Distribution of Subsurface Lower Mesozoic Rocks in the Southeastern United States, as Interpreted from Regional Aeromagnetic and Gravity Maps

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STUDIES RELATED TO THE CHARLESTON, SOUTH CAROLINA, EARTHQUAKE OF 1886—TECTONICS AND SEISMICITY

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By DAVID L. DANIELS, ISIDORE ZIETZ,[1] and PETER POPENOE

ABSTRACT

Aeromagnetic data, in conjunction with data from deep wells, are used to interpret the nature of the pre-Cretaceous "basement" beneath the Coastal Plain in Georgia and South Carolina. These data reveal some of the complexity of the broad early Mesozoic rift basin, which appears to extend at least from the Gulf of Mexico to the Atlantic Ocean. Along the northern edge of this rift, in the Savannah River region, depth-to-magnetic-source calculations delineate two interconnected basins, which are separated from the main rift by a broad horst of crystalline basement. The Riddleville (Ga.) basin appears to contain at least a 2.2-km thickness of basin fill; it is deeper than the Dunbarton (S. C.) basin, which has at least a 1.0 km thickness of fill. A maximum thickness of 3.5 km near Statesboro, Ga., is indicated for the main basin, called here the South Georgia rift.

Abundant lower Mesozoic diabase dikes in the South Carolina Coastal Plain are revealed on the magnetic map by narrow anomalies that have two dominant trends, northwest and north. One set of several north-trending anomalies can be traced continuously northward across the Coastal Plain, Piedmont, and Blue Ridge for 480 km. The two sets, which may represent two episodes of intrusion, have characteristic distributions within the study area: northwesterly trends are to the southwest and northerly trends to the northeast. A broad area of overlap extends from 80° W., in South Carolina, to northern Virginia. Several lower Mesozoic diabase sills within the rift are indicated by circular, low-amplitude magnetic anomalies.

Intense magnetic highs and corresponding gravity highs indicate the presence of abundant large bodies of mafic rocks in the pre-Cretaceous "basement" in addition to the dikes and sills; two groups of mafic rocks are distinguished. Circular or oval anomalies are interpreted as largely gabbroic plutons, which may be as young as early Mesozoic and which are present both within and outside the rift. Elongate anomalies, which form a northeast-trending belt across Georgia and South Carolina, may reflect deformed pre-Mesozoic mafic rocks.

The largest and least understood magnetic feature of the region is the Brunswick anomaly, a long-wavelength anomaly system 1,100 km long, which is mostly offshore but which also bisects the Georgia Coastal Plain. The anomaly divides two regions of differing magnetic character and magnetic trend, which suggests that it is closely related to a Paleozoic suture between a Florida–South Georgia microcontinent and the North American craton.

INTRODUCTION

Detailed aeromagnetic coverage in the Coastal Plain region around Charleston, S. C., reflects the type and distribution of rocks and structures in the pre-Cretaceous basement. This report examines the evidence for subsurface lower Mesozoic rocks in the aeromagnetic data supplemented by gravity and seismic-refraction data, with reference to rocks returned from deep drilling.

Information about the subsurface "basement" rocks in the Coastal Plain of the Southeastern United States has been derived from deep drill samples. Although Alabama and northern Florida have been extensively drilled, the Coastal Plain of South Carolina and eastern Georgia has very few useful wells. Because the samples returned from drilling represent a point source of data, large, horizontally continuous structures, such as sedimentary beds, may be adequately defined by a vertical sample. Many basement structures, however, have steep contacts and are poorly defined by drilling. Further, most deep drilling was performed as oil tests and therefore was terminated shortly after the basement was penetrated.

Existing aeromagnetic surveys (see fig. 1), by contrast, cover the study region (pl. 1) uniformly; flight-line spacing is 1 mi (1.6 km) or less on land and 2 mi (3.2 km) offshore. Magnetic and gravity surveys respond to large volumes of rock and most strongly to structures of large vertical extent. It should be recognized, however, that gravity and magnetic information is subject to multiple interpretations, so the anomalies can never be unequivocally explained unless constrained by other geophysical or geological data.

Therefore, the gravity and magnetic data give us a different, though complementary, picture from that obtained by drilling. Many major features on the magnetic

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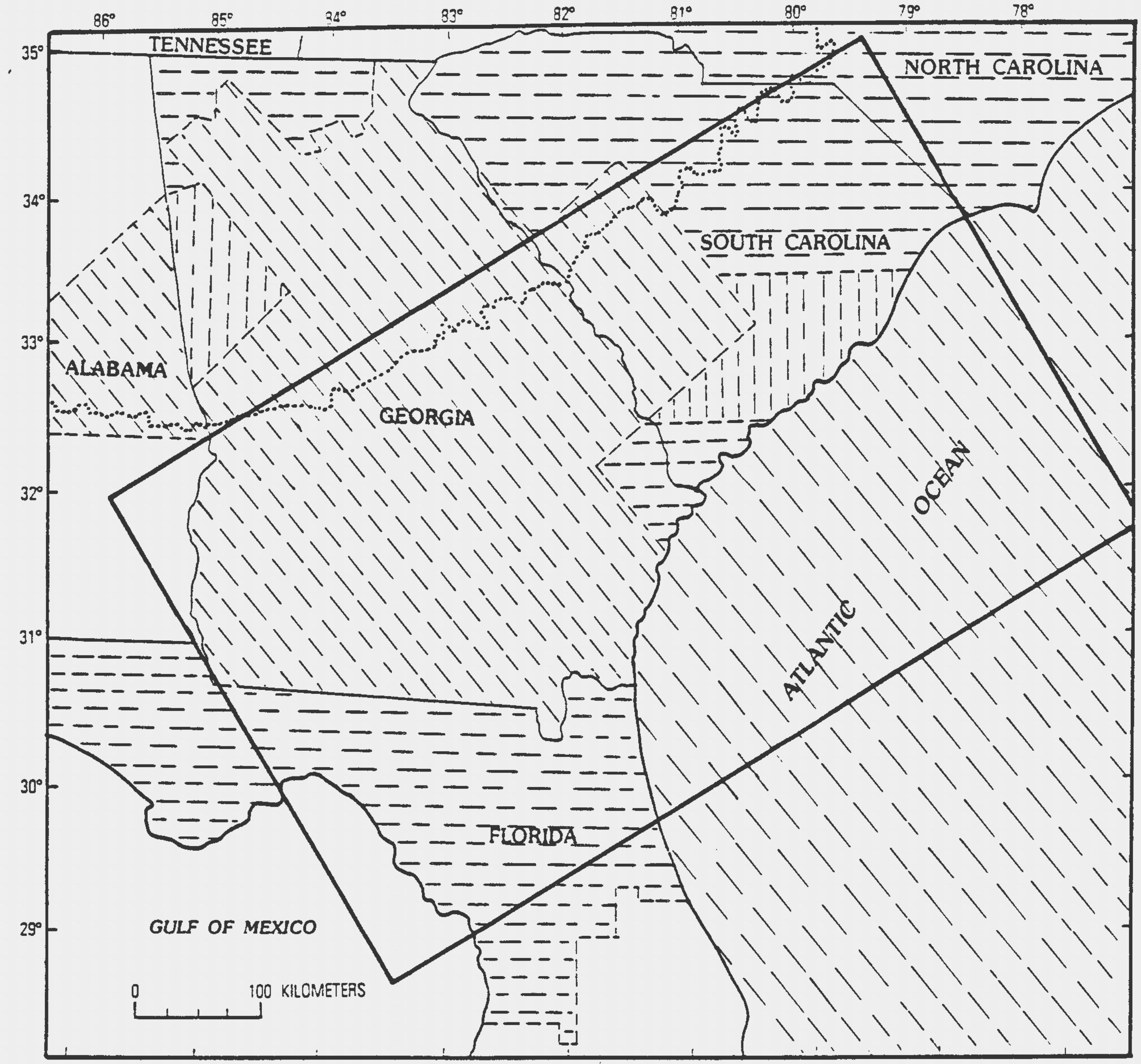


FIGURE 1.–Coverage of aeromagnetic surveys of 1-mi (1.6-km) (land) and 2-mi (3.2-km) (ocean) flight-line spacings in the Southeastern Atlantic States. Dashes indicate directions of flight lines. Dotted line divides Coastal Plain and Piedmont. Rectangle encloses study area.

and gravity maps have not yet been identified by drilling. Nevertheless, the features can be generally identified, and many of them affect strongly the interpreted tectonic history of the region.

Acknowledgments.–Partial support for this research and funding for many of the aeromagnetic surveys of the Coastal Plain of the Southeastern States was provided by the Coastal Plains Regional Commission.

INTERPRETIVE TECHNIQUE

The interpretations in this paper have been based mainly on the aeromagnetic data, because of the greater data uniformity, resolution, and dynamic range of rock magnetic properties (remanent magnetization effects included). Gravity maps, which are more reliable indicators of lithology, were used to further refine the interpretations made from the aeromagnetic maps.

Qualitative Method

Only a limited number of features (six are discussed here) are distinct enough to be recognized on the gravity and magnetic maps of the Southeastern States. These "signatures" are based upon comparison between magnetic and gravity maps of the Piedmont and Blue

Ridge provinces and geologic maps of the same areas. Detailed aeromagnetic maps [flight spacing 1 mi (1.6 km) or less] are now available for more than 95 percent of this region. Many gravity and magnetic features in the Piedmont, however, are currently unexplained geologically and so cannot be used as a guide. The recognizable features may be classified loosely by anomaly shape, orientation, amplitude, and sign (high or low). In order of decreasing confidence in their geologic associations, these six features are:

1. Narrow linear magnetic anomalies with northwest or northerly trends, which are largely correlated with Triassic-Jurassic diabase dikes. Dike anomalies are most easily recognized where they cross nonmagnetic terrain or where they cross the trend of the country rock at an angle greater than about 20 degrees.
2. Circular or oval magnetic anomalies and closely corresponding gravity anomalies. These occur in the following combinations:
   a. Magnetic high–gravity high: Mafic intrusive rocks are indicated where both anomalies are of large amplitude [examples: Concord and Mecklenburg plutons in North Carolina (pluton names from Speer and others, 1980)]. Numerous smaller mafic intrusive bodies having irregular map patterns may also be recognized from the magnetic high–gravity high association, provided the geophysical data have adequate resolution. Metamorphosed mafic rocks may lack the magnetic high.
   b. Magnetic low–gravity low: Many of the cross-cutting, post-metamorphic plutons in the Piedmont correlate with distinct magnetic and gravity lows (examples: Landis and Churchland plutons in North Carolina). Premetamorphic plutons are more difficult to distinguish by means of gravity and magnetic data alone.
   c. Magnetic high–gravity low: A few of the post-metamorphic granitic plutons in the Piedmont have distinct gravity lows but are also moderately magnetic (examples: Liberty Hill and Pageland plutons in South Carolina).
3. Parallel groups of narrow linear magnetic anomalies trending northeast, which characterize folded metamorphic rocks of the Piedmont. The linear pattern is not uniformly developed but seems to be associated with upper greenschist- or lower amphibolite-grade rocks that have undergone tight folding around largely horizontal fold axes and that have the right composition to develop magnetite. Alternatively, some of these anomalies may be attributed to mylonite zones (Hatcher and others, 1977).
4. Elongate regions of low magnetic gradient and intensity and generally small gravity lows, which correlate with parts of many Triassic-Jurassic basins in the Eastern United States. The gravity and magnetic signatures of such basins are quite variable and depend on the thickness of the sedimentary rocks, the presence or absence of diabase intrusive rocks, and the magnetic character of the underlying rocks.
5. Ring-shaped magnetic anomalies, associated with many of the diabase sills in the Gettysburg, Pa. (Bromery and Griscom, 1967), and Culpeper, Va. (Daniels, 1980), Triassic-Jurassic basins. A variety of other, less distinctive shapes is also common. Low-amplitude gravity highs are also associated with these sills but lack the resolution of the magnetic data because of generally wider station spacing.
6. Some straight magnetic or gravity gradients, associated with mapped faults (examples: Jonesboro and Gold Hill faults in North Carolina; Hatcher and others, 1977; Stromquist and Sundelius, 1969).

Note that all or nearly all signatures described above could also arise from pre-Cretaceous intrabasement contrasts in the Coastal Plain region. Since the blanket of Coastal Plain rocks that overlies the pre-Cretaceous basement is weakly magnetic and quite uniform horizontally, its effect on the potential field is one of distance. An increasing thickness of sedimentary cover acts to smoothly decrease the gravity and magnetic gradients. Narrow anomalies decrease in amplitude readily with increasing distance, whereas broad anomalies change little.

