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The Origin of the Southeastern United States Continental Margin: Is it Volcanic or Non-Volcanic?

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ABSTRACT: It has been controversial whether the United States Atlantic margin, which developed during Mesozoic separation of Africa and North America, is a volcanic or non-volcanic rifted margin. To understand its nature, the basement images of multi-channel seismic profiles off the southeastern United States continental margin have been examined. One of prominent results is the presence of seaward-dipping reflector (SDR) wedges, the most diagnostic feature of volcanic rifted margins. Two sets of SDR wedges appear to exist here; one along the basement hinge zone ('the hinge SDR wedge') and another seaward of the East Coast magnetic anomaly ('the outer SDR wedge'). Seaward of the basement hinge zone, the lower crustal high-velocity body previously known as the 7.2 km/s layer and the underlying smooth Moho configuration are also observed. Based on the comparison of these basement images with the crustal structures of the well-known volcanic rifted margin, the southeastern United States Atlantic margin can now be characterized as a typical volcanic rifted margin.

INTRODUCTION

The United States (U.S.) Atlantic passive continental margin, which originated from separation of Africa and North America during Mesozoic continental breakup, is one of the best-studied continental margins in the world. However, lack of accurate information about the morphology and internal structures of basement beneath the rifted basin containing thick postrift sediment has resulted in significant contradictory interpretations about its early evolutionary history. Based on the early (1960s~1970s) multi-channel seismic (MCS) data of the U.S. Geological Survey together with corresponding gravity and magnetic modeling, many studies have suggested that the U.S. Atlantic margin includes highly-attenuated, block-faulted rifted continental crust (e.g., Klitgord et al., 1988). It is similar to non-volcanic rifted margin such as the Bay of Biscay (Montadert et al., 1979; Fig. 1). In contrast, Hinz (1981) first proposed that the U.S. Atlantic continental margin had a volcanic origin based on the observation of seaward-dipping basement reflectors from the central U.S. Atlantic margin. A volcanic rifted margin is characterized by thick crust produced by voluminous extrusive and intrusive magmatism during continental break-up (Mutter et al., 1988; Fig. 1).

Determination of whether the U.S. Atlantic rifted margin has a volcanic origin or not is essential for understanding its early evolution history as well as its subsequent subsidence history. In this study, most of the MCS lines crossing the margin's basins between 28°N and 33°N are reviewed to investigate the nature of crustal basement of the southeastern U.S. Atlantic margin (Fig. 2).

BACKGROUND

Along the southeastern U.S. Atlantic continental rifted margin, two major sedimentary basins, Carolina trough and Blake Plateau basin, are divided by the landward trend of the Blake Spur Fracture Zone (Fig. 2). They are also bounded by two prominent linear magnetic anomalies, the East Coast (ECMA) and the Brunswick (BMA) (Fig. 2). The ECMA has long been considered to mark the continent-ocean boundary, and the BMA has been interpreted to represent either a late Paleozoic suture zone or a Mesozoic features (Klitgord et al., 1988). However, their origins still remain controversial. A basement hinge zone, another major crustal marker, commonly represents the landward edge of the marginal sedimentary basins (Fig. 2). Seaward of the hinge zone, acoustic basement deepens rapidly over a ~30 to 50 km distance, causing poor-quality basement images. Thus, the attendant interpretation ambiguities for its basement characteristics have led to the idea of "thin rift-stage crust" between the hinge zone and the ECMA (e.g., Hutchinson et al., 1983).

Some major geological features are highlighted along the southeastern U.S. margin (Fig. 2): 1) change of trends of the ECMA and BMA; 2) neighbouring of narrow (60 to 80 km) Carolina trough and wide (350 km) Blake Plateau basin; and, 3) broadly distributed Jurassic

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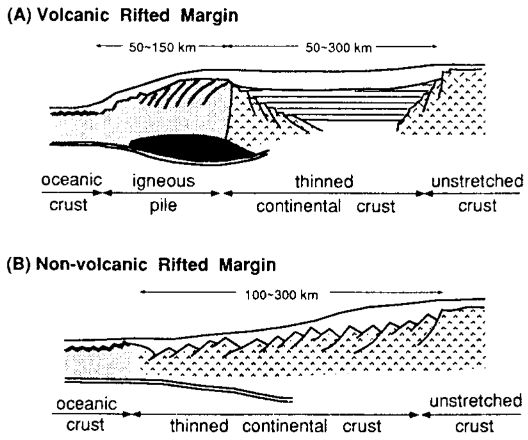

