caused by the influence of nearby hot spots (*26*). Recent modeling (*2, 27*) predicts that at the slow-spreading rate [18 mm/year half spreading rate (*28*)] characteristic of the 33°S area, a transition in axial topography between forming or lacking an axial rift valley would correspond to crustal thicknesses of 7 to 8 km. This prediction is consistent with the seismically observed crustal thicknesses and topography in the 33°S area. This relation may be explained by variations in axial temperature consistent with focused accretion. If axial valley topography results from the stretching of a strong lithosphere, then a deeper axial valley may indicate the presence of a cool, brittle lithosphere, which would be associated with thin crust.

The results from 33°S indicate not only that crustal thickness variations can fully account for the observed MBA, but also that lateral variations of density within the crust are significant enough that they must be considered when gravity data are interpreted. It follows from these results that other bull's-eye MBAs inferred to exist along many ridge segments on the MAR may also be formed by along-axis crustal thickness variations. Such anomalies are also commonly associated with a shoaling of the axial valley similar to that observed in the 33°S area (*4, 29*). The regularity with which these characteristics are being observed suggests that they are a primary feature of the spreading mechanism operating along the slow-spreading MAR.

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The Manson Impact Structure: $^{40}Ar/^{39}Ar$ Age and Its Distal Impact Ejecta in the Pierre Shale in Southeastern South Dakota

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The $^{40}Ar/^{39}Ar$ ages of a sanidine clast from a melt-matrix breccia of the Manson, Iowa, impact structure (MIS) indicate that the MIS formed 73.8 ± 0.3 million years ago (Ma) and is not coincident with the Cretaceous-Tertiary boundary (64.43 ± 0.05 Ma). The MIS sanidine is 9 million years older than $^{40}Ar/^{39}Ar$ age spectra of MIS shock-metamorphosed microcline and melt-matrix breccia interpreted earlier to be 64 to 65 Ma. Grains of shock-metamorphosed quartz, feldspar, and zircon were found in the Crow Creek Member (upper Campanian) at a biostratigraphic level constrained by radiometric ages in the Pierre Shale of South Dakota that are consistent with the $^{40}Ar/^{39}Ar$ age of 73.8 ± 0.3 Ma for MIS reported herein.

An iridium anomaly (*1*), shock-metamorphosed minerals (*2–4*), and relic tektites (*5*) in Cretaceous-Tertiary (K-T) boundary rocks provide evidence that at least one large extraterrestrial object struck the Earth 64.43 ± 0.05 Ma (*6*), probably in continental rocks in or near North America (*3, 7*). The rocks at two impact structures, Chicxulub on the Yucatan Peninsula and Manson in northwest Iowa, have been examined for evidence that might link them to the K-T impact. The Chicxulub structure (~200 km in diameter) has emerged as the leading candidate (*8, 9*), but the Manson structure (35 km in diameter) has also been proposed as a K-T boundary impact site because of its proximity to K-T boundary rocks containing large and abundant shocked minerals (*3, 7, 10*). Moreover, $^{40}Ar/^{39}Ar$ age spectra of MIS minerals and rocks, although complex and ambiguous, suggested to Kunk and colleagues (*11*) that the minerals and rocks underwent a shock-induced thermal event at 64 to 65 Ma, which is the time of the K-T boundary (64.4 Ma). Paleomagnetic data, however, imply that this interpretation is suspect. A high-temperature melt-matrix breccia layer in the MIS has normal remanent magnetization (*12*) and, if taken at face value, excludes the possibility that this structure formed at the K-T boundary, which is in reversely magnetized rocks in the upper part of magnetozone 29R (*13*). In addition, U-Pb ages of shock-metamorphosed zircons from the upper of two thin K-T boundary claystone beds of western North America indicate that their provenance was not Precambrian crystalline basement rocks in the Manson area or sedimentary rocks derived from such rocks (*4*).