Quantitative Method

To supplement the qualitative technique described above, the depth to many magnetic sources in the Coastal Plain was estimated from original profiles and reconstructed profiles, by means of the horizontal-gradient method (Vacquier and others, 1951). The depth estimates were corrected for anomaly-to-flight-line angle, airplane elevation, and approximate ground elevation. In order to smooth the large range in the results, a minimum of three adjacent depth estimates were averaged for each anomaly. In some areas of the Coastal Plain, the magnetic sources are consistently deeper than the average top of the pre-Cretaceous rocks as determined from nearby wells or seismic-refraction measurements, which indicates the existence of an upper layer of nonmagnetic rock within the pre-Cretaceous basement. This nonmagnetic layer is interpreted in most cases to be Triassic and Jurassic sedimentary rocks. It is necessary to assume that crystalline basement rarely has a nonmagnetic upper layer.

In other areas, many magnetic sources plot close to the expected level of the base of the Cretaceous within an error range of ±25 percent of the total depth. These sources are interpreted to be evidence of either crystalline basement or Mesozoic mafic igneous rocks near the top of a sedimentary sequence. Anomaly amplitude and character were then used to distinguish between the two groups. A number of magnetic sources appear to lie above the projected pre-Cretaceous surface and within the Coastal Plain sedimentary section. Because no rocks capable of producing detectable magnetic anomalies are known to occur within the Coastal Plain sediments, these depth determinations are assumed to be too shallow and incorrect. Only two of these, however, were too shallow by more than 25 percent of the total depth. These may indicate either unsuspected relief on the pre-Cretaceous surface or violation of the assumptions required in the depth technique, such as bodies that have nonvertical contacts or significantly nonuniform magnetic properties.

INTERPRETATION OF COASTAL PLAIN MAGNETIC AND GRAVITY MAPS

Features of Probable Early Mesozoic Age

Continental sedimentary rocks of Triassic and Jurassic age (Van Houten, 1977) crop out along eastern North America in a series of fault-bounded basins, displacing rocks of the Piedmont, Blue Ridge, and Valley and Ridge provinces. Red-brown mudstones, arkoses, and conglomerates are common; basalt flows are found in the upper part of the section, and diabase intrusions (some of which are sills) in the more northerly basins. Diabase dikes also cut both the Piedmont and the basins in a regular pattern from Alabama to Nova Scotia (King, 1971).

The existence of similar sedimentary and igneous rocks beneath the Coastal Plain was recognized very early from deep wells that had penetrated the pre-Cretaceous basement rocks – at Florence, S. C. (Darton, 1896), Summerville, S. C. (Cooke, 1936), Laurens, Appling, and Montgomery Counties, Ga. (Applin, 1951), and Camden County, N. C. (Richards, 1954). These and later reports have correlated these rocks with the Newark Group (Atlantic Coast) or the Eagle Mills Formation (Gulf Coast) on the basis of lithologic similarity and association with diabase and (or) basalt (Applin and Applin, 1964; Maher, 1971; Marine and Siple, 1974; Barnett, 1975; Brown and others, 1979).

Currently the number of wells in the Southeastern States that have returned suspected Triassic and Jurassic rocks has increased to about 60, and, in fact, there appears to be a large, continuous rift basin, nowhere exposed, which traverses western Florida, southern Alabama, Georgia, and South Carolina and extends beneath the Gulf of Mexico and Atlantic Ocean (Popenoe and Zietz, 1977; Popenoe, 1977; Gohn and others, 1978; Chowns, 1979). This basin, called here the South Georgia rift (fig. 2), is longer than the largest exposed Triassic-Jurassic basin in the Eastern States (the Culpeper-Gettysburg-Newark basin) and about four times its width. The east-northeast trend of this basin also distinguishes it from the exposed basins, which generally trend northeast. The sediments of this complex basin have been deposited on Piedmont crystalline rocks at its northern edge and on Paleozoic sedimentary rocks, rhyolitic rocks, and assorted granitic rocks along its southern half.

During the past ten years, isotopic age measurements have confirmed that some of the subsurface diabase and basalt are Triassic and Jurassic in age and have implied that the sedimentary rocks are equivalent to those in the exposed Triassic-Jurassic basins (Milton and Grasty, 1969; Barnett, 1975; Gohn and others, 1978; Lanphere, 1983).

Whereas felsic volcanic rocks are unknown in exposed early Mesozoic basins of the Appalachian orogen, rhyolites interlayered with Mesozoic arkose have been reported from several wells within the rift in southern Alabama (Neathery and Thomas, 1975). Radiometric age dating of unmetamorphosed to slightly metamorphosed felsic pyroclastic units in southeast Georgia has resulted in a wide range of ages which includes the early Mesozoic (Chowns, 1979). However, the Georgia rhyolites have been excluded from the rift shown in figure 2 because of uncertainty about the reliability of these dates.

The South Georgia rift may be an extension of the rift that initiated the opening of the Gulf of Mexico (Rankin and others, 1978), as the North American and South American plates separated (Pilger, 1978). The South Georgia rift accumulated continental clastic sediments and mafic igneous rocks from the Late Triassic through the Early Jurassic, at which time it probably became inactive. The Gulf rift, however, experienced continued crustal thinning and depression and was invaded by Pacific Ocean waters, which entered across the Mexican peninsula in the Middle Jurassic (Salvador, 1979). Thick salt deposits that overlie continental red beds in the Gulf region (fig. 2) indicate that the Gulf rift remained a relatively restricted basin during the Jurassic. The spreading center that developed in the Gulf of Mexico may have been connected to Atlantic spreading centers along a northwest-trending transform fault across south Florida, the Bahamas fracture zone (Klitgord and others, 1983).

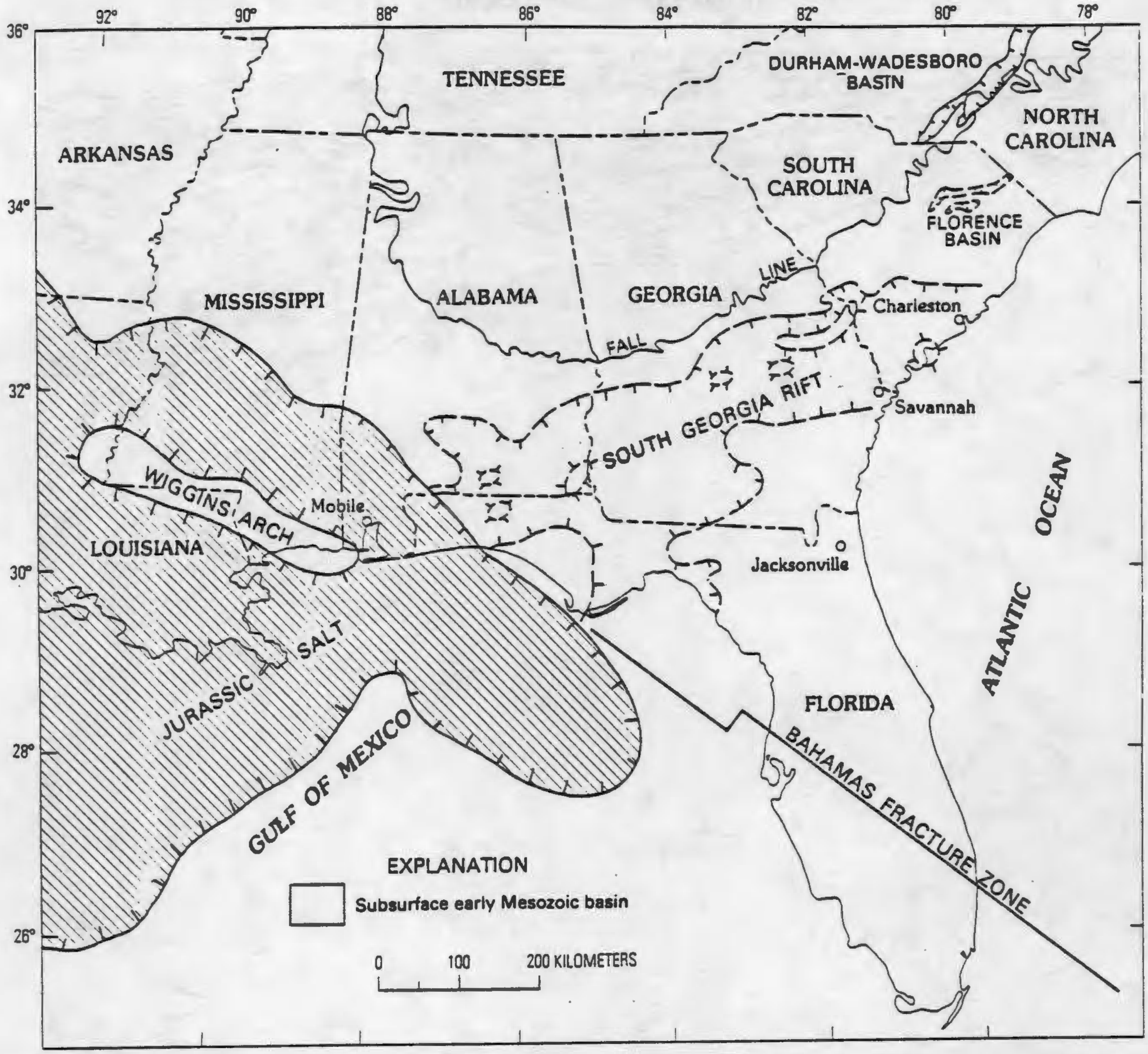


FIGURE 2.–Map of interpreted distribution of subsurface early Mesozoic basins. Boundaries have been generalized from well data and magnetic data. Bahamas fracture zone from Klitgord and others (1982). Extent of Jurassic salt from McGookey (1975). Well data from Applin (1951), Bridge and Berdan (1951), Milton and Hurst (1965), Milton and Grasty (1969). Marine and Siple (1974), Marine (1974), Barnett (1975), Neathery and Thomas (1975), Gohn and others (1978), Daniels and Zietz (1978) and unpublished data. Durham-Wadesboro basin in North Carolina and edge of Coastal Plain (dotted line) from King (1969).

SEDIMENTARY ROCKS

Large areas of the Coastal Plain in Georgia and South Carolina are characterized by low magnetic gradients that may be caused by subsurface lower Mesozoic sedimentary rocks (pl. 1). However, it is known from deep well samples that, although much of this low-gradient area is underlain by rocks of probable early Mesozoic age, some parts are underlain by other rocks: Paleozoic sedimentary rocks, felsic volcanic rocks, felsic plutons, diorite, schist, and felsic gneiss, all of which seem to be weakly magnetic and produce a low-gradient magnetic field. Only in the shallow part of the Coastal Plain, in the region of the Savannah River, where basement crystalline rocks are strongly magnetic, is sufficient contrast available to define the thicker areas of rift sediments. Because northeast-trending anomalies are characteristic of the Piedmont, the presence of these anomalies can identify areas where thick sections of Triassic and Jurassic red beds are probably absent. Narrow linear magnetic anomalies are not equally abundant