Fig. 1. Typical crustal differences and structural elements of volcanic and non-volcanic rifted continental margins (modified from Mutter et al., 1988). The most conspicuous difference between two rifted margin types is the presence of the thick igneous pile in (A) where both the seaward-dipping reflectors in the upper part and the high-velocity (7.0~7.5 km/s) lower crustal layer in the lower part exist.

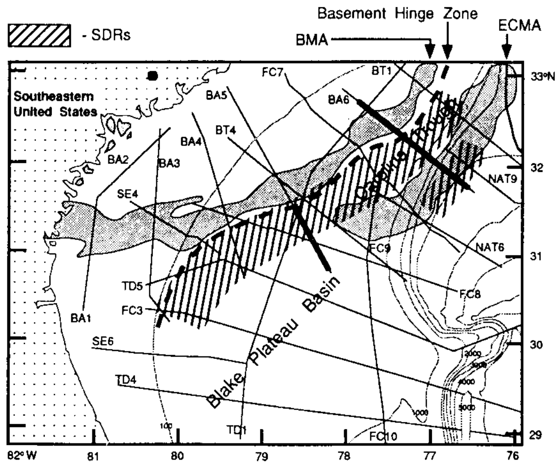

Fig. 2. Location map of existing MCS profiles showing seaward-dipping reflector (SDR) wedges with bathymetric contours in meters and selected magnetic anomalies along the southeastern United States continental margin. The landward part of the BMA(Brunswick magnetic anomaly) is not shown. Two sets of SDR wedges are observed; one along the basement hinge zone and the other seaward of the ECMA(East Coast magnetic anomaly). Location of the basement hinge zone north of 30°N is inferred from Klitgord et al. (1983, 1988) based on the magnetic depth estimation as well as the seismic control. A closed circle represents onshore drill sites where basalt/diabase layers with 184 ± 3 Ma age are intersected. Heavy solid lines along BA 4 and 6 profiles indicate locations of Figs. 3 and 4, respectively.

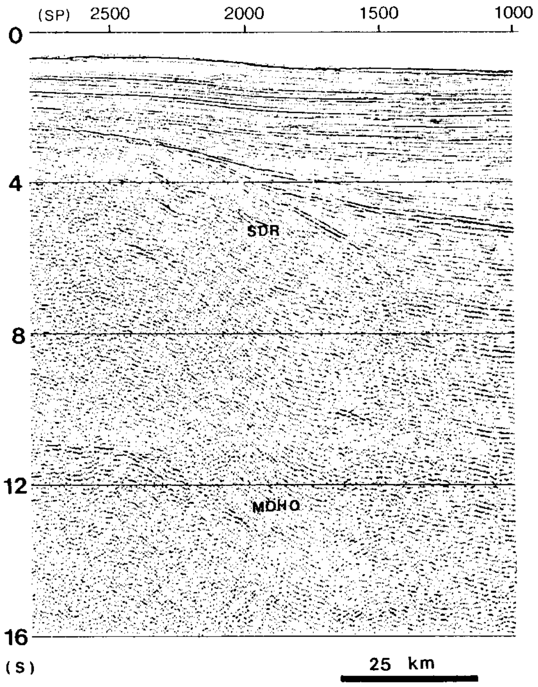

Fig. 3. Unmigrated stack of BA 4 with full 16 seconds (two-way travel time) record length. See Fig. 2 for location. It shows seaward-dipping reflectors (SDR) within the upper part of the basement and the Moho discontinuity (Moho) at the base of the basement. Note that one of the SDRs penetrates as deep as ~8 s.

volcanic layer beneath the postrift sediments ("J" reflector with 1×10^5 km^2; Behrendt et al., 1983). To examine these features the University of Texas Institute for Geophysics collected 1,200 km of deep-penetration MCS data in conjunction with ocean bottom instruments records from a large (10,800 in^3) tuned airgun source array with a 6-km-long receiver off the southeastern U.S. in 1988 (BA lines, Fig. 2; Austin et al., 1990; Oh et al., 1991; Oh, 1993). This experiment was the first attempt to collect simultaneous MCS and ocean bottom instruments data along the U.S. Atlantic margin.