In 1992, 12 holes were drilled to explore the MIS and to investigate further the isotopic age of the impact (*14*). The M-1 hole, on the flank of the central peak, penetrated a high-temperature, melt-matrix breccia layer 40 m thick (*15*). Examination of core from this rock revealed the presence of rare, chalky-white, microcrystalline feldspar (Fig. 1) with the optical properties of sanidine ($2V_x$ = 20° to 22°). The feldspar makes up centimeter-sized clasts in the melt matrix. Scanning electron microscope analysis showed that these clasts, which differ from the more common shocked and partially melted potassium feldspar (microcline) clasts, generally consist of spherulitic, radially bladed sanidine [K_2O (11.4 ± 0.7% w/w); $Or_{68}Ab_{31}An_1$] and trace amounts of

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quartz. The texture and composition of the sanidine clasts imply that they crystallized from a liquid derived from melted, older microcline clasts. If so, the sanidine could yield an isotopic age reflecting its time of crystallization and, thus, the time of the Manson impact.

To date the sanidine isotopically, we used a state-of-the-art $^{40}Ar/^{39}Ar$ laser-fusion analytical system described in (*16–19*). Although this technique has important advantages relative to the conventional K-Ar method, the ages of unknown samples are relative to ages of neutron fluence-monitor minerals. We calculated or recalculated all relevant ages using the age of a secondary, intralaboratory neutron fluence-monitor mineral [sanidine from the Taylor Creek Rhyolite (Oligocene) of New Mexico]. This sanidine has a $^{40}Ar/^{39}Ar$ age of 27.92 Ma, relative to a K-Ar age of 162.9 ± 0.8 Ma for a primary fluence-monitor standard SB-3 biotite or 513.9 Ma for an international hornblende standard MMhb-1 (*20*).

Ten individual fragments of a Manson M-1 sanidine clast were dated (Table 1), and the weighted mean of 12 laser-fusion $^{40}Ar/^{39}Ar$ ages is 73.83 ± 0.31 Ma (*21*). This result places an upper limit on the age of the sanidine because a small but significant amount of ^{40}Ar might have been trapped in its lattice as it cooled. To evaluate this possibility, we plotted the analytical data on an inverse correlation diagram (Fig. 2), resulting in an isochron age for the sanidine of 73.52 ± 0.79 Ma. This age is slightly younger but not statistically different from the weighted mean age and establishes a lower limit for the age of the sanidine and the MIS. The trapped argon component in the sanidine has a ^{40}Ar to ^{36}Ar ratio of 308 ± 31, not statistically different from the ratio of these isotopes (295.5) in atmospheric argon. Given the relatively large amounts of argon obtained for 10 of the individual analyses (Table 1), the marginally higher ^{40}Ar to ^{36}Ar ratio of 308 would reduce the age only slightly from 73.83 ± 0.31 Ma (weighted mean age) to 73.52 Ma (isochron age). Thus, the sanidine does not appear to contain a significant amount of trapped argon, and we propose that the crystallization age of the sanidine and the time of the Manson impact is in the range of 73.8 to 73.5 Ma. We consider the weighted mean age of 73.8 ± 0.3 Ma to be best for the sanidine and thus for the MIS because it has a higher precision than the isochron age.

With our new $^{40}Ar/^{39}Ar$ age of 73.8 ± 0.3 Ma, we reasoned that the extraterrestrial object must have struck the Manson area when it was covered by the western interior Cretaceous seaway (*22*). A physical record of the impact, including tsunami deposits, shock-metamorphosed mineral grains, and altered tektites, might be found in the Pierre Shale (Upper Cretaceous) at a stratigraphic horizon commensurate with our proposed age for the MIS.

We focused our attention on outcrops of the Pierre Shale along the Missouri River in southeastern South Dakota. In this area, the lower part of the Pierre consists typically of 55 m of shale and some marl and includes, in ascending order, the Sharon Springs, Gregory, Crow Creek, DeGrey, and Verendrye members (*23*). Near Chamberlain, the lower part of the Gregory Member contains the ammonites *Baculites gilberti* and *B. gregoryensis*. The ammonites *B. scotti* and *Menuites* occur in the upper part of the Gregory within 4 m of the overlying Crow Creek Member. These ammonites are indicative of late middle Campanian age (Fig. 3). The species *B. rugosus* (late form having a weakly ribbed venter), which is found in black, manganese-rich concretions of the overlying DeGrey Member, is restricted to the zone of *Didymoceras cheyennense* of early late Campanian age. The Verendrye Member contains *B. cuneatus* and *B. reesidei* of late Campanian age.