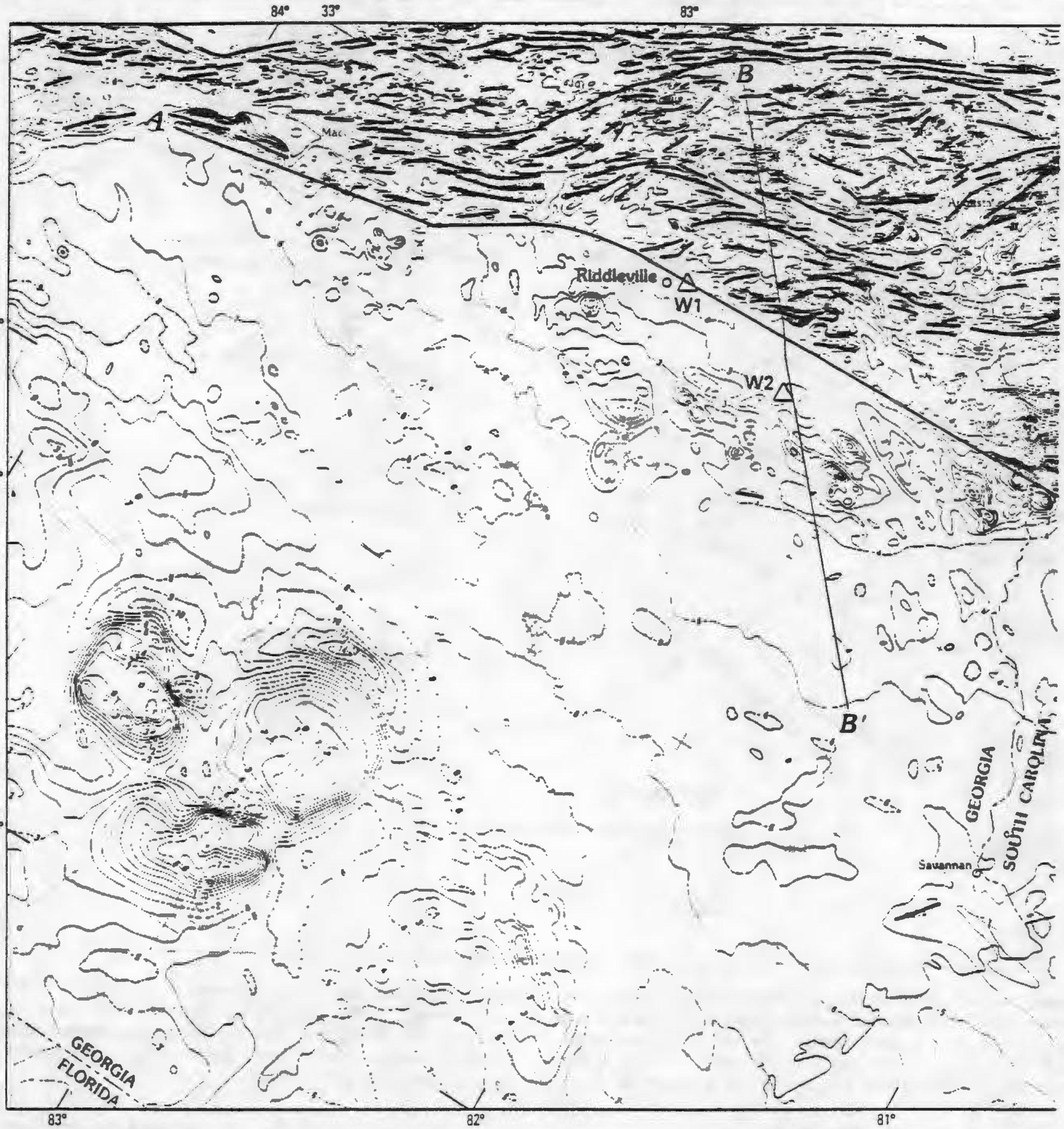


FIGURE 3.–Aeromagnetic map of the Coastal Plain and part of the Piedmont, South Carolina and Georgia. Contour interval 100 nT. Heavy lines trace northeast-trending linear anomalies interpreted as characteristic of Piedmont rocks. Line *A–A′* marks the southern boundary of the region of abundant northeast-trending anomalies. Line *B–B′* marks the location of cross section shown in figure 6. Triangles mark two wells that penetrated red beds in the Riddleville basin.

everywhere in the Piedmont and so can only be used as a general indicator of relatively shallow subsurface extension of Piedmont terrain. Progressively deeper burial of these rocks causes the anomalies to broaden and diminish in amplitude until they lose character.

Instead of a smooth attenuation with distance from the Fall Line, the linear grain ends abruptly in certain areas, indicated by line *A–A′* on figure 3. This line follows several strong linear magnetic trends and may mark the approximate northern edge of the main rift

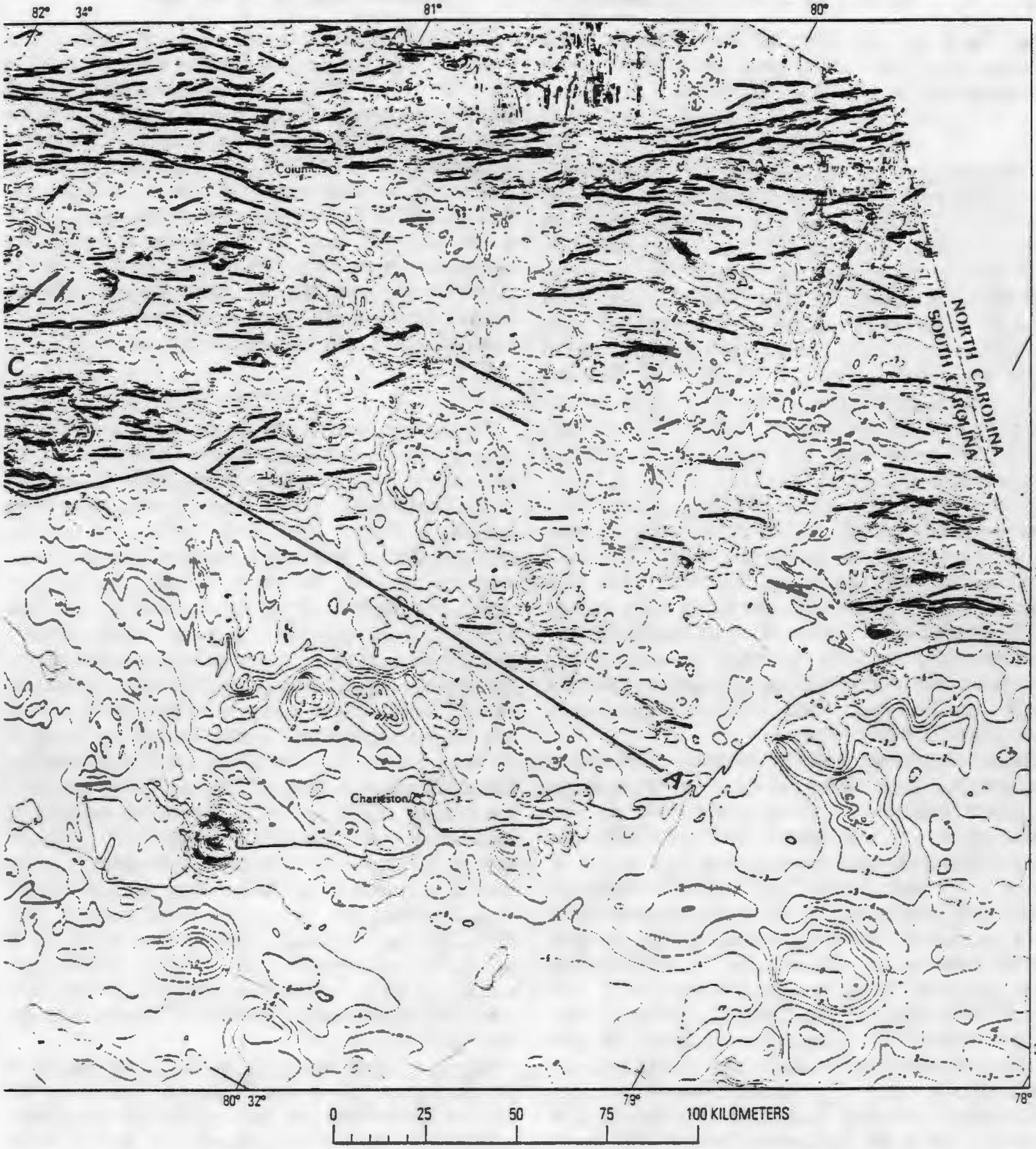


FIGURE 3. – Continued.

zone. A few northeast-trending anomalies lie south of line *A–A'* and may indicate southward continuation of Piedmont crystalline rocks beneath the rift sediments or as horsts of crystalline basement. Comparison with a plot of wells that reached the pre-Cretaceous basement shows that nearly all of the wells that returned foliated metamorphic rocks characteristic of the exposed Piedmont lie north of line *A–A'*. Rocks judged to be of probable Triassic and Jurassic age (red beds, diabase, and basalt) are mostly confined to wells that lie south of this line. The wells that identified the Dunbarton basin (Marine and Siple, 1974) and the Florence basin (Popenoe and Zietz, 1977) are exceptions.

Riddleville basin

Immediately south of line *A–A'*, an exceptionally featureless magnetic low extends east from Riddleville, Ga. (fig. 3). This feature led Daniels and Zietz (1978) to predict a subsurface Triassic-Jurassic basin there. Recent wells in the area of the magnetic low have confirmed this interpretation. Near Riddleville, Ga., more than 500 meters of red conglomerate and fanglomerate of probable Triassic and Jurassic age were penetrated in a gas test well (T.R. Taylor 1; W1, fig. 3) (R. Bennett, oral commun., 1978). Three other wells in the immediate vicinity also struck red beds (D. Ziegler, oral commun., 1980). Red beds were also recovered beneath the Cretaceous in a U.S. Geological Survey (USGS) hydrologic test well at Midville, Ga. (W2, fig. 3) (Harold Gill, oral commun., 1980). For clarity in this paper we refer to these rocks as the "Riddleville basin." The aeromagnetic contours suggest that this basin trends east-west and that maximum thickness occurs along the axis of the magnetic low. Piedmont crystalline rocks have been recovered from wells on the north side of the basin, and mafic rocks of uncertain character are inferred to lie to the south (Daniels and Zietz, 1978), although none has been identified from drilling.

Depth-to-source estimates on magnetic anomalies in the Savannah River region are shown on figure 4. Approximate structure contours on the pre-Cretaceous basement drawn from depths from deep wells and seismic-refraction measurements are also shown in figure 4. To estimate the thickness of nonmagnetic rocks below the Cretaceous, the magnetic-source depths were subtracted from the basement elevation as interpolated from the structure contours. These thicknesses were contoured where an adequate number of data points was available (fig. 5). The solid lines on figure 5 enclose sources for which the thickness of pre-Cretaceous nonmagnetic rock is zero or less than the probable error range of the magnetic depth technique ($\pm$25 percent), including those sources that appear to lie above the base of the Cretaceous. These sources are interpreted to be a subcrop of crystalline basement, and, in the region north of the Riddleville and Dunbarton basins, some are directly associated with wells that returned foliated metamorphic rocks characteristic of the exposed Piedmont. Because of the wide range of shallow depths accepted as evidence of crystalline basement subcrop, the area of these rocks may be smaller than indicated. Some magnetic sources that plot close to the base of the Cretaceous were measured on low-amplitude anomalies, and these were interpreted to be lower Mesozoic diabase or basalt (open squares, fig. 5).

Those sources that indicated a large thickness of nonmagnetic rock (open circles, fig. 5) were interpreted to be evidence of early Mesozoic sedimentary basins. Magnetic sources in the Riddleville basin confirm the east-west elongation and indicate at least 2.2 km of sedimentary fill. The more closely spaced isopach contours along the north edge of the basin (fig. 5) suggest that the Riddleville basin is asymmetrical, bounded by a major east-west fault on the north, and that the sedimentary rocks dip generally north (fig. 6). Cook and others (1980) report seismic-reflection evidence in this location for a possible listric-normal fault that may dip south and join a deep master décollement.

Dunbarton basin

The Dunbarton basin was discovered as a result of a deep corehole in southern Barnwell County, S. C. Continental red beds similar to rocks found in exposed Triassic and Jurassic basins were recovered beneath the Cretaceous (Christl, 1964). Siple (1967) noted that the well was located in a broad, northeast-trending aeromagnetic low (Petty and others, 1965) (C, fig. 3) and inferred that the low defined the limits of a subsurface Triassic and Jurassic basin. A steep, linear magnetic gradient that limits the magnetic low on the southeast suggests this edge of the basin is fault bounded (Daniels, 1974). Four additional coreholes across the northwest half of the magnetic low verified the inferred extent of the basin in that direction. Maximum red-bed penetration of 925 m was achieved at the center of the magnetic low (Marine and Siple, 1974). Additional geophysical data (seismic-reflection, gravity, and ground magnetic surveys) led Marine (1974) to suggest, however, that the basin is not confined to the aeromagnetic low but extends southeast well beyond the linear magnetic gradient. The maximum basin thickness was estimated to be 1,615 m, and a region of high intensity to the southeast of the magnetic low was interpreted to be mafic rocks overlain by a thinner section of Triassic sedimentary rocks (Marine, 1974).

Magnetic depth estimates in the same region in general support the model offered by Marine (1974). Like the Riddleville basin, the Dunbarton basin appears to be nearly enclosed by a subcrop of crystalline rocks but is apparently connected to the main rift basin, to the south, across a saddle of thinner lower Mesozoic rocks (fig. 5). Marine and Siple (1974) have suggested that the general dip of the basin is southeast.