The main advantage of BA data acquisition, compared with previous MCS lines with both shorter streamers and smaller energy, was the ability to apply the effective multiple suppression using frequency-wavenumber filtering and following inner trace muting (Oh et al., 1991). The resultant high-quality BA line's images of the basement structure have now allowed reinterpretation of the previous MCS data, using the BA data as a type of "ground truth". Also, the success of the BA imaging encouraged to reprocess selected portions of pre-BA lines, which significantly improved their basement images (Oh, 1993).

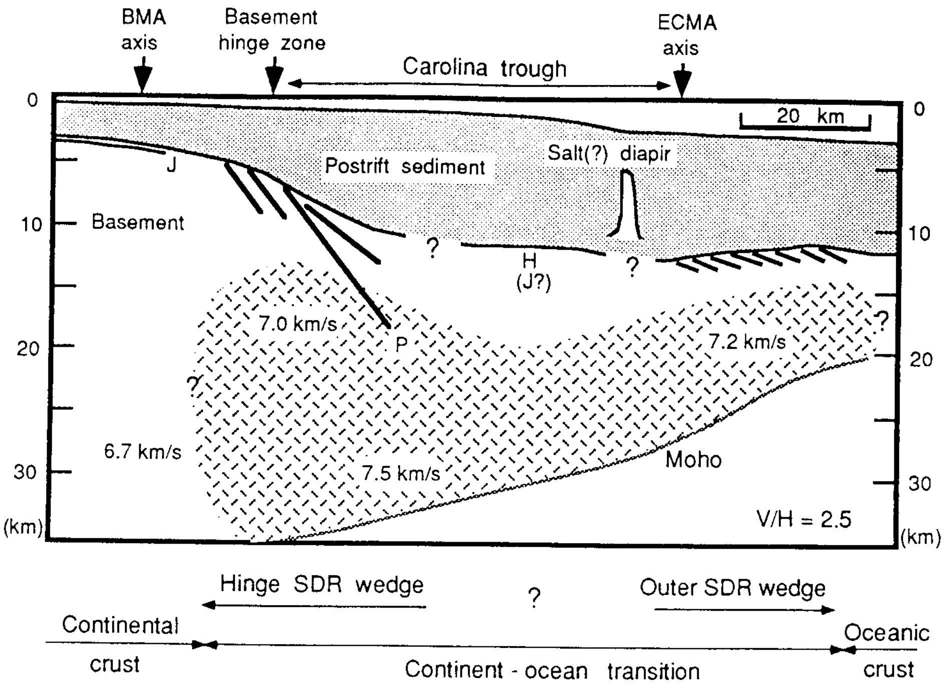

Fig. 4. Schematic cross-section of specific crustal features along BA 6. See Fig. 2 for location. The high-velocity (>7.0 km/s) lower crustal layer below the hinge SDR is inferred from Holbrook et al. (1994), whereas "7.2 km/s" layer below the outer SDR is from Tréhu et al. (1989). BMA axis: the minimum of the BMA. ECMA axis: the maximum of the ECMA. The "P" reflector : a deep-penetrating SDR within the hinge SDR wedge. Moho : the Moho discontinuity. Basement hinge zone : the landward limit of the hinge zone from Klitgord et al. (1983, 1988). A basement high is observed on the seaward edge of the outer SDR wedge, although not on adjacent profile NAT 9 (Fig. 2). It is problematic that the "J" reflector erupted at 184 ± 3 Ma extends seawardly across the basement hinge zone to the "H" (i.e., horizontal) reflector as the top of the SDR wedge.

