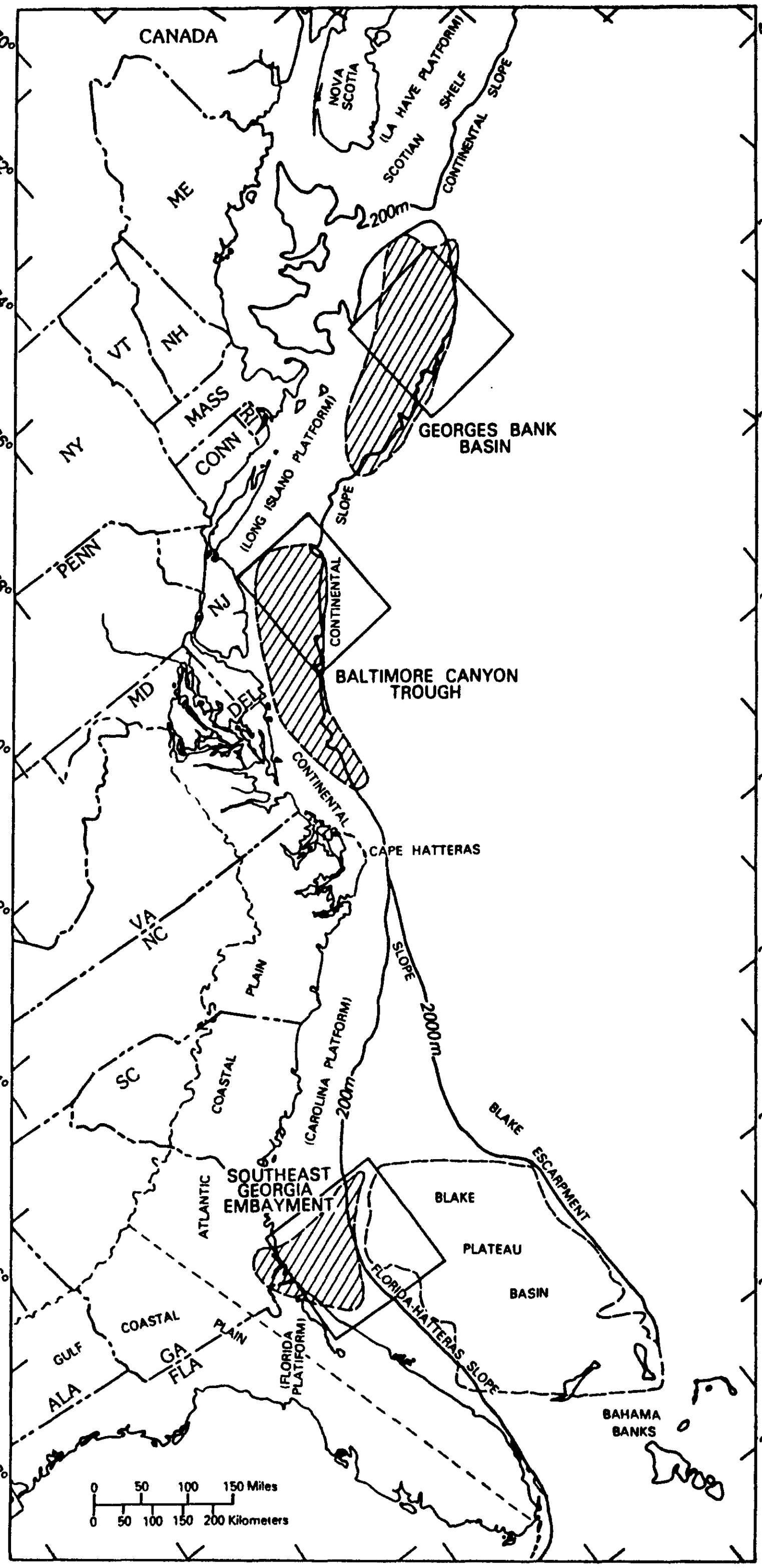

Figure 1. Eastern U.S. Atlantic continental margin. Study areas are hachured. Location of figures 2, 4, and 6 shown by boxes. Base modified from Maher and Applin (1971, p. 7). Additional information sources include Dillion and others (1979, p. 5), Perry and others (1975, p. 1536), and Klitgord and Behrendt (1979, p. 86)

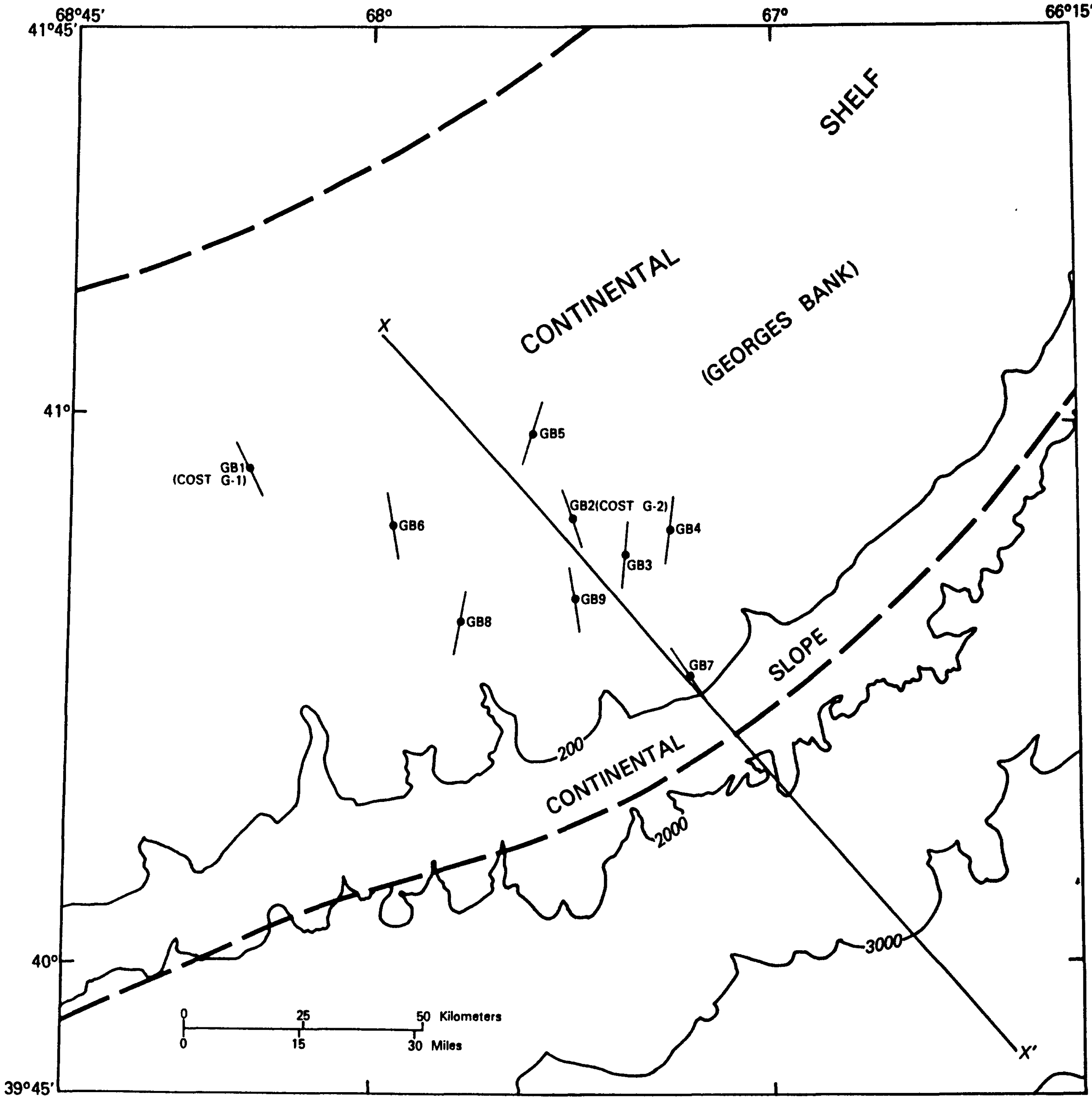

Figure 2. Georges Bank basin study area. Well location (dots) with mean breakout orientation indicated. Basin boundary indicated by heavy dashed lines after Perry and others (1975, p. 1536). Bathymetric contours in meters.