Several factors, although they are not well established at this time, indicate a difference in character between the Riddleville and Dunbarton basins even though the two basins are adjacent and appear to be connected (fig. 5). The indications of northeast elongation, southeast dip, and relatively small thickness of the Dunbarton basin suggest affinity with the nearest exposed early

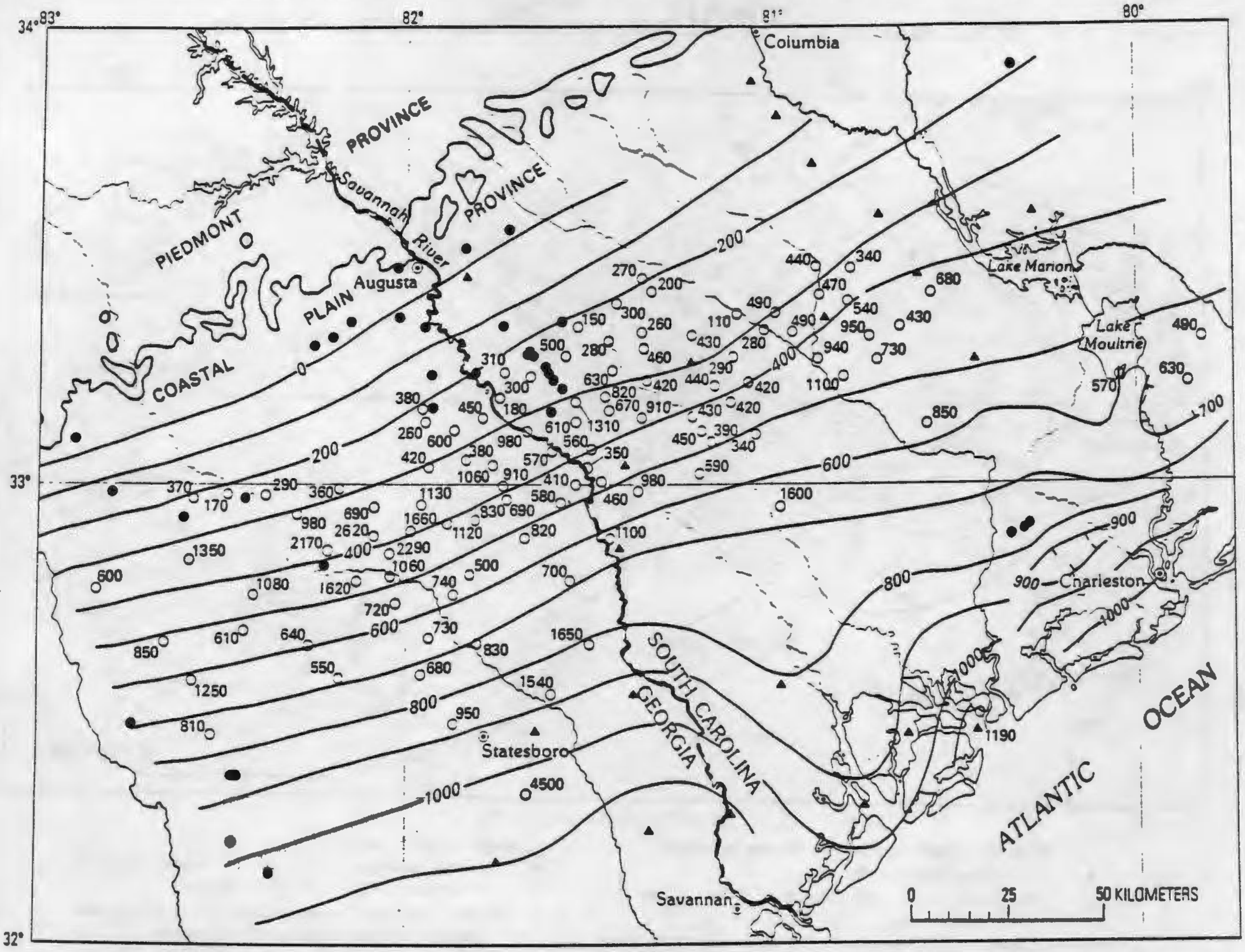


FIGURE 4.—Map of the Savannah River region, Georgia and South Carolina, showing calculated depths to magnetic sources (open circles, in meters), structure contours on the top of the pre-Cretaceous basement surface (contour interval 100 m), and data points from which the contours were derived (solid circles, well data; triangles, seismic-refraction data). Refraction data from Woollard and others (1957), Pooley (1960), and Ackermann (1983).

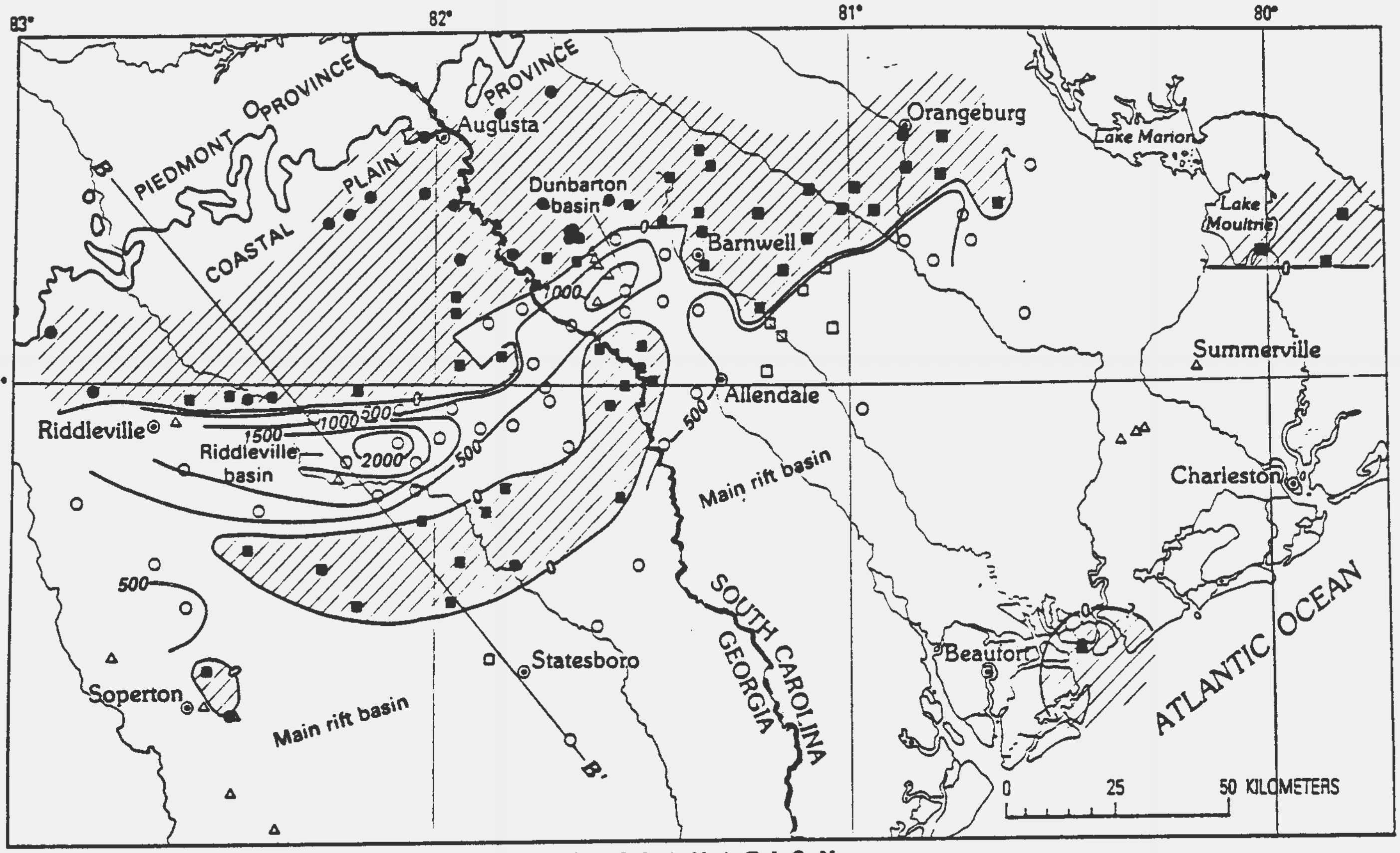
Mesozoic basin, the Durham-Wadesboro basin in North Carolina. In contrast, the Riddleville basin's east-west elongation, northerly dip, and greater thickness suggest that it is part of the main rift system to the south. The position of line *A–A′* (fig. 3), which divides the two basins, further supports this concept. The Dunbarton basin may be the southernmost basin that parallels the Appalachian trend.

Main rift basin

The deepest magnetic source (4,500 m) found in the area examined is located south of Statesboro, Ga. (fig. 4), where about 3.5 km of pre-Cretaceous nonmagnetic rock is indicated. Because depths were obtained for only a limited part of the main rift basin, this figure might not be typical. For comparison, the maximum thickness of Triassic and Jurassic rocks proven by drilling in this basin is 1.8 km in southwest Georgia (Chowns, 1979). Although the Statesboro area contains no wells to basement and only a few magnetic depth determinations have been made, a deep basin is inferred because of the flat magnetic field.

Florence basin

The rocks retrieved from two wells at Florence, S. C., constitute the major evidence for an early Mesozoic basin in that area. Darton (1896) reported that brown and gray sandstones identified as "Newark Formation"



EXPLANATION

Wells that penetrated pre-Cretaceous basement

- ● Crystalline Piedmont rocks
- △ Red beds, basalt, and diabase of probable Triassic and Jurassic age
- —0— Isopach of Triassic-Jurassic red beds—Based on magnetic depth measurements. Contour interval is 500 meters

Magnetic depth sources

- ■ Shallow sources, moderate to large anomaly amplitude—Inferred Piedmont source
- □ Shallow source, low-amplitude anomaly—Inferred source is Triassic-Jurassic mafic sill or flow
- ○ Deep source—Inferred source is crystalline rocks beneath Triassic-Jurassic red beds

FIGURE 5.—Map showing crystalline basement subcrop (patterned areas) and thickness of lower Mesozoic red beds in the Coastal Plain, Savannah River region, Georgia and South Carolina derived from magnetic depths (fig. 4) and well data.

were terminated by a black trap rock; olivine diabase was recovered from a more recent well there (Siple, 1958). Bonini and Woollard (1960) suggested further that the seismic-refraction measurement 47 km west of Florence, which gave an unusually low basement velocity (3.93 km/s, station 43), may indicate that the basin extends west to include this location. An aeromagnetic low (*A*, fig. 7) is associated with both the well sites and the seismic-refraction site, although the character of this low is less suggestive of a basin than are those of the lows associated with the Riddleville and Dunbarton basins. Popenoe and Zietz (1977) inferred a basin that follows the dimensions of the low. Inspection of the magnetic maps shows magnetic lows of similar character at *B* and *C* (fig. 7). Lows *A* and *B* may be a continuous basin whose center is at Florence, and a separate parallel basin may lie at *C*. Seismic velocities of the pre-Cretaceous rocks of 4.9 and 4.8 km/s (Woollard and others, 1957) within these lows (*B* and *C*, fig. 7) are compatible with velocities for lower Mesozoic sedimentary rocks (Ackermann, 1983). The magnetic lows and low seismic velocities, although supportive of an interpretation of early Mesozoic sedimentary basins, are equally characteristic of predominantly metasedimentary parts of the Carolina slate belt, so the extent of the basin at Florence must remain uncertain at this time.

DIABASE DIKES

The lower Mesozoic rocks most easily recognized from the magnetic maps of the Southeastern States are diabase dikes generally considered to be Late Triassic to Early Jurassic in age (Van Houten, 1977; de Boer and Snider, 1979). Narrow linear magnetic anomalies trend-

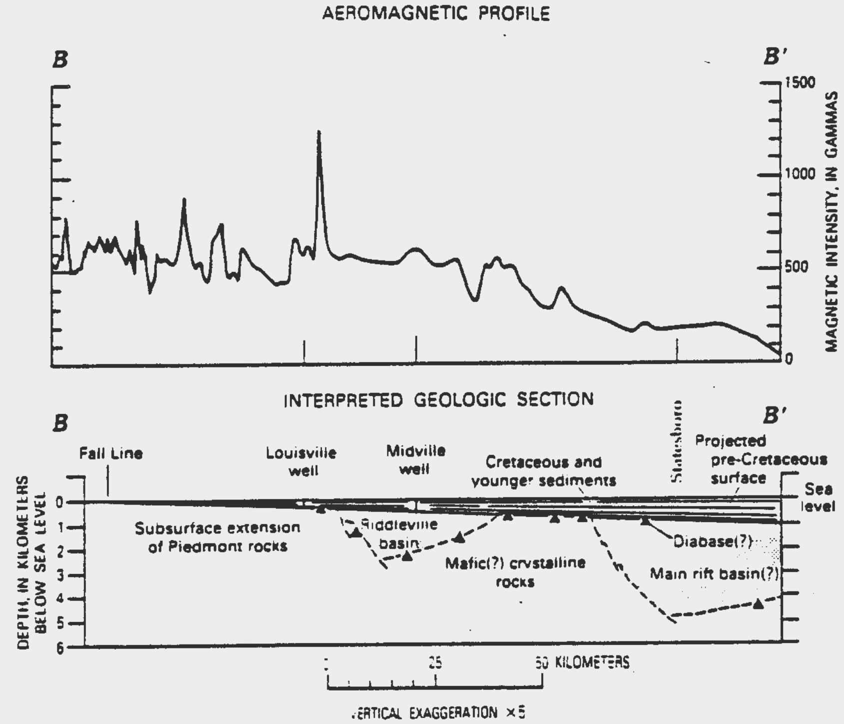


FIGURE 6.—Aeromagnetic profile and interpreted geologic section along line *B–B'* (figs. 3, 5). Magnetic sources shown by triangles, projected onto line of section. Early Mesozoic basins shown by pattern.

ing predominately northwest or north dominate the magnetic maps of central North Carolina and eastern South Carolina and clearly are generated by diabase dikes (Burt and others, 1978). In this region magnetic maps are almost essential tools for mapping dikes in the Piedmont and Coastal Plain. Investigations by Bell and others (1978) have shown that some, and probably many, of the major aeromagnetic anomalies attributed to dikes are caused not by continuous, single, wide dikes but by parallel groups of several narrower dikes of limited continuity. Most of the dikes trend northwest, but in a restricted area of central North Carolina there is a conspicuous swarm of very long dikes trending north, which were largely unknown before magnetic mapping of the region was completed (U.S. Geological Survey, 1974, 1977a, 1977b, 1977c).

