Confirmation of the Carolina Slate Belt as an Exotic Terrane

Abstract. *An assemblage of Middle Cambrian Atlantic faunal province trilobites has been found in the rocks of the Carolina slate belt near Batesburg, South Carolina. Geologic and paleomagnetic data suggest that the Carolina slate belt and the adjacent Charlotte belt constitute an exotic terrane that was accreted to North America in early to middle Paleozoic time.*

Reconstruction of the history of ancient orogenic belts in terms of plate tectonics has motivated much geologic research during the past 15 years. Although tectonic models (*1*) involving the interaction of simple plate margins led to convincing explanations for some of the gross features of orogenic belts, many of the explanations were simplistic. For example, new evidence shows that a major part of the Cordilleran orogenic belt is made up of terranes that were accreted to the west side of North America during oblique plate convergence in Mesozoic and early Cenozoic time (*2*). Many of these terranes are truly exotic, having originated thousands of kilometers from their present locations. Recently, it was suggested that a major part of the Appalachian orogen is similarly composed of accreted terranes (*3–5*).

In the southern Appalachian Piedmont confirmation of the exotic character of terranes is difficult because fossils (which indicate biogeographic affinities) are scarce (*6*) and because most of the orogen is so strongly deformed and metamorphosed that paleomagnetic data (which provide information about rotation and paleolatitude) are difficult to interpret. A recent fossil discovery and further geologic studies reported here confirm that the southeastern part of the Appalachian Piedmont province includes an exotic terrane that in Cambrian time was located away from the North American craton.

Along the southeast side of the Carolina slate belt in South Carolina, a 5-km-thick sequence of metasedimentary rocks conformably overlies a 3-km-thick sequence of metavolcanic rocks (Fig. 1). The metavolcanic sequence, thought to have accumulated in association with a volcanic arc (*7*), consists predominantly of intermediate to felsic volcanic and volcaniclastic rocks and associated epiclastic deposits. Radiometric dating of metavolcanic rocks judged by us to be equivalent to this sequence indicates accumulation in Early to Middle Cambrian time (*8*). The metasedimentary rocks consist of complexly intertonguing sequences of mudstone, wacke, quartz siltstone, and quartz sandstone. Well-preserved sedimentary structures in the quartz-rich units suggest deposition in shallow water on a tidal shelf (*9*). The youngest rock unit in the metasedimentary sequence is a mudstone that has now yielded a diverse trilobite assemblage near Batesburg, South Carolina (Figs. 1 and 2).

Trilobite fragments have been found in several small outcrops of weathered hornfelsic mudstone adjacent to the northwest boundary of the Clouds Creek igneous complex. The best fossils come from localities along Highway 26 between 300 and 650 m southeast of the bridge across Clouds Creek in the northwestern part of the Batesburg quadrangle (USGS 7½′ topographic series). Hundreds of trilobite fragments have been found. In situ blocks at several stratigraphic levels are fossiliferous. The fragments show various degrees of strain, and some are silicified. Most of the trilobite remains represent *Paradoxides* (or *Acadoparadoxides*) (Fig. 2, a and b). Other trilobite remains include two types of agnostids, *Peronopsis* (Fig. 2, c and d) and *(?) Tomagnostus* (Fig. 2e), as well as two species of Agraulidae (Fig. 2, f and g). The age of the above assemblage is restricted to the upper two-thirds of Middle Cambrian time. The presence of *Paradoxides* (or *Acadoparadoxides*) and Agraulidae is characteristic of the Atlantic faunal province. Before this discovery, paleogeographic interpretation of the Carolina slate belt rocks depended on a single loose boulder containing two trilobite thoraxes and one attached pygidium questionably assigned to *Paradoxides* (*6*). Atlantic province trilobite faunas in the northern Appalachians are all in exotic terranes that were not integral parts of Cambrian North America (*3–5, 10*) and that are collectively assigned to the Appalachian Avalon zone (*11*). The Carolina slate belt has also been assigned to the Avalon zone (*11*) [or the Avalon terrane (*3*)] on the basis of