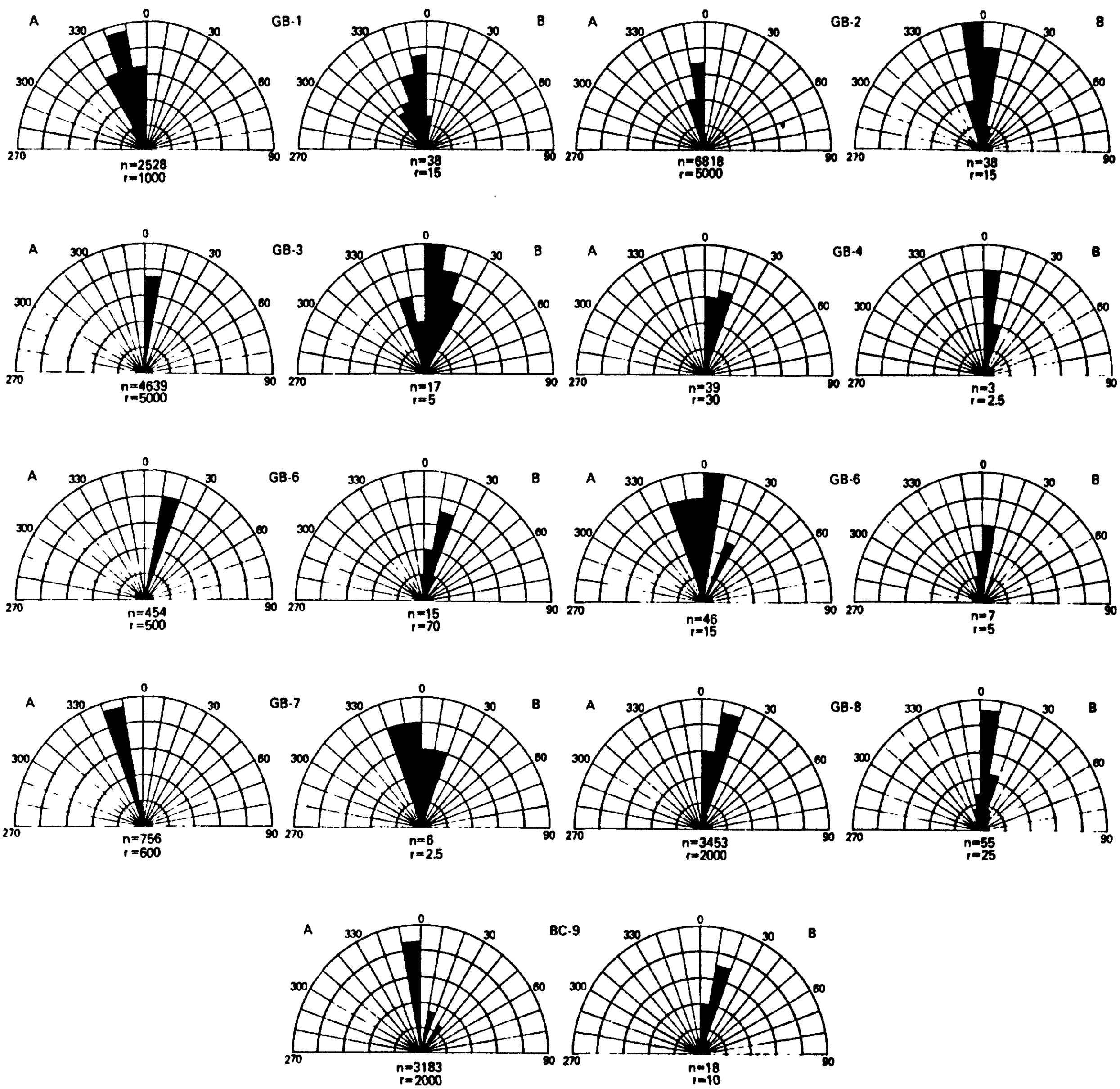

Figure 3. Rose diagrams of breakout orientations for individual wells in the Georges Bank basin.. Breakout orientations are weighted as to length (feet) in (A) and number of breakouts (B). Totals of length and number are given as the values of n; values of r are the radii of the diagrams.

lithostratigraphic units within basins and chronostratigraphic units between basins, imply similar depositional and tectonic histories for all three areas (Adinolfi and Jacobson, 1979; and Grow 1980). Given below is a brief summary of the geology of each of three basins.

Georges Bank Basin

The Georges Bank Basin is a sediment-filled structural depression in underlying the continental margin east and south of Cape Cod between the La Have platform to the northwest and north and the Long Island platform to the west (Schlee and Klitgord, 1982). Approximately 7,930 m of Mesozoic and Cenozoic sedimentary rock fill the basin forming a seaward thickening wedge. The basin extends northeast-southwest for about 195 km (Schultz and Grover, 1974).

The primary source of information on the depositional and tectonic history of Georges Bank Basin is the COST wells G-1 and G-2 (Figure 2) and the many miles of seismic reflection profiles run over the entire area (Scholle and Wenkam, 1982; Amato and Simonis, 1980; and Amato and Bebout, 1980). COST well G-2 is located approximately 4.5 km seaward of G-1 and contains primarily deep water sedimentary strata whereas sedimentary rocks at G-1 are more clastic.

The biostratigraphy of the depositional cycle (Poag, 1982) and correlations between lithologies of the two COST wells (Arthur, 1982) suggest a depositional history of the Georges Bank Basin that is characterized by intervals of marine carbonate and nonmarine sediment accumulation during periods of sea level fluctuation and basin subsidence. Triassic interbedded nonmarine siltstone, mudstone and shale, and marine limestone, dolomite and anhydrite accumulated on a subsiding, post-rift, block-faulted basement surface. Throughout the Late Triassic and Early Jurassic a carbonate platform developed on which sequences of marine dolomite and prograded detrital sands and muds were deposited. This entire shelf was covered by nonmarine sands and gravels during the Cretaceous. Throughout the Tertiary the earlier pattern of carbonate development alternating with clastic sediment deposition was repeated with the formation of a white chalk limestone and detrital sandstone, mudstone, siltstone and shale. Most recently, Pleistocene glacial sediment was deposited onto the shelf.

Baltimore Canyon Trough

The Baltimore Canyon Trough is a narrow northeast-trending structural basin filled with as much as 13.7 km of post-Paleozoic sedimentary rock and shallow unconsolidated sediments. As in the Georges Bank Basin, the sedimentary fill forms a seaward-thickening wedge that unconformably overlies a faulted basement surface or continental-oceanic transitional crust (Scholle, 1977). The Baltimore Canyon Trough is located off New Jersey (Figure 1) southwest of the Georges Bank Basin between the Long Island platform to the northeast and the Carolina platform to the southwest near Cape Hatteras.

Correlation of biostratigraphic and lithologic data from COST wells (B-2 and B-3) combined with the analysis of multichannel seismic reflection profile provides the primary source of information on the stratigraphic history of the Baltimore Canyon Trough (Scholle, 1977 and 1980; Amato and Simonis, 1979; and Smith and others, 1976). COST well B-2 is located on the shelf whereas well B-3 is located approximately 50 km seaward on the continental slope (Figure 4).

Sedimentary strata within the trough dip gently seaward except for an upwarping of Jurassic and Cretaceous strata beneath the shelf by a large isolated basement instrusion known as the "Great Stone Dome" (Schlee and others, 1976; Mattick, 1977; and Grow, 1980). Other structural features having a disruptive effect on basin stratigraphy include salt diapirs associated with Triassic evaporite deposits (Grow, 1980) and a series of apparent high-angle normal faults that strike N 70°E and dip NW offsetting sedimentary strata ~ 1.5 meters within 7 meters of the sea floor. Sheridan and Knebel (1976) suggest that these faults are the result of basin subsidence under the continental shelf, and that they might be related to other high-angle normal faults at depth. Another northeast-striking fault, thought to be down-to-the-basin, was detected at a depth of 2,152 m in the COST B-2 well (Smith and others, 1976).

The depositional history of the Baltimore Canyon Trough is very similar to that of the Georges Bank Basin. Schlee (1981) and Poag (1979) have summarized the two major depositional events: 1) Triassic and Jurassic deposition of near shore nonmarine sandstone, shale and coal interbedded with shallow marine limestone and restricted marine evaporites onto the block-faulted, post-rift Paleozoic and Precambrian metamorphic and Triassic igneous rocks (Mattick and Bayer, 1980). 2) Throughout the remainder of the Mesozoic and during the Tertiary period sediment accumulation within the subsiding basin consisted of periods of marine limestone and nonmarine deltaic and detrital sandstone, shale and claystone deposition.

Southeast Georgia Embayment

The Southeast Georgia Embayment forms a structural depression on the edge of the Coastal Plain which extends eastward from onshore and merges with the broad Blake Plateau Basin (Figure 6). Faulted basement rocks are continental under the eastern edge of the embayment to modified oceanic beneath the Blake Plateau Basin (Dillon and others, 1978). The southern Atlantic continental margin differs from the more typical margin physiography of shelf, slope and continental rise found north of Cape Hatteras. South of Cape Hatteras the continental slope divides forming the Florida-Hatteras Slope and the Blake Escarpment, a second, seaward extension of the continental slope forming the eastern edge of the Blake Plateau. The southeast Georgia Embayment is bound by the Cape Fear Arch to the northeast and the Peninsular area to the southwest (Buffler and others, 1978). The Embayment is filled with approximately 9.7 km of Mesozoic (predominately Cretaceous) and Cenozoic sedimentary rock. This seaward thickening wedge is composed principally of carbonate sediments that form part of the broad carbonate shelf between Cape Hatteras, south Florida and the Bahamas. The carbonate composition of this shelf represents a significant transition from the more siliceous clastic shelf sediments north of Cape Hatteras (Uchupi, 1970; Buffler and others, 1978; Dillon and others, 1978 and 1979).

Stratigraphic and depositional sequences of Southeast Georgia Embayment sediments are based on the published interpretations of COST well data (GE-1) and multichannel seismic reflection profiles of the Southeast Georgia Embayment and Blake Plateau Basin (Scholle, 1979; Buffler and others, 1978; Dillon and others, 1978).

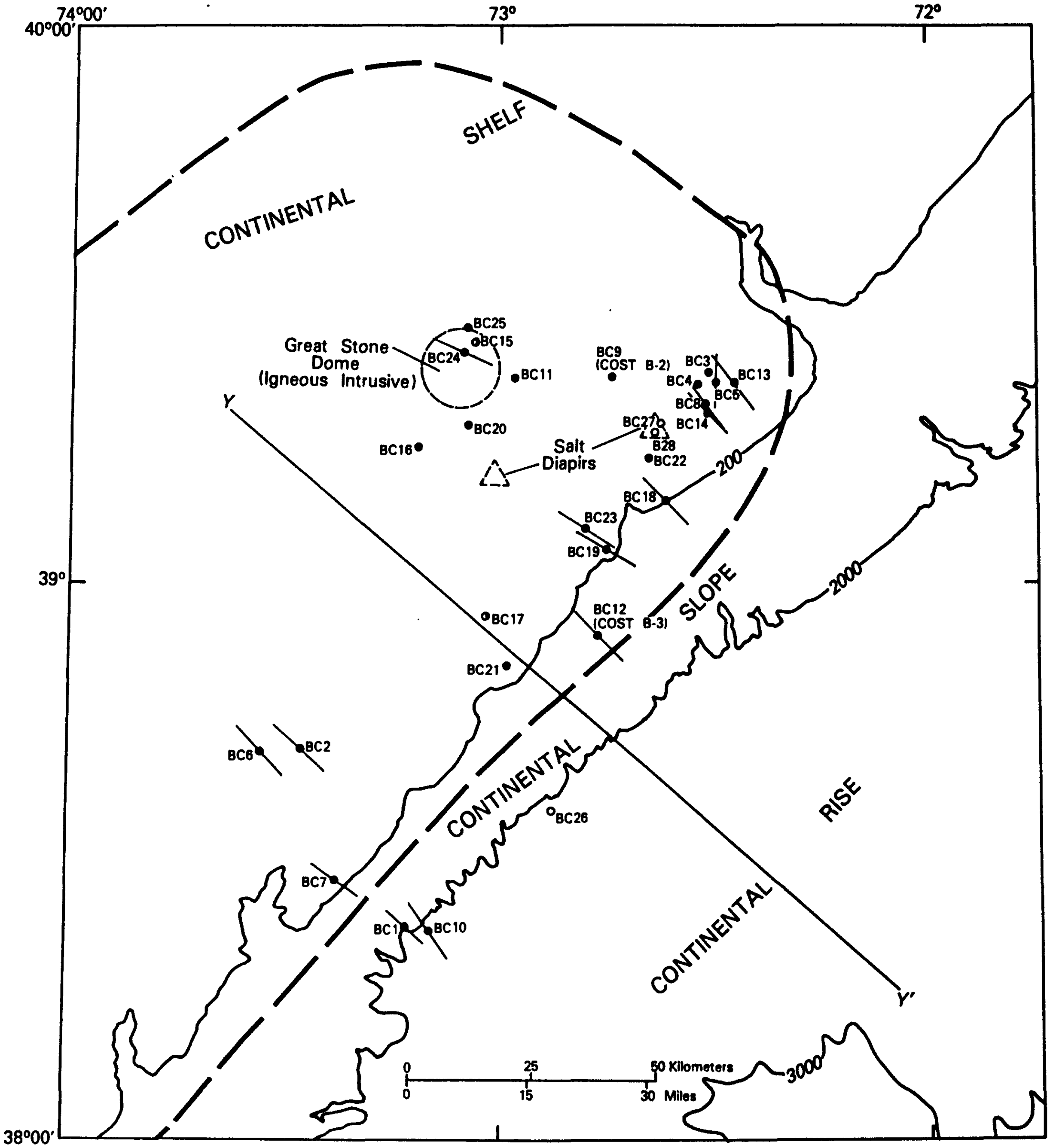

Figure 4. Baltimore Canyon trough study area. Dots without azimuths are wells lacking usable breakout data; open circles are wells without dipmeter logs. See figure 2 for further explanation. Trough boundary after Perry and others (1975, p. 1536).