Anomalies of both trends can be traced on the magnetic maps of North and South Carolina far out onto the Coastal Plain until increasing depths put the dikes beyond the detection range of the magnetometer. Those anomalies considered to be generated by subsurface dikes are shown in figure 8 (see also Popenoe and Zietz, 1977; Daniels and Zietz, 1978). The north-trending anomalies identify a set of dikes that are unique because of their orientation, length, and continuity. This set can be traced, by means of the magnetic maps, from the vicinity of the Santee River just north of Charleston, S. C., north, across the Piedmont and the Blue Ridge near Buena Vista, Va., a distance of about 480 km (Daniels and Zietz, 1978). The significance of the north-trending dikes in central North Carolina lies with the local coexistence and overlap of the northerly and northwesterly trends. The northerly trends are characteristic of areas to the north (Virginia and Maryland), whereas the northwesterly trends are typical in the southernmost Appalachians (Alabama and Georgia). King (1961, 1971) described a regular change in trend, but there was a conspicuous void for the North Carolina area in his data. The new magnetic data suggest a discontinuity in trend instead of a regular change and imply two distinct ages for the dikes, corresponding to the northern and southern locations. The southern (northwest-trending) set extends from Alabama to northern Virginia, whereas the northern (north-trending) set begins at about 80° W. in eastern South Carolina and central North Carolina and continues northeast (fig. 9). North of Maryland the dikes bend to northeasterly trends. Much of Virginia, North Carolina, and eastern South Carolina contain both trends (overlapping patterns, fig. 9).

The abundance of dikelike magnetic anomalies in the Coastal Plain of eastern South Carolina continues the unusual concentration of dikes found in the immediately

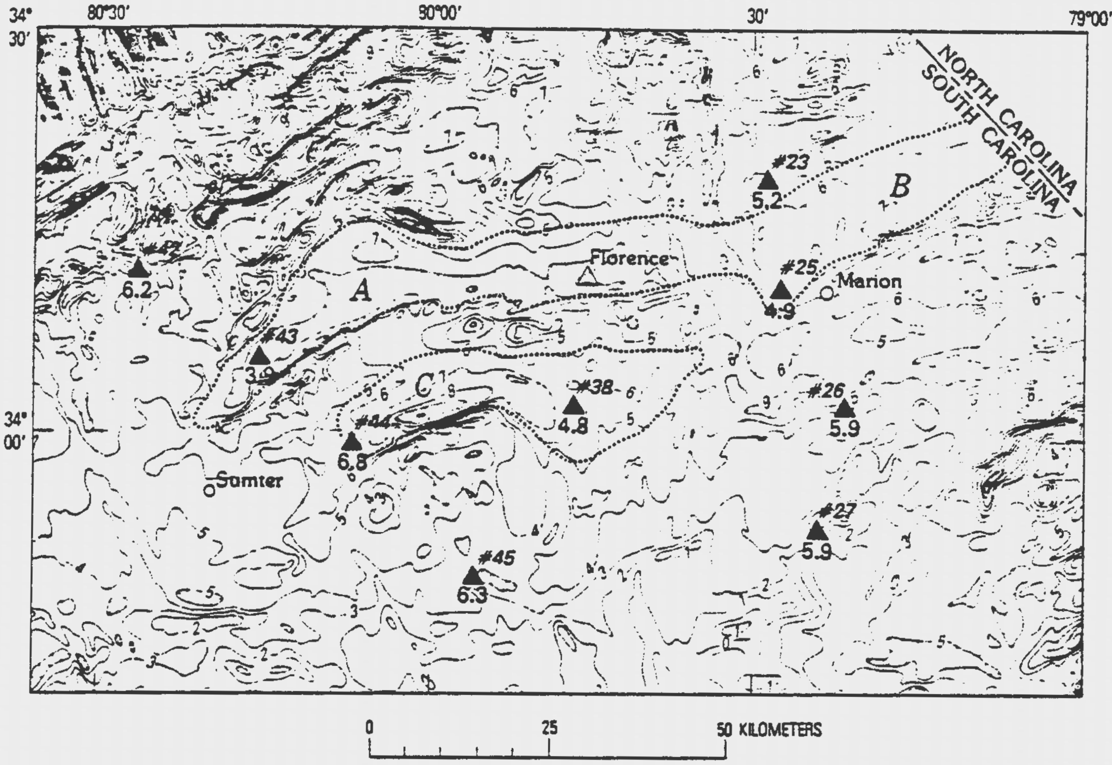


FIGURE 7.—Magnetic map of the Florence, S. C., area, showing magnetic lows that may be underlain by subsurface early Mesozoic basins (areas *A*, *B*, *C*, outlined by dotted lines). Probable Triassic-Jurassic rock recovered from two wells at Florence (open triangle). Sites of seismic-refraction measurements marked by solid triangles [seismic velocity of basement rocks indicated by value below triangles, given in kilometers per second (Woollard and others, 1957)]. Contour interval 100 nT.

adjacent Piedmont. The comparative lack of similar anomalies seen in the Coastal Plain of Georgia (pl. 1), however, is probably related to the similar lack of anomalies over the abundant dikes in the adjacent Piedmont of that area (Pickering and Murray, 1976). De Boer and Snider (1979) have shown that the apparent absence of anomalies there is owing largely to northwest flight lines but also to weaker dike magnetizations. Northwest-trending flight lines in Georgia are nearly parallel to average dike trends in the Piedmont and to the expected trends under the Coastal Plain. Contouring on aeromagnetic maps is usually strongly biased in favor of trends perpendicular to the flight lines, which in this case is the regional Appalachian trend.

It is reasonable to expect, therefore, that a density of diabase dikes similar to that found in the Piedmont exists in the Coastal Plain of Georgia but is not clearly shown by the aeromagnetic maps.

DIABASE SILLS AND BASALT FLOWS

Diabase and basalt, often associated with continental clastic rocks of presumed Triassic and Jurassic age or with Paleozoic marine sedimentary rocks, have been reported from more than 50 wells in the Coastal Plain in South Carolina, Georgia, Alabama, and northern Florida (Applin, 1951; Milton and Hurst, 1965; Milton, 1972; Barnett, 1975; Gohn and others, 1978). In spite of this abundance and the consistent anomalies produced by diabase and basalt in exposed basins, it is difficult to correlate their occurrence in these wells with magnetic anomalies. The magnetic maps of the Coastal Plain were searched for distinctive ring-shaped anomalies indicative of certain diabase sills or basalt flows, and several low-amplitude anomalies, each associated with a low-amplitude gravity high, were located: one near Jeffersonville, Ga., a second near Vidalia, Ga., and a third near Fairfax, S. C. (fig. 10). Magnetic depth estimates place both the Vidalia and Fairfax anomalies level with the base of the Cretaceous. Only the Vidalia anomaly appears to be identified by well samples (diabase in wells GGS 964 and GGS 190, fig. 10; Daniels and Zietz, 1978). The pre-Cretaceous depth control comes from wells near the Vidalia anomaly and from seismic-refraction measurements (Woollard and others, 1957, stations 59 and 60) within 25 km of the Fairfax anomaly. The low-amplitude Vidalia and Fairfax magnetic anomalies are discernible only because they lie in a low-gradient region. Nearby anomalies of other shapes may also be generated by diabase.

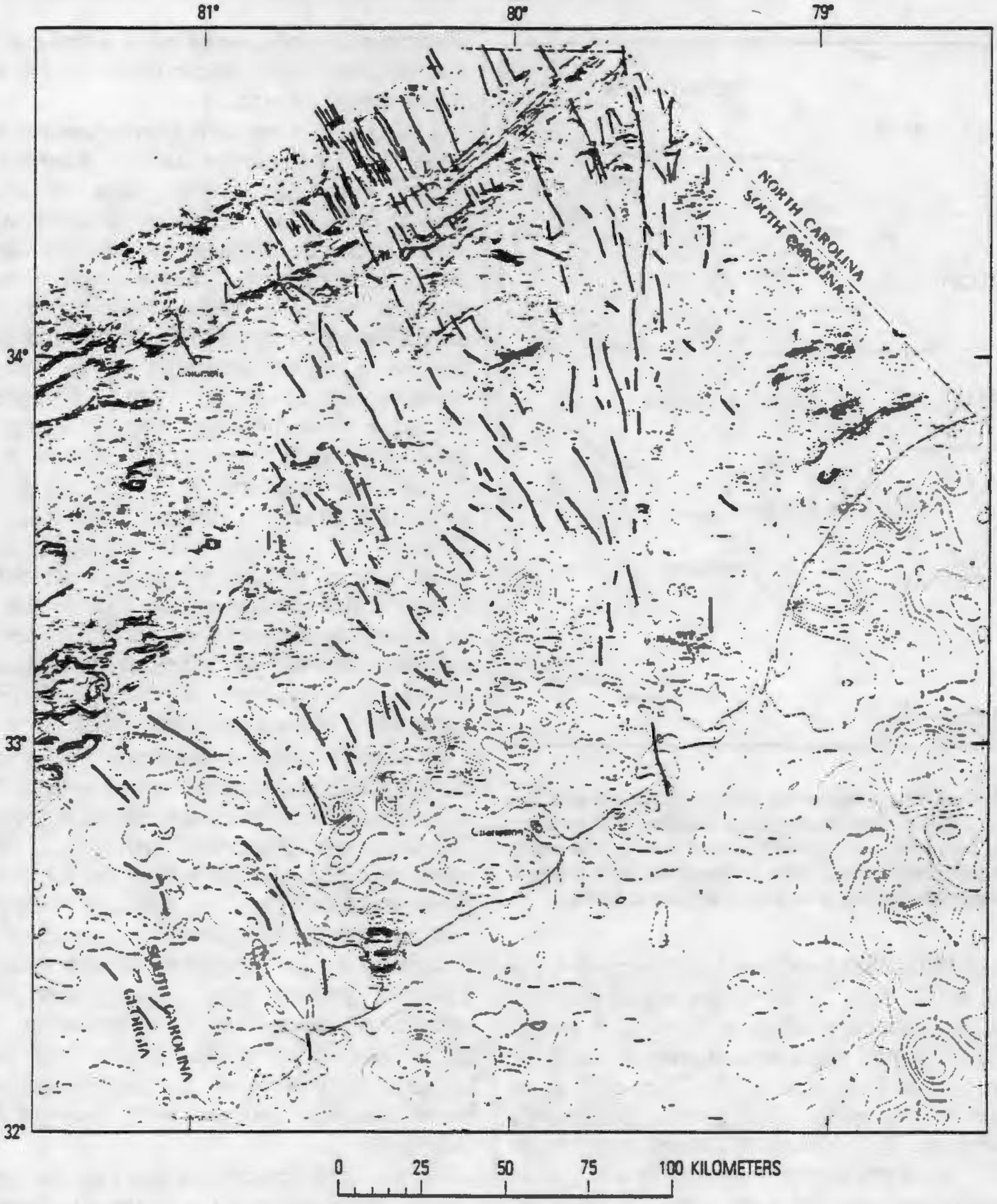


FIGURE 8.–Aeromagnetic map of the South Carolina Coastal Plain. Contour interval 100 nT. Heavy lines trace linear magnetic anomalies that are probably caused by lower Mesozoic diabase dikes. The anomalies interpreted as dikes were picked from larger scale magnetic maps with a 20-nT contour interval. Anomalies having amplitudes of less than 100 nT do not show well on this map.