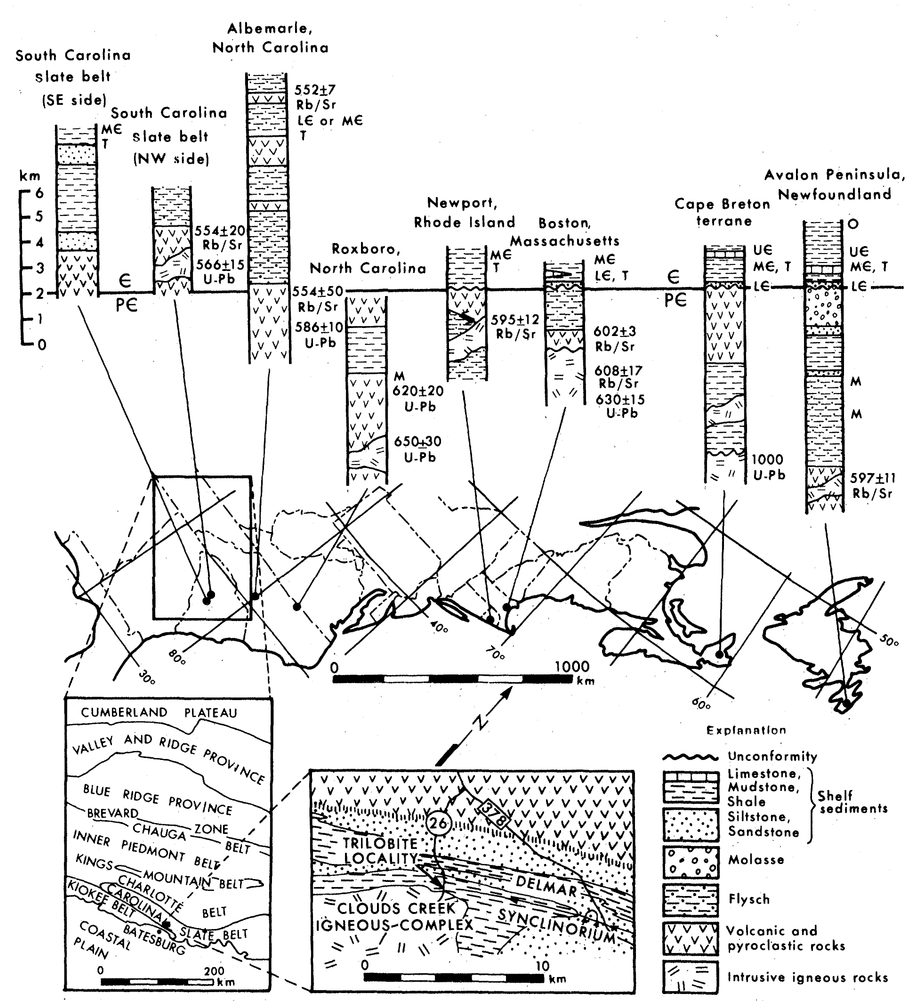

Fig. 1. Geology of the trilobite locality and comparison of Avalonian stratigraphic sequences in the Appalachian orogen. *T* indicates the occurrence of Atlantic faunal province trilobites and *M* the occurrence of Precambrian metazoans. Ages are in millions of years; Rb/Sr ages are whole-rock and U-Pb ages are from zircon analyses.