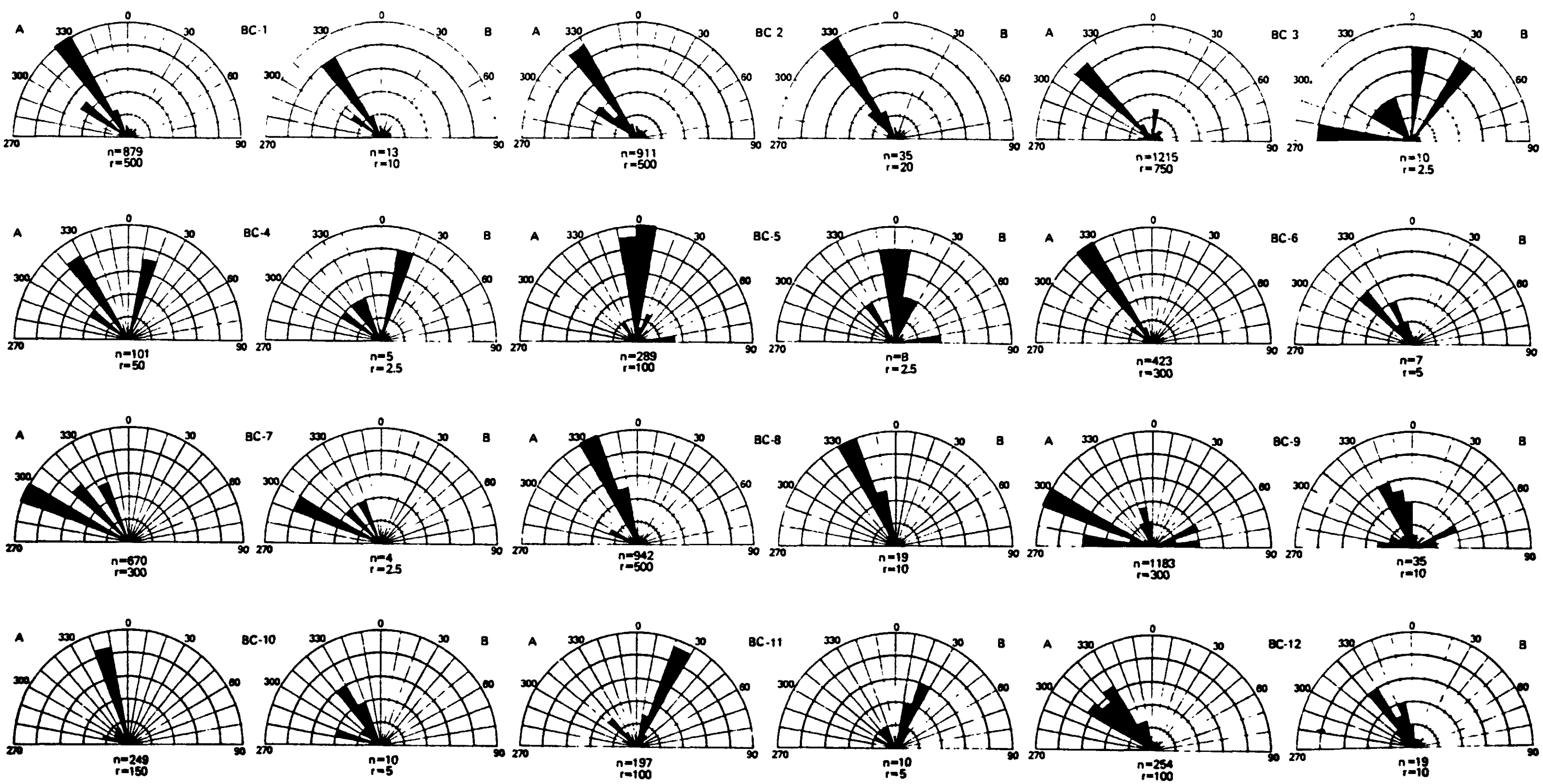

Figure 5. Rose diagrams of breakout orientation for individual wells in Baltimore Canyon trough. Breakout orientations are weighted as to length (feet) (A) and number (B). Totals of length and number are given as the values of n; values of r are the radii. Wells BC-15 and BC-17 had no breakout data and are not shown.