The lack of magnetic anomalies near most of the wells from which diabase or basalt has been recovered may be due to the size, orientation, and depth of these bodies. Most are probably thin, nearly horizontal sheet structures, which typically do not generate large-amplitude magnetic anomalies, even though moderately magnetized, except at sharp vertical edges. The magnetic intensity of a test model chosen to approximate the dimensions and magnetic properties of the basalt recovered in the Clubhouse Crossroads drill holes near Charleston, S. C. (Phillips, 1983), was calculated to test this effect. The model consisted of a horizontal sheet of basalt 255 m thick at a 775-m depth with 3.5 A/m (amperes/meter) magnetization. Only about 15 nT is produced at a level equivalent to 150 m above ground at the broad center of the model (Daniels and Zietz, 1978).

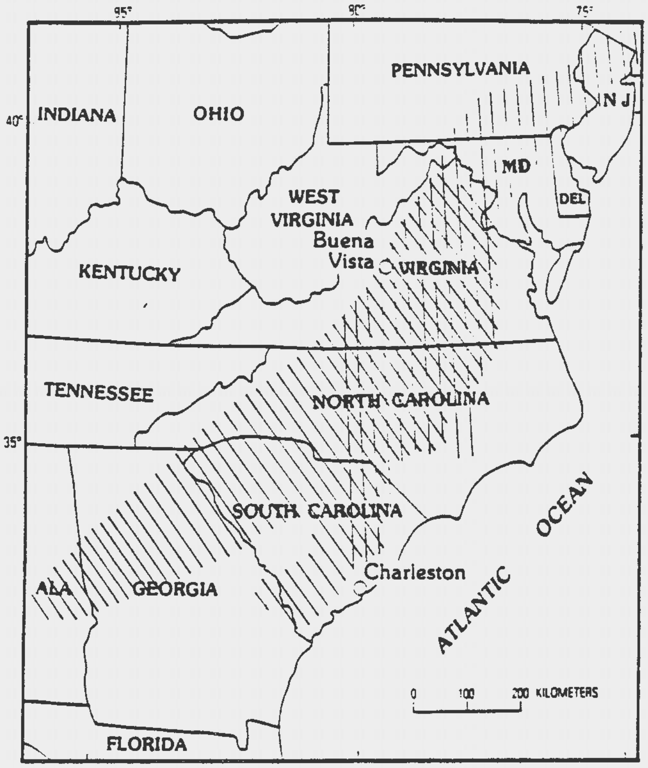


FIGURE 9.—Map of the Southeastern Atlantic States showing two provinces of lower Mesozoic diabase dikes classified on the basis of dike trends. Both trends are present in area of overlap. Dike trends in Virginia and the Carolinas largely determined from magnetic maps. Dike trends elsewhere from King and Beikman (1974).

Anomalies of 150 nT are produced at the vertical edges of the sheet model, but a 255-m vertical edge is probably not typical for a diabase sill or a basalt flow except where faulted. Tapered edges seem more reasonable for basalt flows. Broad anomalies of 15 nT are difficult to discriminate among anomalies of several hundred nT typically produced by contrasts in the crystalline basement, and in fact there does not seem to be a magnetic anomaly clearly associated with any part of the basalt at Charleston.

Features of Possible Early Mesozoic Age

MAFIC INTRUSIVE ROCKS

Three types of mafic rock seem to be present in the pre-Cretaceous basement beneath the Coastal Plain. Lower Mesozoic diabase sills, dikes, and basalt flows have already been discussed. A second type of mafic rock is represented by elongate magnetic anomalies and associated gravity anomalies oriented parallel to magnetic trends in the nearby Piedmont province. These anomalies extend from Alabama near the Fall Line to the vicinity of Cape Fear, N. C. (figs. 11, 12). The Piedmont anomaly trends indicate that the source rocks may be folded mafic metamorphic rocks in an extension of the Piedmont terrain.

A third type of mafic rock is represented by a series of large-amplitude circular or oval magnetic highs and closely matching gravity highs of equally large amplitude (figs. 11, 12). Some of these appear to cut across anomalies of the second type and may, therefore, be younger, perhaps of Mesozoic age. Some are alined along a northerly trend, especially a set of four anomalies off the coast of South Carolina (figs. 11, 12). Several magnetic anomalies of the third type are characterized by an outer ring of higher intensity around a lower intensity core. The most completely developed ring is found on the anomaly at St. Helena Sound near Beaufort, S. C. The St. Helena Sound anomaly is similar in size and shape to an anomaly at Concord, N. C., produced by a gabbro pluton with an outer ring of syenite, which suggests that the ring-shaped anomalies may indicate alkalic-mafic complexes. In general, anomalies of the third group are interpreted as unmetamorphosed mafic-ultramafic intrusive complexes consisting largely of gabbroic rocks (Popenoe and Zietz, 1977; Daniels and Zietz, 1978).

No direct evidence of the age of emplacement of the mafic rocks of the third group is available. Comparison with similar occurrences can suggest approximate ages. The Concord pluton already mentioned is the largest of many gabbroic plutons within the Charlotte belt of North and South Carolina. Although these gabbros currently cannot be dated directly, contact relations show that many are contemporaneous with middle to upper Paleozoic granitic plutons, but there is no direct evidence of Mesozoic age (Speer and others, 1980). Most of the Coastal Plain anomalies differ from the Charlotte belt plutons (other than the Concord pluton) by their larger diameter and the more common ring-shaped anomalies.

Circular mafic plutons as large as the largest in the Coastal Plain occur in the continental interior (as inferred from anomalies on regional magnetic and gravity maps). Two examples in the Mississippi embayment region lie in an environment similar to the Charleston area. One anomaly is associated with exposed alkalic igneous rocks at Magnet Cove, Ark. (Erickson and Blade, 1963). Preliminary lead-alpha measurements on a nepheline syenite dike associated with the complex gave dates of 178 and 184 million years (Jurassic) (Erickson and Blade, 1963). The second example is the Bloomfield anomaly, of possible Mesozoic age, near New Madrid in southeast Missouri, one of several inferred mafic plutons in the region associated with a buried rift system (Hildenbrand and others, 1977).

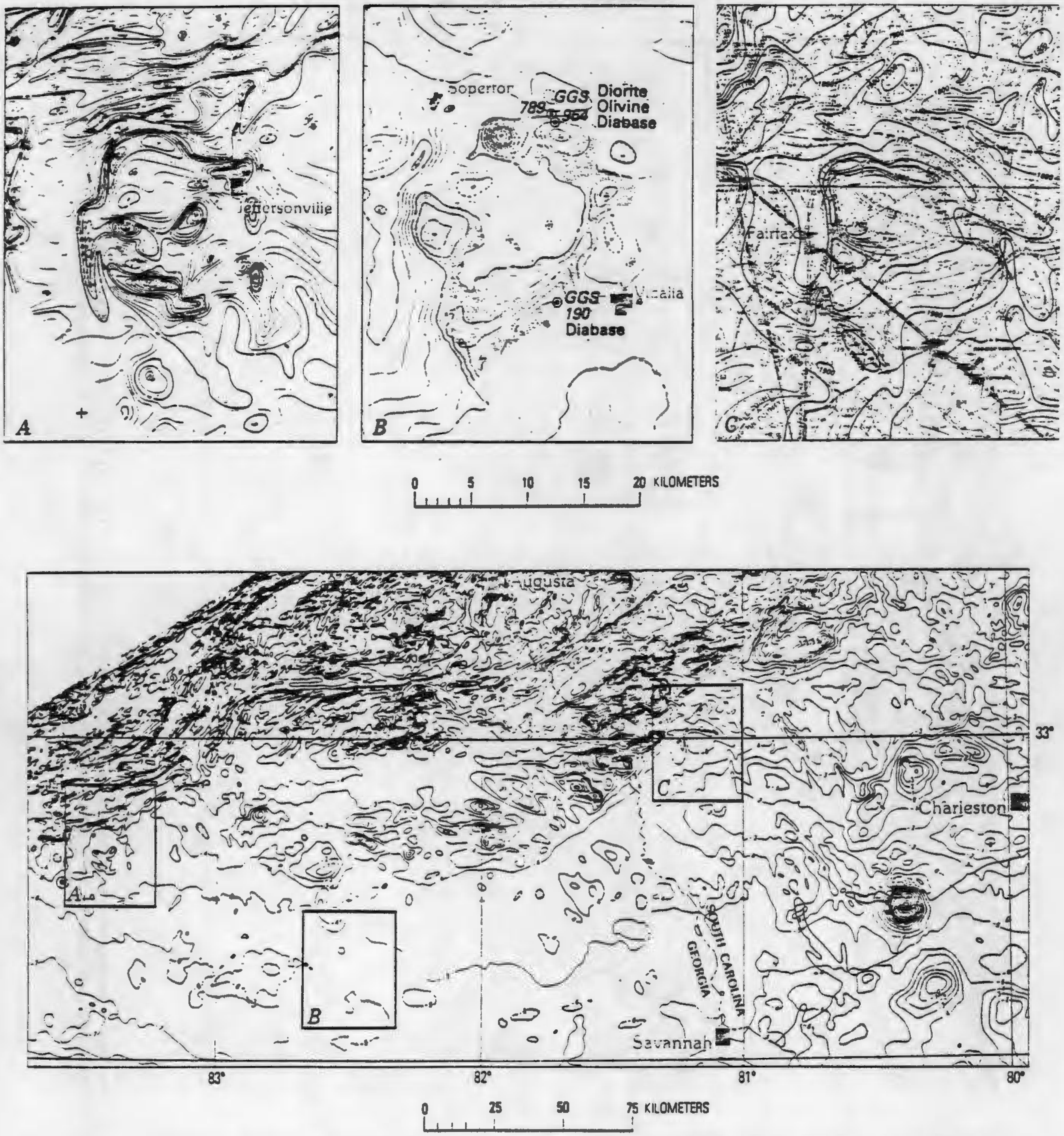


FIGURE 10.–Detailed aeromagnetic maps showing features interpreted as subsurface lower Mesozoic diabase sills (shaded areas in *A*, *B*, and *C*). *A*, Jeffersonville, Ga.; *B*, Vidalia, Ga.; *C*, Fairfax, S. C.; *D*, index aeromagnetic map. Basement rock types from oil tests shown in *B*.

One other example of a large circular mafic intrusive body occurs in the opposite direction, on the edge of the African Coastal Plain at Freetown, Sierra Leone. This location was not as distant in the early Mesozoic, prior to continental separation (Bullard and others, 1965), as it is now. The Freetown layered mafic intrusive body is only partly exposed, but, on the basis of the shape of the gravity anomaly, it is estimated to be circular in outline

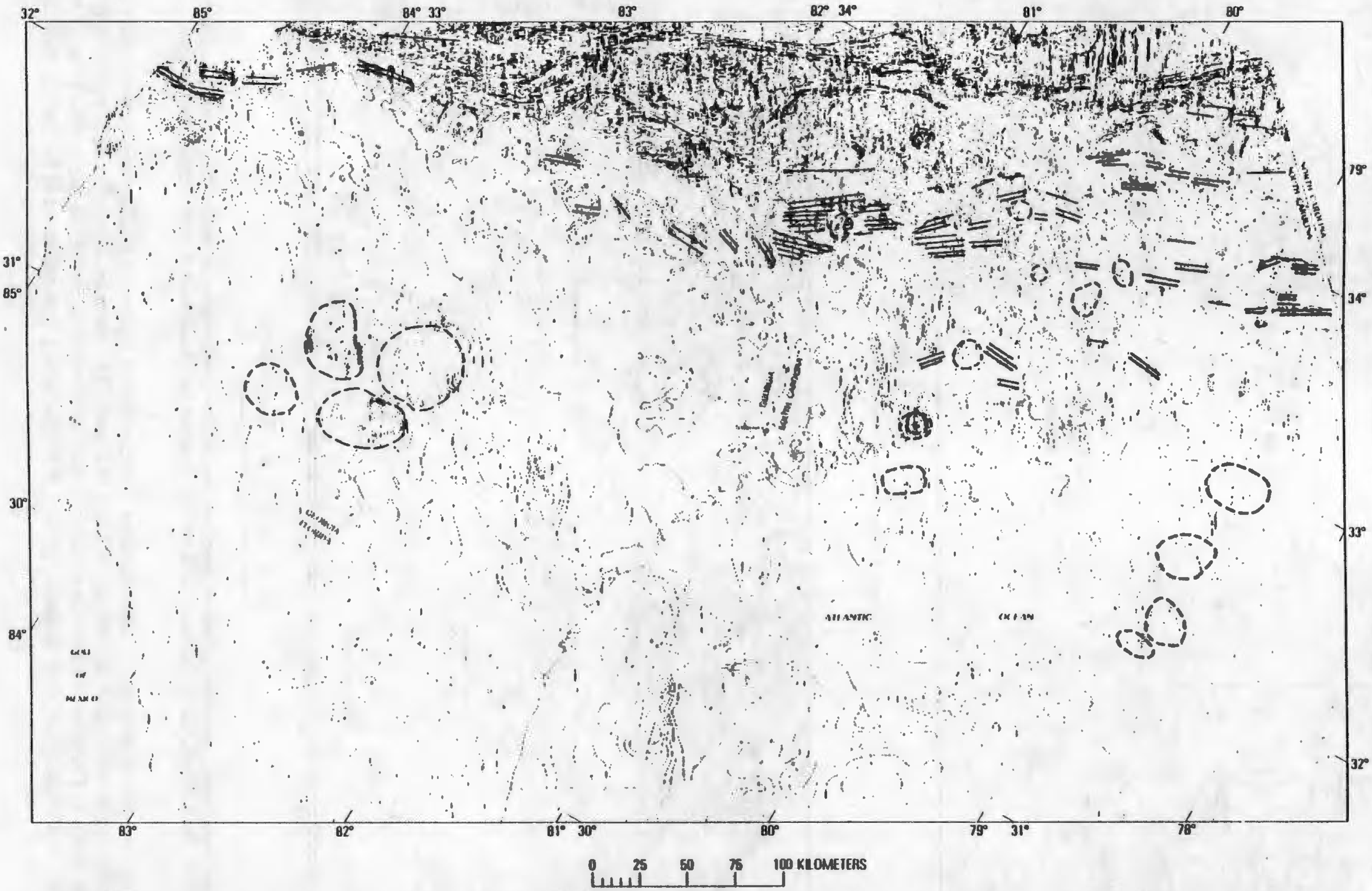


FIGURE 11.–Aeromagnetic map of the Coastal Plain region of the Southeastern United States showing anomalies that may be produced by subsurface mafic rocks. Anomalies marked by lines are thought to reflect deformed mafic metamorphic rocks. Dashed lines enclose roughly circular anomalies interpreted to be cross-cutting gabbroic plutons. Contour interval 100 nT.