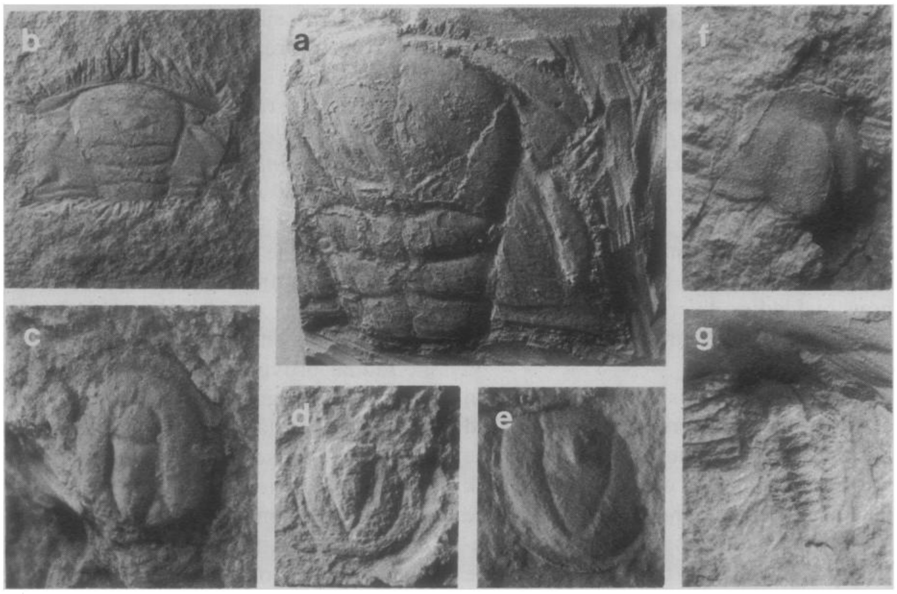

Fig. 2. Photographs of incomplete trilobite fossils from the South Carolina slate belt. (a and b) *Paradoxides* (or *Acadoparadoxides*) (×1.2), (c) *Peronopsis* (×7), (d) *Peronopsis* (×4), (e) *(?) Tomagnostus* (×7), (f) Agraulidae (×2.5), and (g) Agraulidae (×2).

the earlier trilobite discovery and because of an apparent lithologic similarity with other Avalonian terranes (*11, 12*).

Although the stratigraphic sequences in the Carolina slate belt are superficially similar to Avalonian sequences that have been described (*10, 12, 13*), a close comparison with some well-studied sections of Avalonian rocks in the northern Appalachians reveals some important differences (Fig. 1). The thick sequences of Cambrian felsic volcanic and volcaniclastic rocks in the Carolinas are not matched in these northern Appalachian sections, and neither limestone nor red and black shales characteristic of some of the northern Appalachian Avalonian sections are known in the Carolina slate belt.

Geochronological evidence indicates an early Paleozoic age for the first deformational event (D_1) to affect the South Carolina slate belt. Recent geologic studies in central South Carolina (*14*) indicate stratigraphic and structural continuity between the Carolina slate belt and the adjacent Charlotte belt (Fig. 1). The boundary between the two belts is a metamorphic gradient, and the same D_1 fabric elements are present in both belts. The intensity of D_1 deformation and M_1 regional metamorphism increases progressively to the northwest, and a 415-million- to 385-million-year-old (mid-Paleozoic) suite of late- to postkinematic plutons has been emplaced in the central and northwestern parts of the Charlotte belt (*15, 16*). The $^{40}Ar/^{39}Ar$ hornblende ages in the North Carolina Charlotte belt (*16*) and whole-rock K-Ar ages from low-grade slates in the North Carolina slate belt (*17*) suggest an Ordovician age for D_1. The effects of early Paleozoic deformation are also found in terranes farther to the northwest, including those with clear North American affinities (*3*). These relations are interpreted as indicating an early Paleozoic age for the initial accretion of the Carolina slate–Charlotte belt terrane. In contrast, middle and late Paleozoic ages are suggested for the first Paleozoic deformational event in the Avalonian terranes of Canada and New England, respectively (*5, 18*).