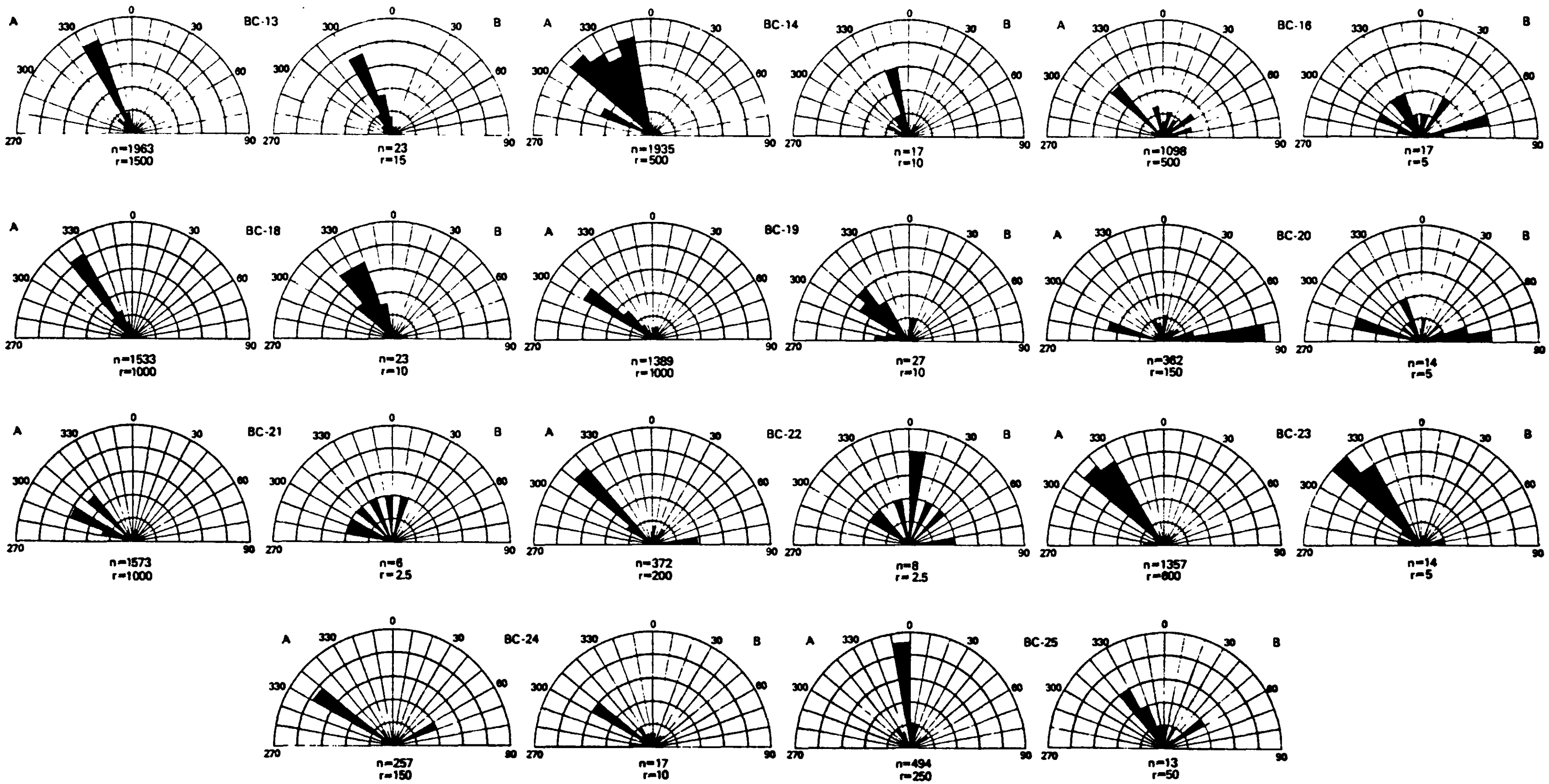

Figure 5.--Continued

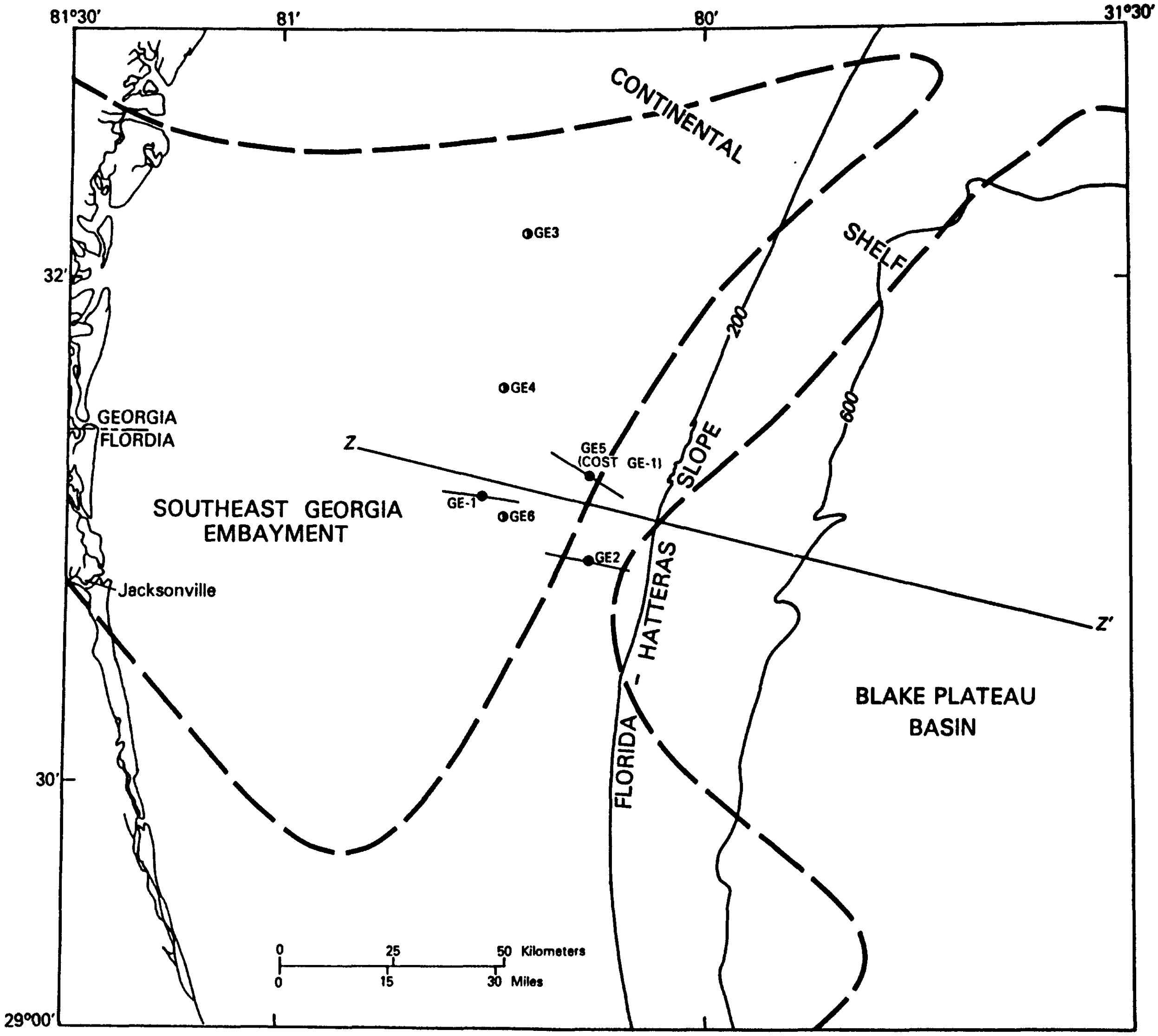

Figure 6. Breakout orientations for individual wells in the Southeast Georgia embayment study area. Embayment and basin boundary shown by heavy dashed line. Explanation same as for figures 2 and 4. Embayment and Blake Plateau basin boundary after Dillon and others (1979, p. 5).

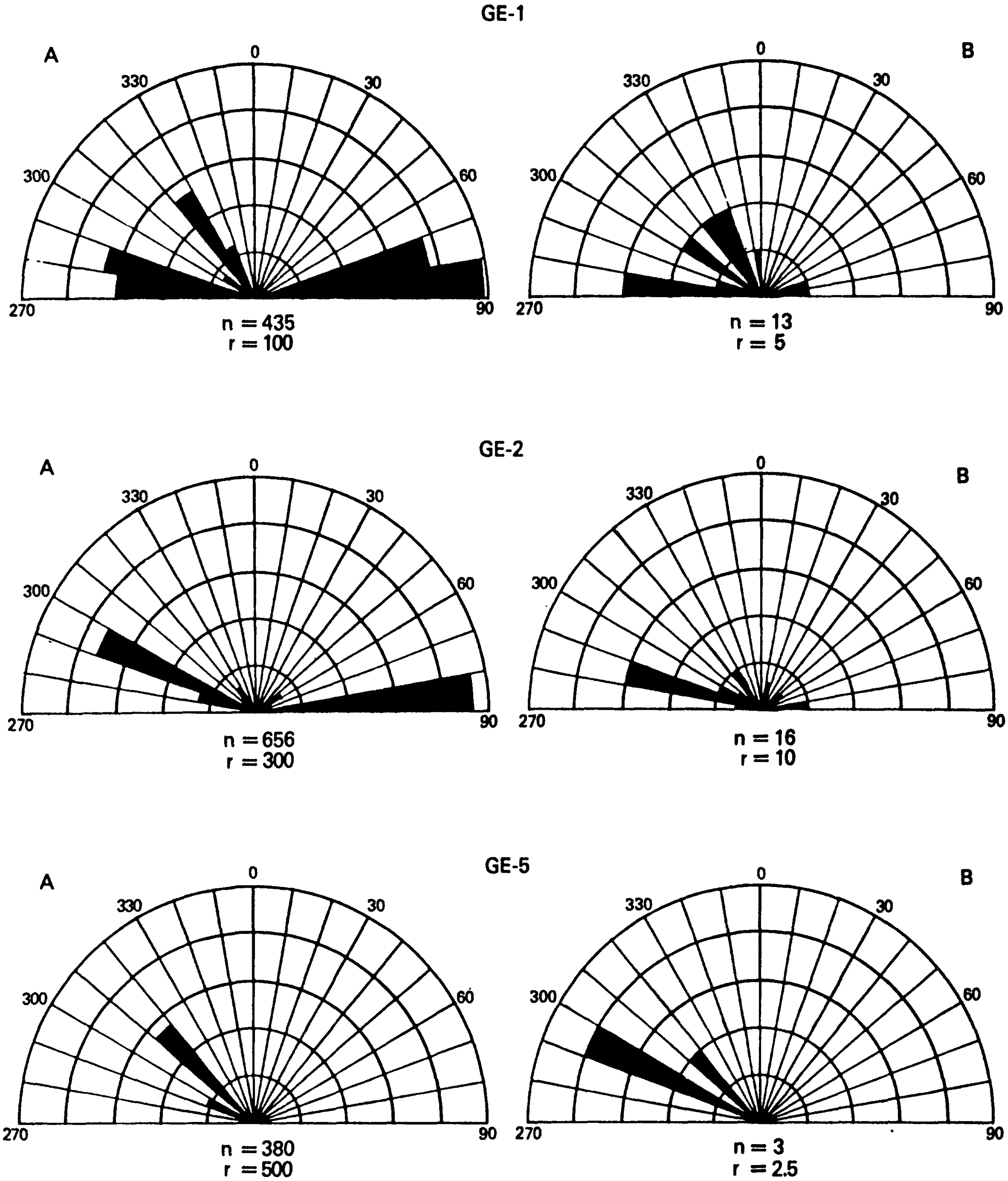

Figure 7. Rose diagrams of breakout orientations for individual wells in the Southeast Georgia embayment. Breakout orientations are weighted as to length (feet) (A) and number (B). Totals of length and number are given as the values of n, values of r are the radii.

Buffler and others (1978) subdivide the depositional history of the Southeast Georgia Embayment into three intervals based on regional uncomformities as seen on seismic reflection profiles. These are: 1) a sequence of Early Cretaceous (possibly Jurassic) to Late Cretaceous nonmarine sandstone and shale that intertongue southward with limestone and dolomite. These Cretaceous sediments unconformably overly an eroded Paleozic metamorphic basement on which Early Jurassic volcanics were deposited. 2) A Late Cretaceous carbonate shelf section consisting of fine-grained carbonate limestones, sandstone and shale. 3) Largely unconsolidated Tertiary sediments including principally chalk limestone and minor quartz sand.

RESULTS

Two types of elliptical well-bore elongation are observed in the well logs we analyzed. The shallow portions of most wells exhibited long sequences of washout zones (intervals in which both caliper diameters exceed bit-size). The orientation of the major axis of this enlargment is often quite variable both within an individual and in adjacent wells. By contrast, breakout zones (intervals in which one caliper showed an enlargement and the other is at bit size) are generally found deeper in the wells and have consistent orientations.

Referring to detailed lithologic descriptions for COST wells and a number of mud logs from other wells (see Table A-1), it appears these shallow, long washout zones occurred in poorly consolidated sandstones, siltstone, mudstones, claystones and soft limestones, and largely unconsolidated coarse quartz sand and sticky clay. True breakouts are generally found at greater depths in consolidated formations that are predominantly interbedded sandstone, shale, siltstone and limestone, and in a few cases metamorphic basement rock (Table A-2). Based on available lithologic data and the character of the dipmeter logs this transition from unconsolidated to consolidated sediments, referred to here as "consolidation depth", typically occurs gradually; in the Southeast Georgia Embayment the transition occurs between about 1.4 to 1.65 km, in the Georges Bank Basin between about 1.0 to 1.9 km, and in the Baltimore Canyon Trough between about 1.5 and 2.5 km (see Table A-1). Washout zones as well as and poorly consolidated to weakly indurated strata occasionally occur below the observed "consolidation depth". However, in the majority of dipmeter logs analyzed in all three areas the long well-developed washouts (typically about a hundered meters in length), observed in the shallow parts of the logs clearly reflected a change in sediment consolidation.

The orientations of the long axes of the washout zones in the shallow portions of the logs do not necessarily agree with the orientation of breakouts and washouts occuring beneath the "consolidation depth". Like breakouts, the deep washouts are thought to be reliable indicators of the least horizontal stress orientation because of: 1) their occurrence below the "consolidation depth" in largely consolidated sediments, 2) the relative consistency of their orientations, and 3) general agreement with the orientations of breakouts. A well by well comparison of the orientation of washouts above the "consolidation depth" and orientations of hole elongation below the consolidation depth reveals that the shallow washouts have orientations which fall into three classes: 1) random, 2) approximately the same as the deeper elongations, or 3) at approximately 90° to the trend of the deeper elongations. Table 1 lists the results of this well-by-well comparison.

In all three areas a significant percentage of the shallow washouts have random orientations. However, it is interesting to note that in both the Georges Bank Basin and the Baltimore Canyon Trough a high percentage of the shallow washouts have orientations that are orthogonal to the trend of breakouts and prefentially oriented washouts (POW) that occured below the "consolidation depth". One possible explanation of hole elongation orthogonal to the breakout direction (i.e. in the direction of maximum horizontal stress) is the occurrence of drilling-induced hydraulic fractures and preferential erosion of the well-bore in this direction.

Results of our borehole elongation determinations for each well are given in the rose diagrams in Figures 3, 5, and 7. In these three figures two sets of orientation determinations (A and B) are shown for each well. In A, orientations weighted by length (feet--the standard industry practice on well logs is to scale depth in feet) are plotted, n gives the total length of elongated wellbore (ft) and r is the radius (also in feet) of the rose diagram. The second set of determinations (marked B) are based on number of observed elongations (independent of length). In this case n refers to the total number of elongations and r is the radius (in number of observations). Both representations of the data are presented to check for consistency. Occasionally, long intervals of the wellbore may be elongated for reasons other than true breakout formation (possibly due to tool wear). We are suspicious of single long breakouts that have an orientation inconsistent with other observations in the well. Typically however, the statistical results of orientations determined by the length-weighted and non-length-weighted methods agree within a few degrees as is clear from Tables 2, 3 and 4. Also given in Tables 2, 3 and 4 are quality rankings for the determinations from each well based on the ranking system for quality of tectonic stress orientations inferred from reliable data (Zoback and Zoback, in press). Their quality rankings for the borehole elongation data are as follows:

- A - orientations for a single well with a standard deviation (S.D.) of $<$ 15°, or average of orientations in 2 or more wells in close geographic proximity.
- B - orientations in a single well with 15° $<$ S.D. $\leq$ 25°
- C - less than 4 distinct elongations (of uniform orientation) in a single well
- D - elongations in a single well with S.D. $>$ 30° (generally bimodal results), or a single elongation in a well.