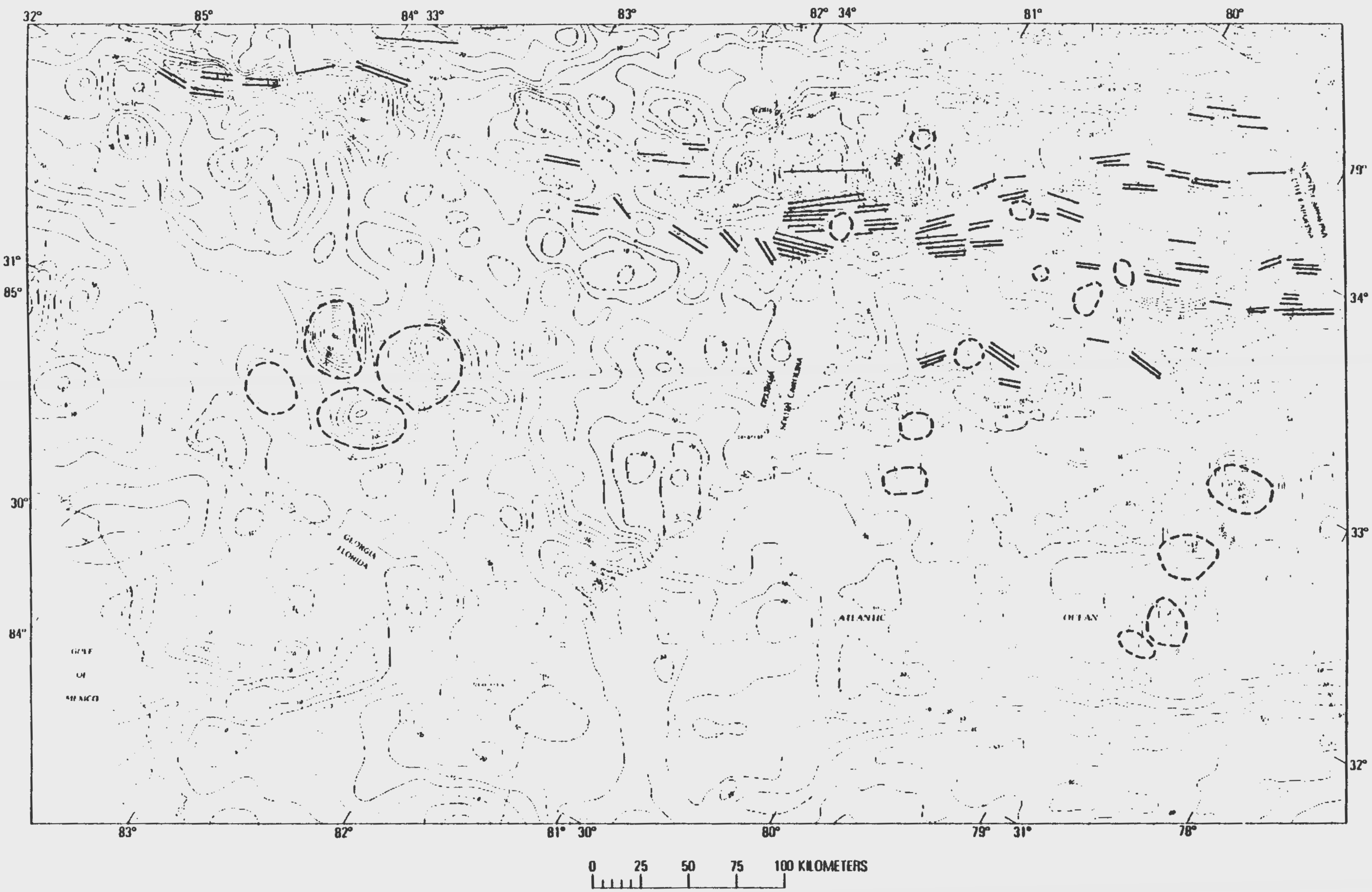


FIGURE 12.–Simple Bouguer gravity anomaly map of part of the Southeastern United States showing correspondence between magnetic interpretation (fig. 11) and gravity anomalies. Gravity data from Krivoy and Eppert (1977), Long and others (1972, 1976), Long and Champion (1977), Oglesby and others (1973), and unpublished data including U.S. Department of Defense gravity file. Contour interval 5 mGal (land), 10 mGal (ocean).

and to have a diameter somewhat larger than those of the Georgia anomalies (Baker and Bott, 1961). The age of the complex has been placed at early Mesozoic on the evidence of paleomagnetic and radiometric measurements (Briden and others, 1971). The occurrence in the African Coastal Plain suggests the geologic setting there is similar to that of the inferred mafic plutons in Georgia and South Carolina.

Circumstantial evidence, based largely on similarity of the anomalies in shape, diameter, and amplitude to anomalies in other regions, suggests that the circular magnetic-gravity anomalies in the Coastal Plain may be generated by lower Mesozoic mafic-ultramafic (alkalic?) complexes or layered mafic complexes.

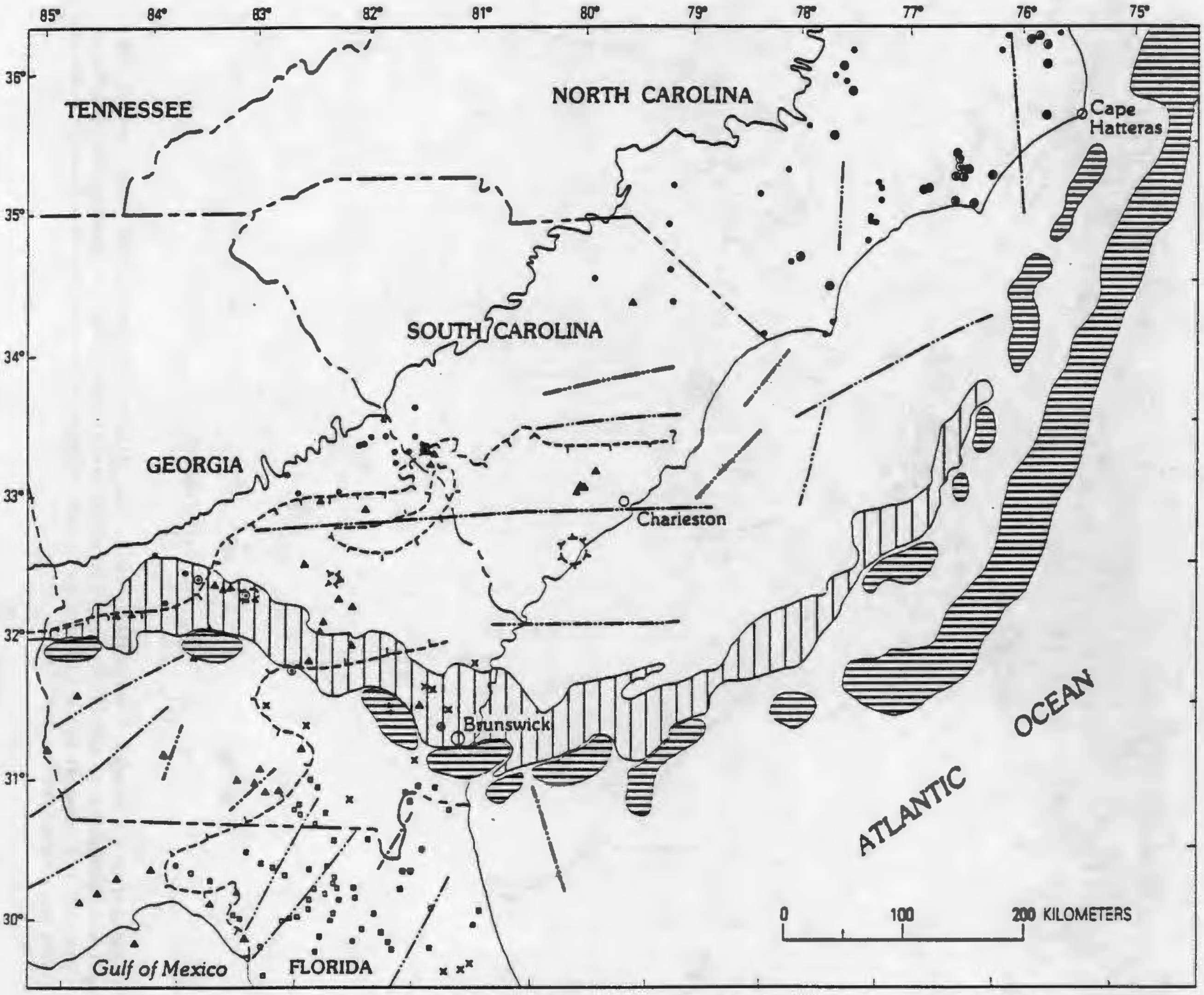
EAST COAST AND BRUNSWICK MAGNETIC ANOMALIES

The tectonic significance of the East Coast magnetic anomaly (Drake and others, 1968; Taylor and others, 1968) has long been recognized, but the origin is still debated. Taylor and others (1968) used the term "East Coast magnetic anomaly" to include a series of landward, parallel but not continuous magnetic highs and the associated magnetic trough that develop south of Cape Hatteras and cross the coastline at Brunswick, Ga. (fig. 13). Recent workers (Grow and others, 1979; Klitgord and Behrendt, 1979) reserve the name "East Coast anomaly" for the broad, continuous, and larger amplitude magnetic high that terminates close to the shelf edge at 31° N. and apply the term "Brunswick anomaly" to the parallel anomalies, about 1,100 km in length, that continue westward beyond the termination of the East Coast magnetic anomaly. This distinction between the East Coast and Brunswick magnetic anomalies is useful, as several factors suggest that the features are not of the same age even though they are spacially associated. First, the East Coast anomaly coincides with the westernmost edge of Jurassic oceanic crust, on the basis of seismic-reflection data (Klitgord and Behrendt, 1979), whereas the Brunswick anomaly is underlain by crust which is largely continental or transitional in nature (Dillon and others, 1983). Second, the Brunswick anomaly on land is associated with a variety of pre-Cretaceous basement rocks. These include rhyolitic volcanic and pyroclastic rocks near the Georgia coast, granite, probable lower Mesozoic red beds and diabase, and rocks characteristic of the Piedmont (schist, biotite gneiss, granodiorite) near the inner edge of the Coastal Plain. The Brunswick anomaly cannot be related to all these rocks. Further, the anomaly cuts across the trend of the subsurface South Georgia rift (fig. 13), which would tend to rule out a Mesozoic age. The Brunswick anomaly appears to be generated by a structure situated beneath all these rocks, because it does not conform to the distribution of any of these groups. Klitgord and Behrendt (1979) calculated a depth of 2–3 km to the top of the source of this anomaly at the coastline, which places the source at about 0.5–1.5 km below the base of the Cretaceous. The Brunswick anomaly does bound, on their north, the distinctive, flat-lying, Ordovician to Devonian clastic rocks found in numerous wells in northern Florida and southeastern Georgia that may underlie Triassic rocks in southwestern Georgia (Applin, 1951; Bridge and Berdan, 1951; Carroll, 1963; Barnett, 1975). On the basis of palynological evidence, these rocks were separated from the Alabama Valley and Ridge rocks by about 7 degrees of latitude more during the Silurian than they are now (Cramer, 1971). This suggests that a Paleozoic suture between North American rocks and a Florida microcontinent lies somewhere north of the Florida Paleozoic rocks and that the Brunswick magnetic anomaly may mark the position of a structure associated with this suture (Nishenko and Sykes, 1979). Evidence supporting the suture interpretation can be seen by comparing the trends of long-wavelength magnetic anomalies (generated by deep crystalline basement) on either side of the anomaly. North of the Brunswick anomaly the trend is generally east-west, whereas northeast trends predominate south of the anomaly (fig. 13; pl. 1). This suggests that two terrains having different orogenic imprints have been juxtaposed and welded together.