TWO TYPES OF SEAWARD-DIPPING BASEMENT REFLECTORS

The most remarkable observation of BA and older MCS data is the almost ubiquitous occurrence of seaward-dipping reflectors (SDRs) seaward of the basement hinge zone from 30° to 33°N (Fig. 2). South of 30°N where BA lines do not cover, the presence of SDR is not clear due to poor basement images in older MCS data. The SDRs showing either linear or gentle upward convexity form a wedge without any distinct basal reflector (e.g., Fig. 3). Also, SDRs clearly persist after migration (Oh et al., 1991). It appears that two sets of SDR wedges exist : one along the basement hinge zone ('the hinge SDR wedge') and another seaward of the ECMA at the seaward edge of the Carolina trough ('the outer SDR wedge') (Fig. 2). The basement image of transition zone between the two wedges is very poor, even along BA 6, since it is obscured by reverberations from overlying flat Mesozoic carbonates. It is possible that two sets of SDR wedges are a single continuous entity, but they are clearly distinguishable by their seismic characteristics, location, thickness and depth of burial (Oh, 1993). Images of the outer SDR wedges are commonly weaker than their landward counterpart probably due to the thick overlying sediments as well as the increased water depth.

Fig. 4 represents a simplified cross section across the Carolina trough using the BA 6 images integrated with the velocity models by Tréhu et al. (1989) and Holbrook et al. (1994). It can be interpreted that these SDR wedges have an extrusive volcanic, rather than sediment depositional, origin on the basis of : 1) the velocity structure (6.1~7.1 km/s); 2) the presence of one SDR penetrating as deep as ~9 s (~20 km depth) where the high velocity (>7.0 km/s) lower crustal layer lies (e.g., "P" reflector in Fig. 4); and 3) most of all, similar patterns with dipping reflectors from known volcanic rifted margin, especially along the North Atlantic Tertiary volcanic margins (Eldholm and Grue, 1994).

In fact, SDRs have been identified along the other U. S. Atlantic continental margins since Hinz's (1981) first observation (Emery and Uchupi, 1984; Benson and

Doyle, 1988; Sheridan et al., 1993). Like the SDRs of the study area, they can be classified into two groups based on their locality : one between the basement hinge zone and the ECMA and the other between the ECMA and the landward limit of well-defined oceanic basement. Furthermore, their reflection configuration suggests that each SDR group may correspond to the hinge SDR wedge or the outer SDR wedge, as shown in this study, respectively. Nonetheless, no previous interpretations have suggested the existence of two sets of SDR wedges along the same MCS line, as in this study.

Existence of the two sets of SDR wedges along the U.S. east coast does not appear to be unusual. Multiple SDR wedges also occur along the North Atlantic Tertiary volcanic margins where they are commonly associated with identifiable seafloor spreading magnetic anomalies (e.g., Skogseid and Eldholm, 1987), while only the ECMA can be associated with the SDR wedges across the U.S. Atlantic margin. Another difference is that the higher seismic velocities (6.1~7.1 km/s; Holbrook et al., 1994) of the SDR wedges beneath the Carolina trough than those (4~6.5 km/s; Mutter et al., 1988) of North Atlantic SDR wedges which is probably related to thicker sediment overburden (i.e., 5~10 km vs 1~2 km, respectively).

EVIDENCE FOR THE VOLCANIC MARGIN

In comparison with a "typical" volcanic margin's crustal structure (Fig. 1), the basic components of volcanic rifted margin can be identified along the southeastern U.S. continental margin.

Three-fold zonal structure

Three zones appear to be characteristic along a volcanic rifted margin : an inner zone with sills and dikes, a central 50~100 km wide zone of SDR, and an outer zone of crust produced by "normal" seafloor spreading (Mutter et al., 1988; Fig. 1). In the southeast Greenland margin, down-flexed basement underlying a continental flood basalt is also observed in the inner zone (Larsen and Jakobsdóttir, 1988). The SDRs, first recognized by Hinz (1981), are the most diagnostic features of volcanic rifted margins. They have been shown by drilling to consist of lava flows and interbedded volcaniclastic sediments erupted in a subaerial to shallow-marine environment (Roberts, Schnitker, et al., 1984; Eldholm, Thiede, Taylor et al., 1987). This study documents two sets of SDR wedges along the southeastern U.S. continental margin (Fig. 2).