Zoback and Zoback (in press) concluded that only the A, B and C rankings give reliable orientations of the tectonic stress field. For this reason and the fact that the North American stress database is so large, the D quality data are not included in regional compilations.

Table 1 -- Comparison of Deep Breakout and Shallow Washout Orientations

[The orientations of long shallow washouts above the "consolidation depth" were compared with orientations of deeper well bore elongations in individual wells. Washout orientations are separated into three classes: 1) random, 2) at approximately the same orientation trend of breakout and POWs (0°), or at approximately 90° to the trend of breakouts and POWs (90°). Percentages are given collectively by area.]

	Random	at 0°	at 90°
Southeast Georgia Embayment	45 percent	20 percent	35 percent
Georges Bank Basin	14 percent	14 percent	72 percent
Baltimore Canyon Trough	33 percent	0 percent	67 percent
All Areas Combined	36 percent	15 percent	48 percent

Georges Bank

The necessary field dipmeter or fracture identification logs were obtained for 9 of the 10 exploration wells drilled on the outer Georges Bank shelf. The location and names of the wells with logs are shown on Figure 2. As indicated on the figure, the wells are located from 70 to roughly 5 km from the shelf-slope break (taken as the 200 m bathymetric contour). Total depths of the wells vary between 2969 m and 6656 m (see Table 2).

The result of the orientation determinations are shown on Figure 3 and summarized in Table 2. The data were generally high-quality and very consistent. Mean orientations ranged from N 13°W to N 13°E, the overall mean for the 9 wells sampled in the basin was N 3°E, implying an maximum horizontal compressive stress (S_{Hmax}) orientation of about E-W (N 87°W). As shown on Figure 2, the trend of the continental slope is curved through this region with an overall trend of about N 60°E. The breakout orientations (believed equivalent to the minimum horizontal compressive (S_{hmin}) orientations) are plotted on Figure 2 and are aligned at a high angle, 55°-60°, but not truly perpendicular to the continental slope, with the possible exception of well GB7 located only a few kilometers from the slope.

Baltimore Canyon Trough

A total of 23 logs were obtained for the Baltimore Canyon region. The location, names, and mean breakout orientations of the wells are shown on Figure 4, note that the D quality orientation determinations were not plotted. Most of the wells were drilled on the slope itself or within 15 km of the shelf-slope break.

The orientation results are presented on rose diagrams in Figure 5 and summarized on Table 3. Note that wells with highly scattered results or bimodal orientations (BC-3, BC-4, BC-9, BC-11, BC-16, BC-20, BC-21, BC-22 and BC-25) received a D quality ranking based on their standard deviations. Ignoring these D quality points, the overall mean breakout orientation for the region (equivalent to S_{hmin}) was N 35°W, almost exactly perpendicular to the local trend of the continental slope. The inferred mean S_{Hmax} orientation was N 55°E (Table 6).

Southeast Georgia Embayment

Dipmeter logs were obtained from six wells in the Southeast Georgia Embayment however, reliable borehole elongations were determined in only 3 of these wells. The wells and these orientations are plotted on Figure 6. The orientation determinations are shown on the rose diagrams on Figure 7 and the results are summarized in Table 4. The results are rather scattered, particularly in the determination weighted by length. As indicated in Table 4, GE-2 was given a B quality and GE-1 and GE-5 were given C quality rankings.

As discussed previously, the typical shelf-slope physiography of the western Atlantic margin is disrupted in the vicinity of the Southeast Georgia Embayment. The continental slope is broken into two smaller slopes, the Florida-Hatteras Slope and the Blake escarpment. The wells investigated are all located with 30 km of the ~600 m high NNE-trending Florida - Hatteras Slope. The inferred S_{hmin} orientations (equivalent to breakout orientations) plotted on Figure 6 are roughly perpendicular to this slope and imply a S_{Hmax} orientation of approximately NNE, a substantial deviation from the inferred regional midplate S_{Hmax} orientation of NE to ENE (M. L. Zoback and others, 1986).

DISCUSSION

The results of the borehole elongation analysis indicate a S_{Hmax} orientation between N 25°E to N 93°E for all wells from the continental shelf. The actual borehole elongation and inferred stress orientations are quite consistent within each of the three study areas (Table 5, Figure 8). However, there is considerable and statistically significant variability in the mean orientation between areas: approximately E-W in Georges Bank area, N 55° E in Baltimore Canyon, and about N 20° E in the Southeast Georgia Embayment. As indicated above, in each area the S_{Hmax} orientations are parallel to or nearly parallel to the local orientation of the shelf-slope break, implying a minimum horizontal stress orientation perpendicular to the continental slope.

Several geophysical characteristics of continental margins predict an extensional stress regime with S_{Hmax} orientation perpendicular to the margin. Two major potential sources of stress at passive continental margins include lithosphere flexure related to sediment loading (e.g. Turcotte and others, 1977; Neugebauer and Sohn, 1978; and Cloetingh and others, 1983), and stresses induced by body forces associated with the lateral variation in density and thickness of the continental and oceanic crustal columns (Bott and Dean, 1972). Both of these effects predict extensional stresses within the continental shelf lithosphere, with a least principal stress (S_{hmin}) oriented perpendicular to the continental slope.

Unfortunately, the borehole elongation data do not constrain the relative magnitudes of the stresses (stress regime). Data from seismic reflection profiling in several areas on the U.S. continental shelf indicate late Cenozoic (possibly Quaternary) faulting (Hutchinson and Grow, 1985; Hutchinson and others, 1986) however, these faults are nearly vertical and on the vertically exaggerated seismic profiles the true sense of displacement (normal or reverse) is ambiguous. Offshore from Charleston, South Carolina, Behrendt and Yuan (1987) have identified a major N 66°E trending left-stepping en-echelon fault zone that they named the Helena Banks fault zone. They interpret multiple crossing of the steeply-dipping (70° ± 5°) fault zone by high-resolution seismic profiles to indicated high-angle reverse offset coupled possibly with a major strike-slip (left-lateral) offset inferred from the fault geometry. Thus in the one documented study of young faulting on the continental shelf the style of faulting is compressional (reverse and possible strike-slip).

Further evidence suggesting that the modern state of stress on the continental margin may not be extensional comes from data on in-situ stress magnitudes determined from log data and leak-off tests in wells on the Scotian shelf, offshore Nova Scotia (for location see Figure 9) (Ervine and Bell, 1987). The data indicate that for depths between 815-5783m a strike-slip stress regime exists ($S_{Hmax} > S_{vertical} > S_{him}$), although at 6000 m S_v and S_{hmin} may become equal, resulting in a stress regime transitional to normal faulting. The S_{Hmax} orientations inferred for the Scotian shelf trend NE, (Podrouzek and Bell, 1985) also parallel to the local trend on the continental shelf.

TABLE 2: Georges Bank Basin breakouts

Well No.	Well Name/Loc.	Lat(N)	Long(W)	TD*	BO depth* Interval	Orientation by length (total length ft)	Orientation by number (total number)	Quality
GB-1	COST #G-1 Blk. 79	40.93°	68.30°	4897	4854- 3226	163.7 ± 9.6° (2528)	168.2 ± 14.8° (38)	A
GB-2	COST #G-2 Blk. 141	40.83°	67.50°	6656	6306 3256	173.3 ± 8.5° (6818)	177.8 ± 11.2° (38)	A
GB-3	OCS-A-0182 #1 Blk. 187	40.77°	67.38°	4405	4404 3050	6.3 ± 7.5° (4639)	7.0 ± 13.0° (17)	A
GB-4	OCS-A-0179 Blk. 145	40.82°	67.27°	2969	2793 1913	8.5 ± 4.8° (39)	8.0 ± 4.1° (3)	C
GB-5	OCS-A-0153 #1 Blk. 975	41.00°	67.60°	4453	4042 2489	16.2 ± 4.6° (454)	11.3 ± 8.4° (15)	A
GB-6	OCS-A-0170 #1 Blk. 133	40.82°	67.95°	4304	3738 3529	179.2 ± 11.3° (46)	0.62 ± 10.5° (7)	A
GB-7	OCS-A-0218 #1 Blk. 410	40.55°	67.22°	4746	4576 3125	156.9 ± 8.9° (756)	167.6 ± 14.7° (6)	A
GB-8	OCS-A-0200 #1 Blk. 312	40.65°	67.78°	5649	4873 3973	10.1 ± 8.1° (3453)	6.3 ± 14.4° (55)	A
GB-9	OCS-A-196 #1 Blk. 273	40.68°	67.50°	4750	4662 3256	179.6 ± 20.7° (3183)	12.8 ± 13.1° (16)	A

* METERS BELOW KELLY BUSHING

TABLE 3: Baltimore Canyon Trough Breakouts

Well No.	Well Name/Loc.	Lat(N)	Long(W)	TD*	BO depth* Interval	Orientation by length (total length ft)	Orientation by number (total number)	Quality
BC-1	OCS-A-0336 #1 Blk. 586	38.43°	73.22°	4878	4578 3780	142.5 ± 10.1° (879)	143. ± 10.0° (13)	A
BC-2	OCS-A-0097 #1 Blk. 273	38.75	73.40°	5335	5314 3766	141.8 ± 11.5° (911)	146.9 ± 13.0° (35)	A
BC-3	OCS-A-0028 #3 Blk. 598	39.37°	72.52°	3828	3163 1856	146.4 ± 27.7° (1215)	152.3 ± 36.1° (10)	D
BC-4	OCS-A-0028 #2 Blk. 598	39.37°	72.52°	5398	5345 5081	158.6 ± 25.4° (101)	162.2 ± 25.7° (5)	D
BC-5	OCS-A-0028 #1 Blk. 598	39.37°	72.52°	3811	3003 2271	3.3 ± 23.5° (289)	3.0 ± 25.5° (8)	C
BC-6	OCS-A-0096 #1 Blk. 272	38.72	73.55°	4116	4037 1865	146.7 ± 5.4° (423)	147.6 ± 10.7° (7)	A
BC-7	OCS-A-0131 #1 Blk. 495	38.48°	73.38°	5580	4680 2832	132.7 ± 16.0° (670)	131.5 ± 16.2° (4)	B
BC-8	OCS-A-0038 #1 Blk. 642	39.33°	72.53°	4619	4511 1872	153.7 ± 14.9° (942)	156.8 ± 11.9° (19)	A
BC-9	COST #B-2 Blk. 594	39.38°	72.50°	4891	4860 2014	104.7 ± 31.4° (1183)	147.3 ± 36.4° (35)	D
BC-10	OCS-A-0337 #1 Blk. 587	38.40°	73.17°	4412	4398 3527	152.4 ± 20.2° (249)	142.2 ± 18.5° (11)	B
BC-11	OCS-A-0024 #1 Blk. 590	39.38°	72.97°	2713	2481 2146	14.0 ± 29.0° (197)	5.1 ± 30.8° (10)	D
BC-12	COST #B-3 Blk. 166	38.92°	72.77°	4823	4789 3829	141.6 ± 15.2° (254)	151.3 ± 16.1° (19)	B
BC-13	OCS-A-0029 #1 Blk. 599	39.37°	72.47°	5220	5122 1839	154.5 ± 9.3° (1964)	156.5 ± 11.0° (23)	A
BC-14	OCS-A-0038 #3 Blk. 642	39.33°	72.53°	5023	2718 2122	147.6 ± 16.7° (1935)	155.6 ± 24° (17)	B