LINEAR FEATURES AND FAULTS

The parallel alinement of numerous individual linear magnetic anomalies into long curvilinear traces is a common feature of the aeromagnetic maps of the Piedmont south of Virginia. The association of some individual anomalies with mylonitic rocks (Daniels, 1974; Casadevall, 1977) led Hatcher and others (1977) to propose an eastern Piedmont fault system along one of these alinements. This and other curvilinear magnetic alinements in the Coastal Plain (Daniels and Zietz, 1978) are probably pre-Mesozoic tectonic features.

Linear magnetic gradients are also abundant on the aeromagnetic maps of the Coastal Plain, especially in the region near the Savannah River, and are largely associated with pre-Cretaceous basement here interpreted to be lower Mesozoic. Our interpretation of lineaments that may be significant is shown in figure 14. Some of these linear gradients may be produced by pre-Mesozoic basement faults, and some of these may have been reactivated during Mesozoic rifting. There are undoubtedly many faults which are not expressed in the magnetic maps. The association of the Orangeburg scarp with one of these gradients has prompted speculation that a basement fault has exerted structural control on the scarp (Popenoe and Zietz, 1977). The alinement of the scarp (*A–A'*, fig. 14) (Winkler and Howard, 1977)



EXPLANATION

- Foliated crystalline rocks
- Granite, granodiorite, and diorite
- Felsic volcanic and pyroclastic rocks
- Undeformed Paleozoic sedimentary rocks
- Lower Mesozoic red beds, basalt, and diabase

EAST COAST AND BRUNSWICK ANOMALIES

- Magnetic high
- Magnetic low
- Trend of long-wavelength magnetic high
- Edge of Coastal Plain
- Edge of early Mesozoic rift—Hachures toward rift rocks

FIGURE 13.—Map showing relation between the Brunswick and East Coast magnetic anomalies and the subsurface early Mesozoic rift, trends of long-wavelength magnetic highs, and rock type in basement wells.

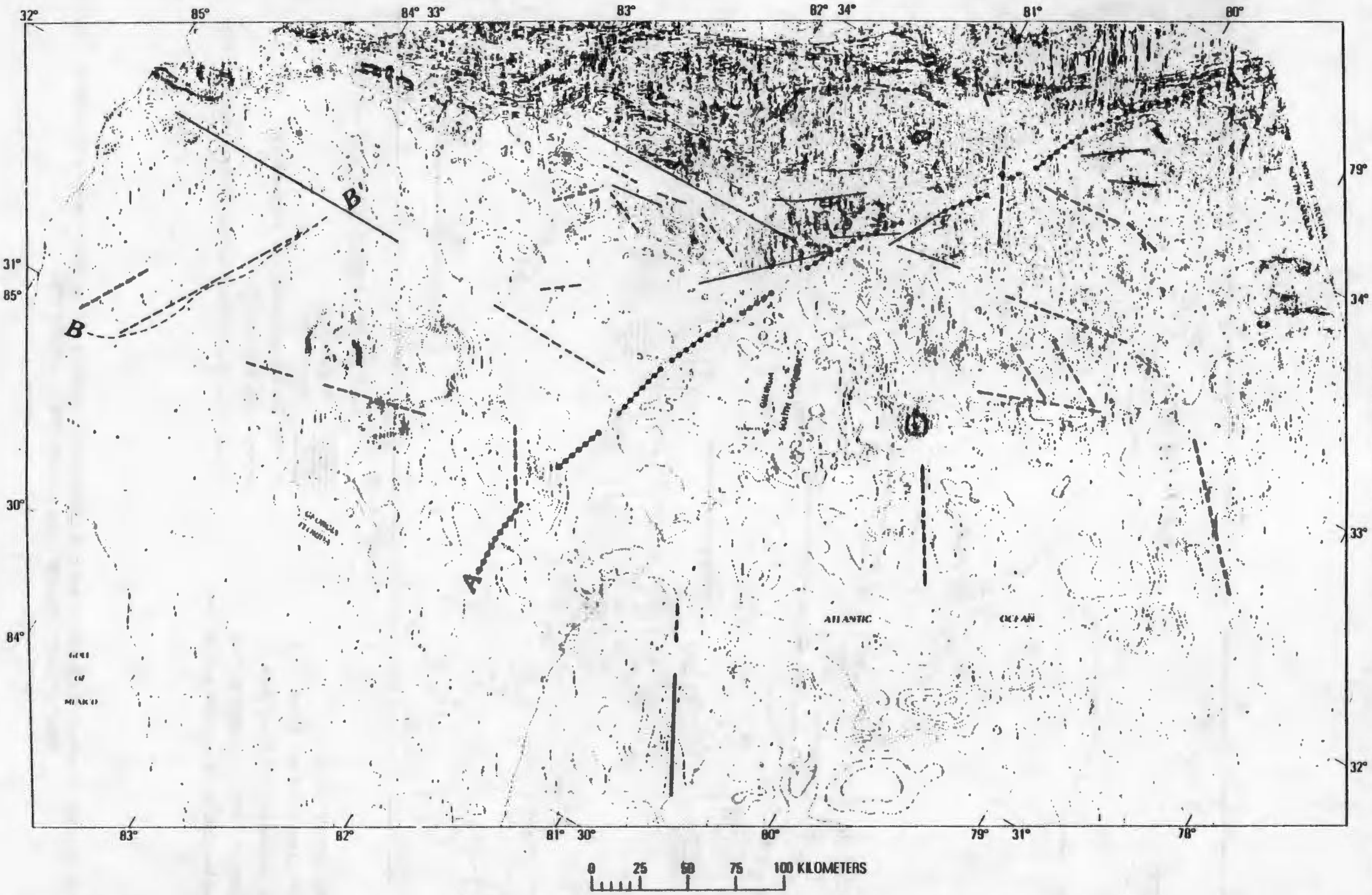


FIGURE 14. – Aeromagnetic map of the Coastal Plain region of the Southeastern United States showing some of the linear magnetic gradients and anomaly alinements that may be related to subsurface faults. Solid lines are judged more significant than dashed lines. Some of these features are more easily seen on maps with a smaller contour interval. The trace of the Orangeburg scarp is shown by a dot-dash line, *A–A'*, after Winkler and Howard (1977). Part of the contact between Eocene and younger rocks is shown by the short-dashed line *B–B'*, after Pickering and Murray (1976). Magnetic contour interval 100 nT.

with the magnetic gradient, however, is limited to a short segment near Fairfax, S. C., which is only a small fraction of the total length of the scarp.

In southwestern Georgia, a subtle linear gradient that divides areas of high and low magnetic intensity is approximately alined with the contact between Eocene and younger rocks (*B–B'*, fig. 14) (Pickering and Murray, 1976). This relationship suggests that basement structure, as indicated by the magnetic map, has influenced the distribution of Tertiary sediments.

CONCLUSIONS

The evidence from aeromagnetic, regional gravity, seismic-refraction, and deep-well data indicates that the Coastal Plain of Georgia and South Carolina is underlain by abundant lower Mesozoic rocks. Several, and perhaps many, individual basins compose a broad, complex rift system, the South Georgia rift, oriented roughly east-northeast and extending from the Gulf of Mexico to the Atlantic Ocean. This rift is filled with continental, subaerial clastic sedimentary rocks, basalt flows, and numerous interlayered diabase sills. North-trending and northwest-trending diabase dikes intrude both the basins and the flanking crystalline basement. In many respects, these subsurface basins are closely similar to exposed early Mesozoic basins within the Piedmont province of the Appalachian orogen. The major differences are scale and trend. The subsurface rift system is longer than and, at its widest point, four times the width of the largest exposed basin of the Appalachian orogen (Culpeper-Gettysburg-Newark basins combined). The trend and alinement of the South Georgia rift suggest an affinity more with the rift that preceded the opening of the Gulf of Mexico than with the exposed early Mesozoic basins along the Appalachian system.

Mapping the subsurface rift by means of the magnetic maps yields uneven results, owing in part to the highly variable magnetic contrast between the lower Mesozoic rocks and the flanking rocks. Most of the basin analysis in this paper is concentrated on a region of the inner (shallow) Coastal Plain on either side of the Savannah River because of favorable magnetic contrasts in that area. There qualitative and quantitative analysis indicates two interconnected basins that are partly separated from the main rift by a broad subcrop of crystalline (probably mostly mafic) basement. The thickness of nonmagnetic rock beneath the Cretaceous was estimated by subtracting the value for depth to the base of the Cretaceous from the value for the top of the magnetic sources. Isopach contours of the nonmagnetic rock (interpreted to be lower Mesozoic rift sediments) outline the two basins and show areas of maximum sediment accumulation. The Dunbarton basin, which is at least 1.0 km thick and has a northeast trend and probable southeast dip, seems similar to exposed basins. In contrast, the Riddleville basin is at least 2.2 km thick, trends east-west, and probably dips to the north; it appears closer in style to the main rift immediately to the south. The main rift may be as thick as 3.5 km near Statesboro, Ga. Well samples and linear northeast-trending magnetic anomalies indicate that highly magnetic Piedmont rocks flank the rift on the north. A few similar anomalies appear within the rift, which indicate possible Piedmont basement. Nonmagnetic rhyolitic volcanic rocks, granites, and Paleozoic sedimentary rocks flank and underlie the rift on the south, making magnetic discrimination of the south edge of the rift difficult. Sharp linear magnetic gradients partly bound the rift and inliers of crystalline rock and indicate basement faults active in the early Mesozoic.

Lower Mesozoic diabase dikes are clearly present in the basement in South Carolina. Owing to unfavorable flight-line direction and weaker dike magnetization, the dikes in Georgia are not detected by aeromagnetic surveys. In South Carolina, only northwest-trending magnetic anomalies, characteristic of the Alabama-Georgia region, are found west of 80° W. East of 80°, prominent north-trending anomalies, characteristic of more northern States, are mixed with the northwest-trending set. The Charleston earthquake epicentral zone is located near the western edge of the overlap zone. One set of north-south anomalies can be traced northward on magnetic maps continuously for 480 km. The existence of two dike sets suggests that two episodes of intrusion may have occurred.

Several circular, low-amplitude magnetic anomalies, thought to characterize certain diabase sills, are identified within the subsurface rift system.

Other types of major magnetic features are generated by rocks of uncertain age, which have not been penetrated by drilling. Intense circular magnetic-gravity anomalies are interpreted to be mafic plutons similar to but mostly larger than the mafic plutons that occur in the Charlotte belt. Comparison with large circular mafic plutons in the Mississippi embayment region and in Sierra Leone suggests that an early Mesozoic age is reasonable for some or all of these plutons. The circular anomalies in the Coastal Plain are considered to be distinct from a belt of elongated magnetic-gravity anomalies, which may be older, metamorphosed mafic rocks.

The largest magnetic feature of the Coastal Plain region is also the least understood. The Brunswick magnetic anomaly is actually a series of long-wavelength, elongate high-low anomaly pairs arranged in a broad S-shaped curve. The low is the dominant feature; it begins in the Atlantic Ocean, landward of and parallel to the East Coast magnetic anomaly. The anomaly crosses the coastline at Brunswick, Ga., and passes into Alabama where the magnetic data terminate. The anomaly cannot be explained in terms of the basement rocks returned from deep wells, because these rocks do not form a coherent group. The basement rocks in the path of the anomaly include felsic volcanic rocks, granites, schist, biotite gneiss, and lower Mesozoic rift rocks (red beds and diabase). The most significant feature of the Brunswick anomaly is that it acts as a division between two terrains of differing magnetic character. North of the anomaly the longest wavelength anomalies have an easterly orientation, whereas south of the anomaly a northeast trend is most characteristic at the same wavelengths. This relationship suggests that the Brunswick anomaly may be closely related to a Paleozoic suture between a Florida-South Georgia microcontinent and the North American continent. Thrusting resulting from the collision may have buried the rocks that produce the anomaly.

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