However, an SDR by itself does not necessarily prove the existence of a volcanic rifted margin. The reason is that similar seismic expressions have been reported in other geological environments, e.g., on the Kerguelen Plateau (Coffin and Eldholm, 1992), although SDRs within the basement in there are interpreted as volcanics. Thus, the inner and outer zones are necessary components of volcanic rifted margins (Fig. 1). Seaward of the outer SDR wedge off the Carolina trough lies presumed normal oceanic crust as the outer zone (Fig. 4). They are located within the Jurassic Magnetic Quiet Zone where the prominent seafloor spreading magnetic anomalies are not shown. However, its top of basement exhibits hyperbolic echoes which are typical for the uppermost oceanic crust layer 2 (Purdy and Ewing, 1986). A basement high is observed on the seaward edge of the outer SDR wedge along BA 6, although not on adjacent profile NAT 9.

In the southeastern U.S. margin, the wide-spread prominent two-cycle "J" reflector is observed on MCS data landward of the hinge SDR wedges (Dillon et al., 1983; Fig. 4). This horizon is correlated with a basalt/diabase layer encountered in onshore drill holes where a minimum thickness of 256 m is recorded (Fig. 2; Gottfried et al., 1983). Because of its large areal extent, "J" erupted at 184 ± 3 Ma has been compared to continental flood basalts (Behrendt et al, 1983). In the Hf/3-Ta-Th diagram, the field for the sampled "J" volcanic rocks is largely coincident with that of the lower andesitic/dacitic series underlying the SDR wedge of the Vøring Plateau at Ocean Drilling Program Site 642, indicating that both were strongly affected by crustal contamination (Gottfried et al., 1983; Viereck et al., 1989; Oh, 1993). This chemical analysis implies that "J" was not emplaced during early seafloor spreading, but erupted onto the continental crust earlier during rifting. Therefore, it is believed that the extensive subsurface volcanic layer "J" can represent the inner zone of the southeastern U.S. volcanic rifted margin.

Lower crustal high-velocity layer (or "7.2 km/s layer")

The existence of a thick plutonic body with the velocity of >7.0 km/s beneath the SDRs has been confirmed by the analysis of ocean bottom instrument records along BA 6 (Fig. 4; Austin et al., 1990; Holbrook et al., 1994), which is similar to the result of Tréhu et al. (1989). Previous refraction surveys have also detected these high-velocity bodies off the Carolina trough and Blake Plateau basin (Hersey et al., 1959) and beneath the Baltimore Canyon trough (Sheridan et al., 1993; LASE Study Group, 1986). However, no such body has been found landward of the basement hinge zone along BA 3 (Lizarralde et al., 1994), which is compatible with the results of seismic experiments off the central U.S. Atlantic margin (Sheridan et al., 1993). Thus, the occurrence of these "7.2 km/s layer" also suggests that they were emplaced during or after the Mesozoic rifting, since the Palezoic terrane does not extend into the basement hinge zone seaward along the U.S. east coast.

These high-velocity lower crustal bodies are also typical for Tertiary North Atlantic volcanic margins (Eldholm and Grue, 1994) as well as for many other large igneous provinces (e.g., Hawaii, Columbia River Basalts, and Ontong Java Plateau; Coffin and Eldholm, 1993). The "7.2 km/s layers" are also reported in some continental settings (e.g., at the depth of 30~35 km in continental shield; Meissner, 1986), except just beneath the non-volcanic rifted marginal basins. In general, the composition(s) and emplacement mechanism(s) of this high-velocity lower crustal plutonic layer are poorly understood.

Thick basement seaward of the basement hinge zone

Across the Carolina trough, two refraction studies reveal the existence of thick (<20 km) basement seaward of the basement hinge zone (Tréhu et al., 1989; Holbrook et al., 1992; Fig. 4). In previous gravity modeling, a two-step configuration in Moho beneath the basement hinge zone and the ECMA have suggested thinned (10 km) rift-stage crust between them (Hutchinson et al., 1983). Thick basement exhibiting a gradual change in depth to Moho matches well other North Atlantic volcanic rifted margins (Mutter et al., 1988; Fig. 1). Along the Galicia margin as a typical non-volcanic rifted margin, however, the basement landward of normal oceanic crust shows the thickness of 5~15 km (Boillot, Winterer et al., 1988).