TABLE 3: Baltimore Canyon Breakouts Trough (CONTINUED)

Well No.	Well Name/Loc.	Lat(N)	Long(W)	TD*	BO depth* Interval	Orientation by length (total length ft)	Orientation by number (total number)	Quality
BC-16	OCS-A-0048 #1 Blk. 718	39.25°	73.20°	3906	3214 2034	151.1 ± 38.1° (1098)	143.3 ± 37.6° (17)	D
BC-18	OCS-A-0055 #1 Blk. 816	39.17°	72.65°	5413	4418 2675	146.5 ± 14.4° (1533)	148.5 ± 18° (23)	B
BC-19	OCS-A-0065 #1 Blk. 902	39.07°	72.75°	4868	1050 531	131.0 ± 18.3° (1389)	132.8 ± 27.1° (27)	C
BC-20	OCS-A-0042 #1 Blk. 676	39.30°	72.08°	3359	2110 1935	90.7 ± 28.4° (362)	99.1 ± 32.8° (14)	D
BC-21	OCS-A-0081 #1 Blk. 106	38.87°	72.98°	5550	3042 2753	125.2 ± 18.2° (1573)	145.3 ± 29.0° (6)	D
BC-22	OCS-A-0052 #1 Blk. 728	39.25°	72.63°	4636	4212 3025	122.4 ± 28.9° (372)	177.2 ± 34.7° (8)	D
BC-23	OCS-A-0059 #1 Blk. 857	39.12°	72.82°	5125	5088 2822	133.9 ± 18.5° (1357)	128.2 ± 21.6° (14)	B
BC-24	OCS-A-0015 #1 Blk. 544	39.43°	73.08°	4235	5281 1642	123.1 ± 28.8° (257)	132.7 ± 25.1° (17)	C
BC-25	OCS-A-0009 #1 Blk. 500	39.47°	73.08°	3736	2523 1546	176.2 ± 19.8° (494)	172.4 ± 27.1° (13)	C

*METERS BELOW KELLY BUSHING

TABLE 4: SE GEORGIA EMBAYMENT Breakouts

Well No.	Well Name/Loc.	Lat(N)	Long(W)	TD*	BO depth* Interval	Orientation by length (total length ft)	Orientation by number (total number)	Quality
GE-1	OCS-G-3695 #1 Blk. 427	30.57°	80.53°	2286	2277 1590	$97.6 \pm 23.7°$ (435)	$120.5 \pm 27.8°$ (13)	C
GE-2	OCS-G-3705 #1 Blk. 564	30.43°	80.27°	3902	3795 2563	$101.4 \pm 19.1°$ (656)	$110.2 \pm 22.3°$ (16)	B
GE-5	COST #GE-1 Blk. 387	30.60°	80.28°	4041	3809 3521	$131.7 \pm 8.8°$ (380)	$130.5 \pm 9.4°$ (3)	C

*METERS BELOW KELLY BUSHING

TABLE 5: Composite maximum horizontal principal stress directions from breadout data for the individual basins

	Number of Wells	mean S_{Hmax} orientation (based on length)	mean S_{Hmax} orientation (based on number)
Georges Bank Basin	9	N 87.1°W ± 13.3°	N 86.4°W ± 14.7°
Baltimore Canyon Trough	14	N 53.1°E ± 17.6°	N 56.2°E ± 20.8°
SE Georgia Embayment	3	N 17.8°E ± 22.7°	N 24.9°E ± 24.5°

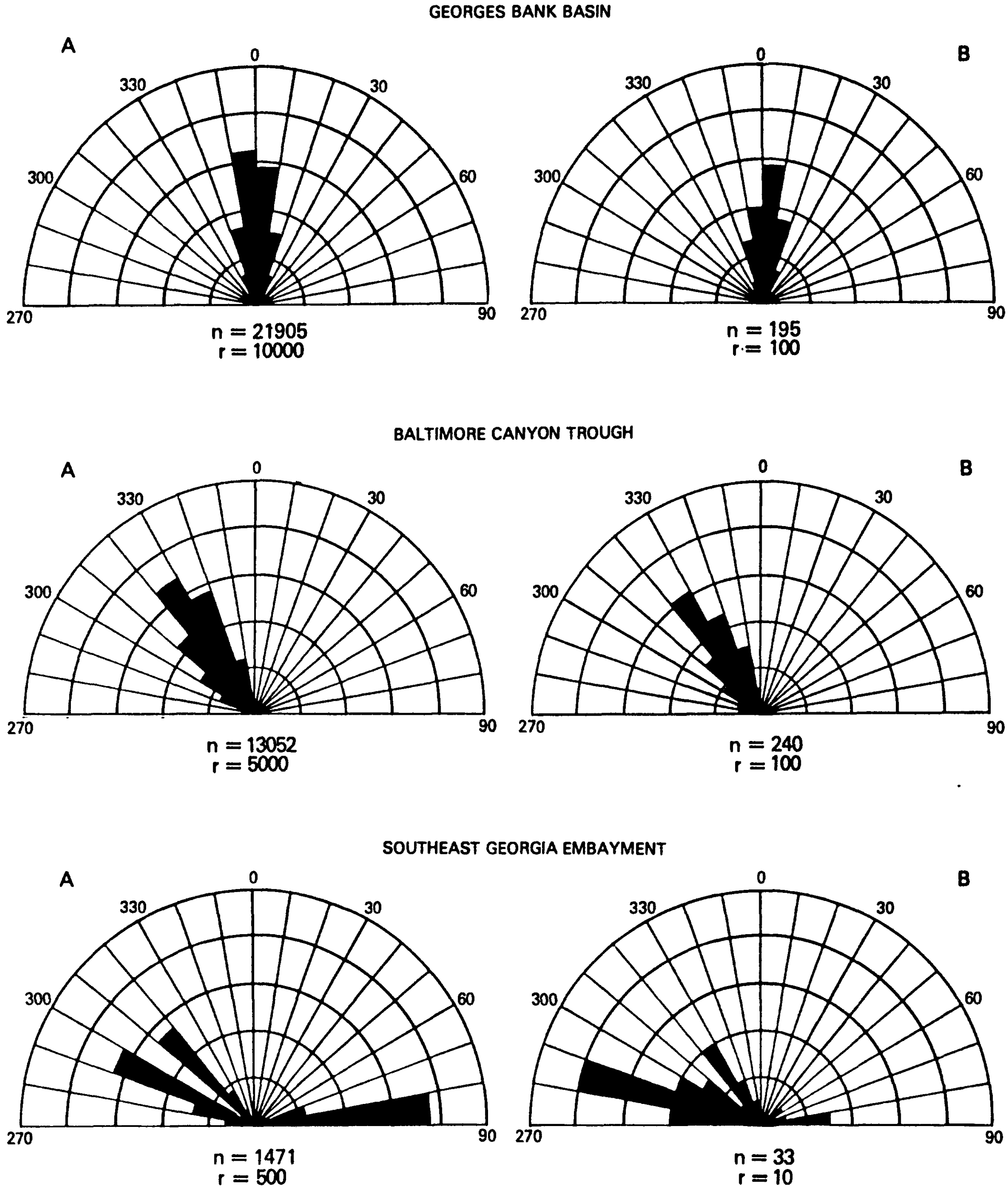

Figure 8. Composite rose diagram of breakouts in the three study areas. Breakout orientations are weighted as to length (feet) (A) and number (B). Totals of length and number are given as values of n, values of r are the radii. Breakout data from wells BC-3, 4, 9, 11, 15, 17, 20, 21, 22, and 25 are not included in the composite for the Baltimore Canyon trough due to lack of usable data or highly scattered or bimodal data.

The faulting and stress magnitude data suggest that although the S_{hmin} orientations obtained in the present study are nearly orthognal to the local trend of the continental slope, the stress regime may be compressional, not extensional, as would be expected from either lithosphere flexure or body forces due to lateral density forces at the continent-ocean boundary.

The inferred S_{Hmax} orientations on the continental shelf (N 25 E to E-W) are broadly consistent with the NE to ENE compression observed throughout most of eastern North America, Figure 10 (M. L. Zoback and others, 1986). The variation in stress orientation between the three study areas (into an approximate parallel and perpendicular configuration with the local trend of the continental margin) can probably best be explained in terms of a superposition of the mid-plate compressional stress field and local continental margin stresses.

CONCLUSIONS

Horizontal stress orientations inferred from wellbore elongations ("breakouts") in petroleum exploration wells in three study areas on the outer continental shelf on the eastern United States yield consistent results within a single well and between wells within each study area. There appears to be, however, a statistically significant variability in the mean orientation of the maximum horizontal stress (S_{Hmax}) between areas: Georges Bank - N 93°E ± 13°, Baltimore Canyon trough - N 53°E ± 18°, and the Southeast Georgia Embayment - N 18° ± 23°. These S_{Hmax} orientations are broadly consistent with the NE to ENE compression observed throughout the eastern United States and Canada. However, in each area, the inferred S_{hmin} orientations are perpendicular or nearly perpendicular to the local trend of the continental slope. Available data suggest a modern compressional stress regime on the continental shelf in contrast to continental margin effects (including lateral density contrast and lithosphere flexure due to sediment loading) which predict extensional stress regimes. It appears likely that the state of stress on the continental shelf is the result of the superposition of the NE to ENE midplate compressive stress regime and local continental margin extensional stress field.