Along the southeast side of the Carolina slate belt, D_1 fabric elements have been overprinted by folds, cleavage, and regional metamorphism of a complex late Paleozoic "Alleghanian" or "Hercynian" orogen (*9, 19*). The character of these D_2 and D_3 fabric elements and the southeastward increase in the intensity of late Paleozoic deformation and regional metamorphism are here interpreted as indicating a late Paleozoic episode of collision with a still more easterly terrane [the African–South American plate? (*20*)]. Similar penetrative deformational effects of late Paleozoic age have been recognized in rocks assigned to the Avalon zone as far north as Rhode Island (*21*) and are locally present in Atlantic Canada (*22*).

Recent paleomagnetic studies of late Paleozoic igneous rocks in the southeastern Piedmont indicate little or no relative movement of the Carolina slate–Charlotte belt terrane relative to North America during late Paleozoic time (*23*). Conversely, in the north paleomagnetic data suggest a late Paleozoic northward movement of 15° to 20° in latitude of the Avalonian terrane relative to North America (*24*). Thus, rocks assigned to the Avalon zone in the northern and southern Appalachians may have different late Paleozoic displacement histories.

The paleontology, stratigraphy, deformational chronology, and displacement history of the Carolina slate–Charlotte belt terrane are sufficiently distinct to suggest that it may be exotic in relation to the Avalonian terrane(s) in the northern Appalachians. In accordance with the philosophical framework of the terrane concept (*2, 3*), we recommend that the Carolina slate–Charlotte belt terrane be viewed as a separate entity and that use of the terms Avalon zone and Avalonian terrane be discontinued in the southern Appalachians until the interrelations of rock sequences in the Appalachian orogen having Atlantic faunal province trilobites have been clarified. In keeping with the possible unique character of the Carolina slate–Charlotte belt terrane, we recommend that it be referred to as the Carolina terrane.

DONALD T. SECOR, JR.
SARA L. SAMSON
ARTHUR W. SNOKE
Department of Geology, University of South Carolina, Columbia 29208
ALLISON R. PALMER
Geological Society of America, Boulder, Colorado 80301

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Martian Gases in an Antarctic Meteorite?

Abstract. *Significant abundances of trapped argon, krypton, and xenon have been measured in shock-altered phases of the achondritic meteorite Elephant Moraine 79001 from Antarctica. The relative elemental abundances, the high ratios of argon-40 to argon-36 (≥ 2000), and the high ratios of xenon-129 to xenon-132 (≥ 2.0) of the trapped gas more closely resemble Viking data for the martian atmosphere than data for noble gas components typically found in meteorites. These findings support earlier suggestions, made on the basis of geochemical evidence, that shergottites and related rare meteorites may have originated from the planet Mars.*

Achondrites are differentiated meteorites believed to have formed by igneous processes on their original parent bodies. Three groups of rare achondrites, the shergottites, nakhlites, and chassignites (SNC meteorites) differ from other achondrites in several important aspects. They generally show a higher oxidation state, are unbrecciated, have more complex abundance patterns of rare-earth elements, and have distinctly different values of certain diagnostic chemical ratios such as K/U and La/W (*1*, *2*). The isotopic composition of oxygen also differs subtly among the SNC meteorites, other achondrites, and Earth (*3*). The igneous formation ages of all SNC meteorites are about 1300 million years, which is far younger than the ages of any other known extraterrestrial material (including lunar rocks), and implies geologically recent igneous activity (*4–6*). These properties have led several investigators to conclude that these meteorites must have formed on a geologically complex and relatively large parent body, most probably the planet Mars (*2*, *4*, *5*, *7–9*).

The Allan Hills (ALH77005) and Elephant Moraine (EET79001) shergottites were recently recovered from the Antarctic ice sheet (*10*). Both closely resemble two known shergottites (*4*, *8*, *11*, *12*). All shergottites have experienced impact shock, whereas the nakhlites show essentially no evidence of shock. The time of this shock event in all four shergottites is determined by their rubidium-strontium isochron ages to have been approximately 180 million years ago (*4*, *12*) and probably coincides with the time when the shergottites were ejected from their parent body by a large-scale impact. The EET79001 meteorite is composed of two distinct igneous lithologies and has abundant shock-glass veins and inclusions probably formed during the dated shock event (*11*, *13*). The compositions of shock glass differ in the two lithologies, probably reflecting the effects of localized melting (*11*).