Possible causes for voluminous magmatism

For the cause of such an intensive magmatism, the hot spot activity during the breakup of Pangea appears to be a prime candidate. Among current mantle plume models, two seem to be plausible for the occurrence of a voluminous magmatism : the passive asthenosphere upwelling model (Courtney and White, 1986) and the starting plume model (Griffiths and Campbell, 1990). Also, based on Morgan's (1981) proposed hot spot tracks, the following hot spots have been passed near the Central Atlantic during Mesozoic continental breakup : Trindade from 200 to 190 Ma, Ascension from 200 to 180 Ma, and Fernando from 170~160 Ma. Although a hot spot frame before 120 Ma is not well constrained, these hotspots may have been close enough to have initiated massive igneous activity generating the foundation of the southeastern U.S. volcanic rifted margin. Comparatively, the "convective partial melting model" by Mutter et al. (1988) for the outburst of magmatism which can occur only after initiation of seafloor spreading is against the existence of SDRs overlying continental crust.

Therefore, all the above observations support the view that the southeastern U.S. Atlantic rifted margin has the volcanic origin. Then, considering the SDR wedges are commonly formed symmetrically, one can expect the presence of conjugate SDR wedges along the Northwest Africa margin, as the supporting evidence. However, no studies have yet documented about their existence. The Northwest Africa margin has been investigated mainly through outcorps and drilling over onshore basins rather than MCS profiling, resulting in poorly-constrained basement structures (Ritz and Dellion, 1989).

Understanding of the origin of the southeastern U.S. Atlantic continental margin in the context of strong igneous activity can help resolve some major tectonic problems. Examples are the location of the continent-ocean transition beneath the SDR wedges (Oh, 1993), the cause of the formation of the basement hinge zone (Oh, 1993), the origin of the ECMA (Austin et al., 1990; Oh, 1993; Holbrook et al., 1994), the origin of the BMA (Austin et al., 1990; Oh et al., 1991; Oh, 1993; Lizarralde et al., 1994), and the sequential formation of the rifted basins during the opening of the Central Atlantic Ocean (Oh et al., 1994).

CONCLUSION

The basic components of volcanic rifted crustal structures have been detected and mapped along the southeastern U.S. continental margin: Two sets of SDR wedges, the hinge and the outer SDR wedges, lie in the central zone; the inner zone of extensive subsurface volcanic layer ("J") and the outer zones are present; the thick basement associated with high velocity (>7.0 km/s) lower crustal layer exists; and the gradual change in Moho depth occurs across the Carolina trough. Furthermore, from the broad occurrence of the SDR wedges overlying the high-velocity lower crustal layer along the U.S. east coast, it is believed that the entire U.S. Atlantic continental margin may be a volcanic margin.

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미국남동부 대륙주변부의 기원 : 화산성 혹은 비화산성?

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요 약 : 미국 대서양 대륙주변부는 북미와 아프리카 대륙의 중생대 분열의 산물로서 화산성 기원 혹은 비화산성 기원인가에 대해 논란이 있어 왔다. 이를 규명하기 위하여 미국 남동부 해안에서 채취한 다채널 탄성파 단면도에 나타난 기반암들의 영상을 조사하였다. 가장 핵심적인 탄성파 영상의 하나는 전체적으로 쐐기 형상을 보이는 해양방향의 경사반사층들(seaward-dipping reflectors; SDR)이다. 이들은 화산성 열개주변부의 상징적인 기반암 구조로 알려져 있다. 연구지역에는 2 개조의 해양경사층 쐐기구조가 존재하였다: 하나는 기반암 경첩대 (basement hinge zone) 부근이고 ('the hinge SDR wedge'라고 명명), 다른 하나는 미국 동해안 자기이상대(the East Coast magnetic anomaly)의 바다 쪽에 위치한다 ('the outer SDR wedge'라고 명명). 또한, 기반암 경첩대의 동쪽 지각에서는 『7.2 km/s 층』으로 알려진 높은 속도의 하부지각층과 함께 원만한 기복의 모호 불연속면 등이 관찰되었다. 이러한 기반암 구조와 잘 알려진 화산성 기원의 대륙주변부의 지각구조를 비교해 보아 미국 남동부 대륙주변부를 화산성 기원의 대륙주변부로 특징지었다.