Acknowledgements

Many of the field dipmeter logs used in this study were obtained, free of charge, from the private companies operating in the study areas. We would like to express our appreciation to these companies, listed below by study area:

Georges Bank
- Mobil Exploration and Producing Services Inc. - Dallas, Texas
- Chevron USA Inc. - New Orleans, Louisiana
- Tenneco Oil Exploration and Production - Houston, Texas
- Exxon Co. USA - Houston, Texas
- Conoco Inc. - Houston, Texas

Baltimore Canyon Trough
Mobil Exploration and Producing Services Inc. - Dallas, Texas
Tenneco Oil Exploration and Production - Houston, Texas
Shell Offshore Inc. - Houston, Texas
Chevron USA Inc. - New Orleans, Louisiana
Texaco USA - New Orleans, Louisiana
Murphy Oil USA Inc. - El Dorado, Arkansas
Exxon Co. USA - Houston, Texas

Southeast Georgia Embayment
Shell Offshore Inc. - Houston, Texas
Texas Producing Inc. - New Orleans, Louisiana
Exxon Co. USA - Houston, Texas
Transco Exploration Company - Houston, Texas
Getty Oil Company - New Orleans, Louisiana

We would also like to thank John Behrendt and Bill Savage, both of the U.S. Geological Survey in Denver, for helpful reviews of this manuscript.

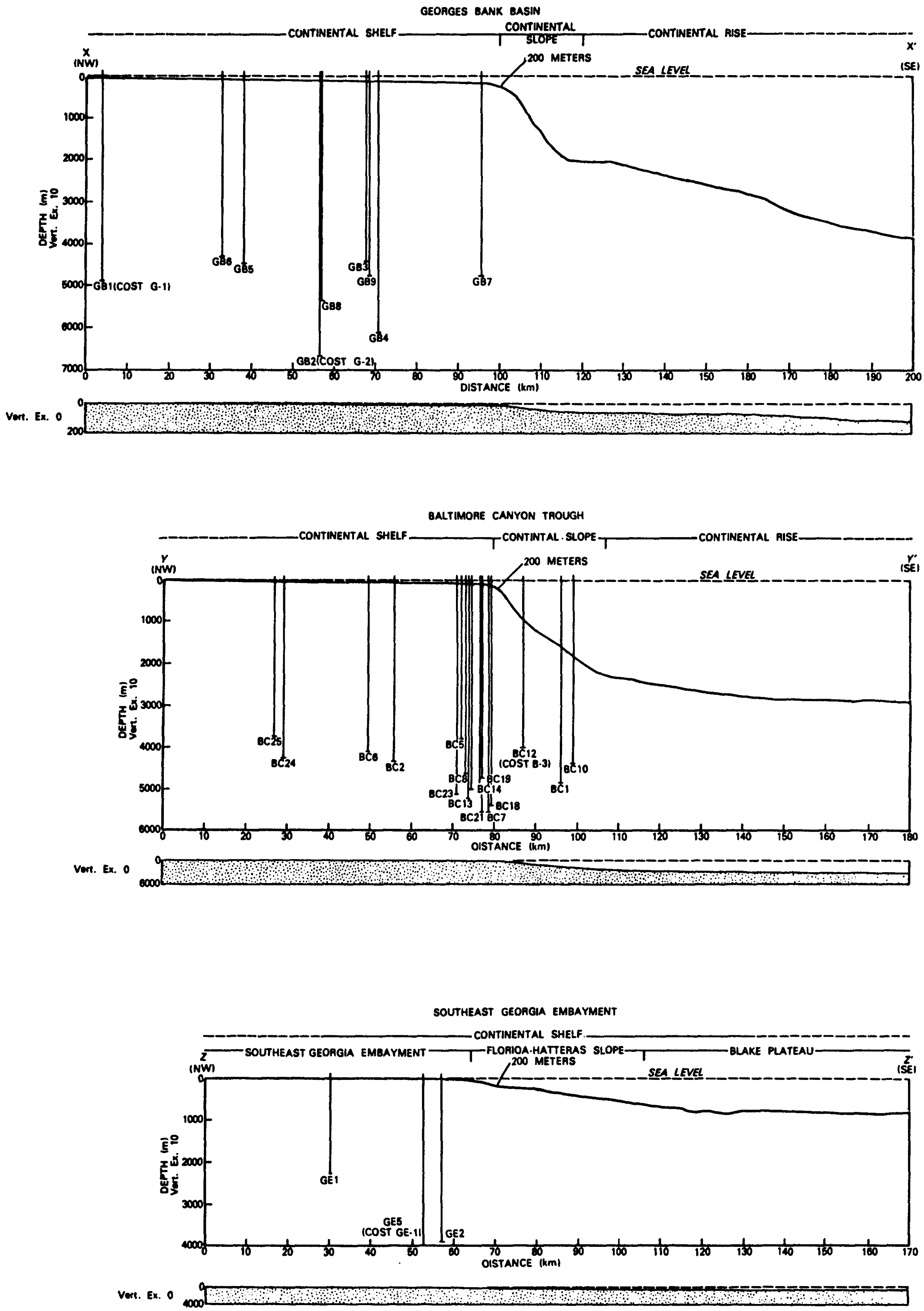

Figure 9. Bathymetric cross section showing projected locations and depths of wells studies. Only wells with usable breakout data are plotted.

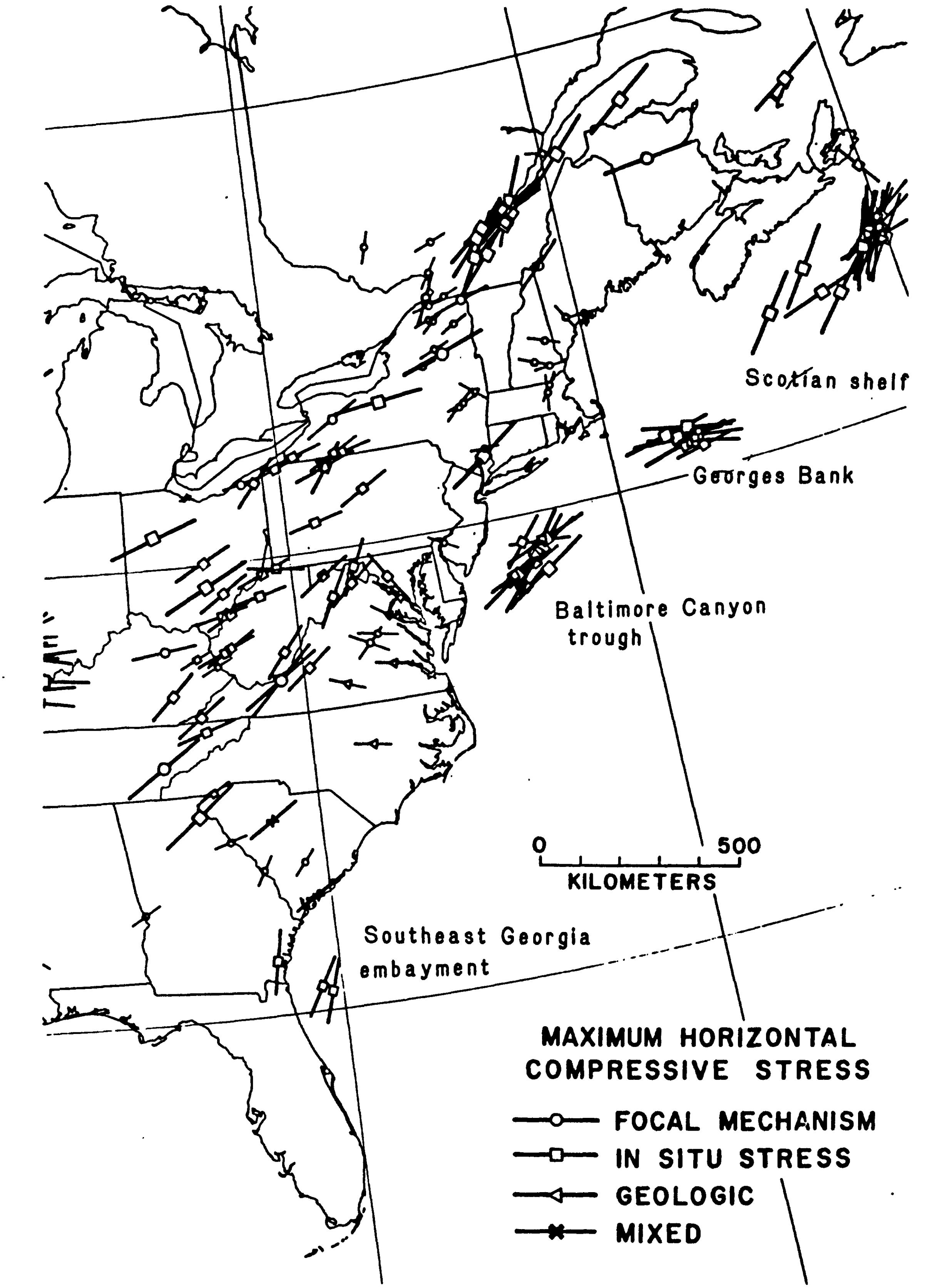

Figure 10. Maximum horizontal orientations for the Eastern United States and Atlantic continental margin (modified from Zoback and Zoback, 1986).

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APPENDIX

TABLE A-1 -- Consolidation Depth Lithology
[Depth of consolidation is based on dipmeter log character]

SE Georgia Embayment

Well 1b	Description of Lithology	Age of Strata	Lithology Data Source
GE5 (COST GE-1)	Near a transition from soft and moderately soft shale to more indurated shale at ~5,400 ft (1,646 m)	Upper Cretaceous	Detailed description (Scholle et al, 1979)
GE2	Near the contact of a moderately to very soft siltstone and moderately soft to firm limestone at ~5,400 ft. (1,646 m)	Unknown	Mud log (Exxon Co., U.S.A)
GE6	At the contact of a firm limey shale and a firm silty, sandy limestone at 5,350 ft (1,631 m)	Unknown	Mud log (Exxon Co., U.S.A.)
	Georges Bank Basin		
GB1 (COST G-1)	Uncertain of exact depth, approximate depth is 3,350 ft (1,021 m) in very coarse to medium quartz sand.	Early Cretaceous	Detailed description (Scholle et al, 1982)
GB2 (COST G-2)	At the contact between firm to hard argillaceous limestone and shaley limestone at 6,100 ft (1,860 m), poorly consolidated strata also occurs at greater depths	Late Jurassic	Detailed description (Scholle et al, 1982)
GB5	At the contact between at moderately hard shale and limestone at 5,650 ft (1,722 m)	Unknown	Mud log (Exxon Co., U.S.A.)
GB6	Uncertain of exact depth, approximately at 5,700 ft (1,738 m) near the contact of a very soft to soft lime-	Unknown	Mud log (Exxon Co., U.S.A.)