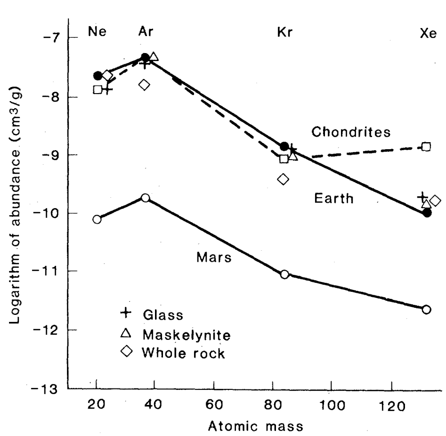

Fig. 1. Elemental concentrations of neon, argon ($^{36}Ar + {}^{38}Ar$), krypton, and xenon of the EET79001 meteorite. The values for Earth (●) are the atmospheric abundances divided by the mass of the Earth minus the core. The values for Mars (○) are the atmospheric abundances divided by the mass of Mars (*15*). The $^{36+38}Ar$ concentrations of chondrites typically lie in the range 0.5×10^{-8} to 100×10^{-8} cm^3/g, and we have arbitrarily normalized chondritic argon to the terrestrial value. Elemental ratios for chondrites (□) are from Mazor *et al.* (*24*). Those few achondrites that contain trapped gases either show an abundance pattern like that of chondrites (ureilites) or contain a helium- and neon-rich component implanted by the solar wind.

Our attempts to measure the potassium-argon age of EET79001 had indicated the presence of a trapped argon component. To determine the nature of these trapped noble gases, we measured the isotopic compositions by mass spectrometry of all five noble gases (helium, neon, argon, krypton, and xenon) in unirradiated whole-rock samples of both igneous lithologies of EET79001, in two shock-glass inclusions from the major lithology (lith-A), and in a ~ 98 percent pure feldspar separate prepared from the minor lithology (lith-B). Stepwise temperature extractions were made on all samples to better separate low-temperature, adsorbed terrestrial atmospheric gases from trapped gases and from gases produced by nuclear processes. Both glass samples, the feldspar, and lith-B whole rock (containing glass) released gases primarily near sample melting at 1100° to 1300°C. Trapped neon apparently was also released from these samples, but the larger neon system blank makes the neon concentrations considerably more uncertain. Total concentrations of ^{36}Ar released were 1×10^{-8} to 4×10^{-8} cm^3 STP/g (STP = standard temperature and pressure), which is ~ 10 to 20 times the ^{36}Ar produced in EET79001 by cosmic-ray interactions. A pyroxene separate and a total melt extraction of lith-A whole rock, however, gave ^{36}Ar concentrations that were lower by factors of ~ 42 and ~ 7, respectively. Those EET79001 samples containing trapped gases also contained ^{40}Ar far in excess of the amounts that could have formed in situ during the past 180 million years, the time of complete shock resetting of the rubidium-strontium ages, or during the past 1300 million years, the probable formation age of the meteorite (*4*, *12*). For example, one glass sample contained ~ 400 and ~ 40 times the amount of ^{40}Ar that could have formed in situ in 180 and 1300 million years, respectively (*14*).

The relative abundances of trapped neon, argon, krypton, and xenon in various EET79001 samples closely resemble those found in the atmospheres of Earth and Mars, but Kr/Xe ratios in these samples are distinct from that in chondrites (Fig. 1). The plotted values for Earth and Mars probably represent lower limits to the noble gas concentrations of the silicate material which accreted these planets because of possible incom-