	Baltimore Canyon Trough		
BC9 (COST B-2)	Near the contact between a calcareous, micaceous sticky clay and a massive, well-consolidated sandstone at 5,976 (1,822 m).	Upper Creteceous	Detailed description (Scholle et al, 1977, and Amato et al, 1980)
BC12 (COST B-3)	At approximately 8,200 ft (2,500 m) at the contact between a silty mudstone and a medium soft, friable claystone. Poorly consolidated sediments and long washouts do occur at greater depths.	Late Cretaceous	Detailed description (Amato et al, 1979, and Scholle et al, 1980)
BC18	At approximately 7,625 ft (2,325 m) near the contact between a moderately soft, friable sandstone and a very hard dolomite.	Unknown	Mud log (Exxon Co., U.S.A.)
BC22	Near the contact between a moderately soft siltstone and a moderately hard limestone at 8,100 ft (2,470 m).	Unknown	Mud log (Exxon Co., U.S.A.)
BC25	Near the contact between a moderately to very coarse sand and a firm moderately hard sandstone at 5,000 ft. (1,524 m).	Unknown	Mud log (Exxon Co., U.S.A.)

TABLE A-2

Well Bore Elongations-Type and Lithology

Only long (approx. 100 ft and longer) well-bore elongations are considered

[Elongation types are: 1) washouts above the consolidation depth (WO), 2) breakouts (BO), and 3) preferentially oriented washouts (POW) below the consolidation depth. Elongation character describes 1) the surface texture as rough (R, pocked and pitted) or smooth (S, without significant textural expression, and 2) the relative depth of well-bore enlargement as minor --- <3 inches or deep -- >3 inches (D). Lithologic terms are sand (Sd), Gravel (Gv), Metamorphic rock (Meta), Argillite (Arg), Sandstone (Ss), and Shale (Sh), Limestone (Ls), Clay (Cly), Claystone (Clys) Siltstone (Slts), Dolomite (Dolo), Anhydrite (Anhy), Mudstone (Muds), Firm (F), Hard (H), Soft (S). Dashed line is inferred "consolidation depth" boundary]

SE Georgia Embayment

Well ID	Depth (Ft)	Length (Ft)	Orientation (Degrees)	Type	Character	Lithology/age
GE 5 (COST GE-1)	12494-12390	104	117	BO	R/M-D	Meta/Devonian
	11736-11620	116	317	POW	S/M-D	Devonian Arg (Locally soft)
	11390-11550	160	317	POW	S/M-D	Devonian Arg, S-H Clys

	5400-5150	250	117	WO	S/M-D	Upper Cretaceous Sh (S)
	5050-4600	450	297	WO	S/D	Upper Cretaceous Sh (H-S)
	2330-2450	120	237	WO	S/D	Upper Eocene slightly in-durated Shell Frags.
GE 2	12446-12330	116	267	BO	R/D	Sh (H)
	12192-11983	209	297	BO	R/D	Ss (H)
	11982-11816	166	267	POW	S/M	Sh (H-S)

	5409-4525	883	17	WO	R/D	Cly, Ls, Slts (F), Ls (H), Ss, Sh, Slts (S), Ls (S)
	4211-3962	249	147	WO	R/M	
	3722-3577	145	187	WO	R/D	Ls (H-S), Cly (S)

GE 6	5350-5000	350	67	WO	S-R/M-D	Cly(S), Sh(F), and Silty-sandy Ls (S)
	4716-4526	190	227	WO	S/M	Cly(S), Ls(H-S)
	3770-3660	110	312	WO	R/D	Slts(S-H), Ls(S)

Georges Bank Basin

Well ID	Depth (Ft)	Length (Ft)	Orientation (Degrees)	Type	Character	Lithology/age
GB 1 (COST G-1)	15756-15619	137	333	BO	R/M	Early Jurassic metadolomite, metaquartzite
	13952-14088	136	357	BO	S/M	Early-Middle Jurassic Sh, Dolo, Ss, Anhy
	13560-13447	113	163	BO	R/M	Early-Middle Jurassic Ss, Dolo, Sh, Anhy
	13428-13246	182	156	BO	R/M	Early-Middle Jurassic Early-middle Jurassic
	13025-12853	172	68	BO	S/M	Dolo, Anhy Early-Middle Jurassic
	12378-11635	743	343	POW	R/D	Dolo, Anhy Sh, Carbonates, Ss, Slts
	11633-11510	123	338	POW	R/M-A	Middle Jurassic Sh, Carbonate, Calcareous Sd
	11483-11154	329	353	BO	R/D	Middle Jurassic Ss/Sh(H), Ss, Slts
	10999-10842	157	148	POW	R/M	Middle Jurassic Ss, Dolo, Sh, Slt, Ls
	10810-10682	128	153	POW	R/M-D	Middle Jurassic Ss, Dolo, Sh, Slt, Ls
	10473-10120	345	168	POW	R/D	Middle Jurassic Sh, Ls, Ss
	2446-2026	420	303	WO	R/D	Late Cretaceous Sh(Gumbo-like/coarse Sd and Gv
	1306-1134	172	163	WO	S/D	Late Cretaceous Ss, Gv and Shell Frags (unconsolidated).

GB 2 (COST G-2)	20365-20480	125	355	POW	S/M	Early Jurassic-Late Triassic Sh, Slts and Muds
	20153-19920	233	353	POW	S/M	Early Jurassic-Late Triassic Dolo, Ls, Anhy
	19096-19143	453	173	BO	R/M-D	Early Jurassic Dolo, Ls, Anhy
	18524-16800	1724	353	POW	R/M	Early Jurassic Ls, Dolo, Anhy
	16808-15100	1700	163	POW	R/M	Middle Jurassic Ls, Dolo, Anhy
	15100-14400	700	173	POW	S/M	Middle Jurassic Ls, Dolo, Anhy
	13574-13450	124	168	POW	R/M	Middle Jurassic Ls, Dolo, Anhy
	13490-13300	190	208	POW	R/M-D	Middle Jurassic Ls, Dolo, Anhy
	13269-13058	211	3	POW	R/M-D	Upper-Middle Jurassic Ls/Sh, Clys
	13050-12816	234	358	BO	R/D	Ls/Sh, Clys
	12177-12030	147	3	POW	R/D	Ls/Sh, Clys
	11413-11300	113	183	POW	R/D	Ls/Sh, Clys
	5816-5556	260	278	WO	R/D	Early Cretaceous-Late Jurassic Muds/Ss, Ls
	5500-5304	196	268	WO	R/D	Early Cretaceous Coarse Sd and Sd/Sh, Muds
GB 5	12843-12567	326	193	POW	S/M	Slts(H), Ss(H)
	9945-9818	127	3	POW	R/D	Ls(S), Sh(F)
	6436-6236	200	138	POW	R/M	Slts(S-F), Sh(F)
	5614-5295	319	203	WO	S/M	Slts(F), Sd(F)
	5192-4954	238	198	WO	S/M	Sh(s)
	4624-4520	104	13	WO	R/M	Cly (unconsolidated), Coal (H)

GB 6	11965-11755	190	358	POW	R/M-D	Ls(S)
	12172-12000	172	23	POW	S/M	Ls(S), Ss(F)
	8009-7257	752	353	POW	R/D	Sandy Slts(F-H), Sh(F-H), Ss(H), Lss(F-H), Slts(S-F), Dolo(H)
	7250 6576	574	3	POW	S/M	Sandy Slts(F-H), (Sh(F-H), Conglomerate (H), Slts(F-H), Ls(S-H)
	4837-4654	183	343	WO	R/M	Sh(S)
	4428-4142	266	353	WO	R/D	Medium coarse Sd(unconsolidated-slightly consolidated), Ss(slightly-moderately consolidated), Slts(H)

Baltimore Canyon Trough

Well ID	Depth (Ft)	Length (Ft)	Orientation (Degrees)	Type	Character	Lithology/age
BC 9 (COST B-2)	13193-3100	93	167	POW	S/M	Lower Cretaceous Ss(F)
	11430-11327	103	272	POW	S/M	Lower Cretaceous Fine-coarse calcareous Ss, Ls and Dolo
	7286-6998	288	297	POW	R/D	Upper Cretaceous Medium-coarse, Ss, Dense Ls and Sh
	5960-5724	176	127	WO	R/M	Upper Cretaceous Calcareous Ss and Ls
	5780-5154	626	142	WO	S/D	Upper Cretaceous Sticky Clay
	5026-4930	96	272	WO	S/D	Paleocene-Eocene Dense Argillaceous Micrite and Clys
	4190-4036	154	92	WO	S/D	Oligocene Sh, Clys

BC 12 (COST B-3)	9934-9284	650	242	POW	S/M	Early-Middle Cretaceous Sandy Sh, Ss, and Ls
	8180 7750	430	12	WO	R/D	Late Cretaceous Fine Sd and Clys
	7444 5800	644	12	WO	R/D	Early-Middle Cretaceous Sandy Sh, Ss, Sd, Ls
BC 18*	7626-7260	366	117	WO	R/D	(Sd, Ls, Slts (S-H), Dolo Sh(S), Ss(S) SS(Freq. unconsolidated), Slts(S-H), Cly(S)
	7052-6710	342	117	WO	R/D	Ls(H), Sh(s), Dolo(H)
	6662-6515	147	247	WO	S/M	Slts(S-H), Ls(S-H), Ss(unconsolidated),
	6368-5090	1139	97	WO	S/D	Cly(S)
	4981-4662	299	217	WO	S/D	Ss(unconsolidated-H), Slts(S-H), Cly(S)
BC 22	13816-13746	170	132	POW	R/D	Ss(S) and Coal(H)
	11869-11740	120	147	BO	R/D	Ls(H), Slts(F-S), Ss(F-H)
	8126-7740	386	217	WO	R/D	Ss(F-H), Slts(F-S), Ls(S) Sh(S)
	7160-6638	522	167	WO	R/D	Ss(F-H), Slts(S-H), Ls(S-H)
	6058-5430	628	87	WO	S/D	Slts(S), Cly(S-H), Ls(H), several hundred ft. of Cly(S)
	5140-4880	260	172	WO	S/M	Cly(H-S)

BC 25	8274-8163	111	92	POW	R/M	SS(H), Coal(H)
	7626-7500	126	352	POW	R/M	Ss(F)
	4946-4796	150	137	WO	R/M	Sd(Loose), Cly(S)
	4668-4270	398	142	WO	R/D	Cly(S)

*No breakout data below the consolidation depth in this well.

Sources of stratigraphic information include mud logs provided by the Exxon Co., U.S.A.; Scholle and others, 1977, 1979, 1980; and Amato and others 1979, 1980.