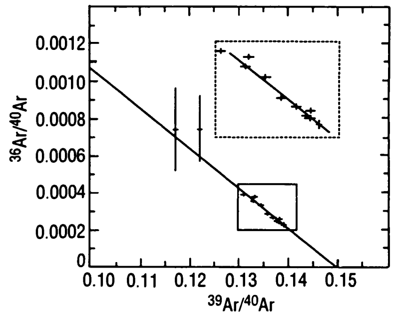

Fig. 2. Inverse correlation diagram for 12 $^{40}Ar/^{39}Ar$ analyses of fragments from a sanidine clast from the 114.2-m level of the M-1 drill core, MIS. The inverse of the intercept on the *x* axis (0.14925) yielded an age of 73.5 ± 0.8 Ma. The inverse of the intercept on the *y* axis (0.003241) yielded a value of 308 ± 31. Note that the *y* axis intercept on the *x* axis is not zero. Two samples with large error bars (1σ) are of reheated material that yielded only small amounts of argon (Table 1). The mean square weighted deviates = 1.27. The dashed-line inset is an enlargement (×2) of the indicated data.

Thus, the intervening Crow Creek Member, which apparently lacks ammonites and other macrofossils, may be of early late Campanian age and be in the highest part of the *Exiteloceras jenneyi* zone or in the lowest part of the *D. cheyennense* zone. Obradovich (*24*) obtained sanidine $^{40}Ar/^{39}Ar$ ages of 74.83 ± 0.72 Ma, 73.71 ± 0.45 Ma, and 72.32 ± 0.39 Ma for bentonite beds in the *B. scotti*, *E. jenneyi*, and *B. compressus* zones, respectively. The Crow Creek Member, which occurs above the zone of *B. scotti* and below the zone of *B. compressus*, must therefore be bracketed by these ages (Fig. 3) and is consistent with our age of 73.8 ± 0.3 Ma for the MIS. Compilations of the paleomagnetic time scale (*25*) and the biostratigraphic consid-

Table 1. Laser-fusion $^{40}Ar/^{39}Ar$ ages of a sanidine clast from the 114.2-m level of the M-1 drill core of the MIS. Errors associated with individual ages are estimates of the analytical precision at the 1-σ level and include the error (0.33%) of the fluence-calibration parameter, J = 0.00621. Weighted mean age was calculated with the inverse of the variance as the weighting factor. Analyst, G. A. Izett.

Experiment number	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^{*}/^{39}Ar$	$^{40}Ar^{*}$ (mol × 10^{-13})	$^{40}Ar^{*}$ (%)	Age (Ma)	Error (1 σ)
93Z0406	0.0048	0.00180	6.7255	4.12	92.6	73.79	0.34
93Z0407	0.0036	0.00295	6.7734	3.72	88.5	74.31	0.35
93Z0408†	0.0030	0.00632	6.6772	6.04‡	78.1	73.27	5.86
93Z0409	0.0033	0.00162	6.7126	1.23	93.2	73.65	0.44
93Z0410	0.0035	0.00210	6.7569	4.02	91.5	74.13	0.35
93Z0411†	0.0023	0.00607	6.4053	7.61‡	78.0	70.34	4.47
93Z0412	0.0048	0.00266	6.7476	4.13	89.5	74.03	0.35
93Z0413	0.0049	0.00194	6.7375	3.98	92.0	73.92	0.34
93Z0414	0.0047	0.00245	6.7203	3.98	90.2	73.73	0.35
93Z0422	0.0049	0.00282	6.7097	5.13	88.8	73.62	0.35
93Z0439	0.0041	0.00173	6.7320	4.49	92.8	73.86	0.34
93Z0440	0.0036	0.00185	6.6885	3.43	92.3	73.39	0.35

*Radiogenic. †Analysis of sanidine previously heated with laser (93Z0407 and 93Z0410). ‡Moles $\times 10^{-15}$.

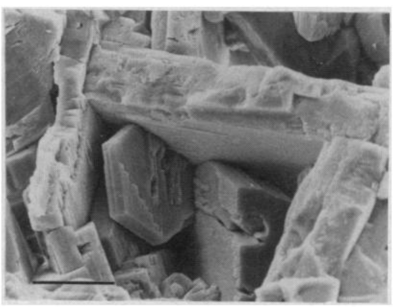

Fig. 1. Scanning electron microscope image of sanidine from a clast at the 114.2-m level of the M-1 drill core, MIS. Sanidine is generally microcrystalline, and grain size varies from about 5 μm to 3.0 mm. Scale bar, 20 μm.

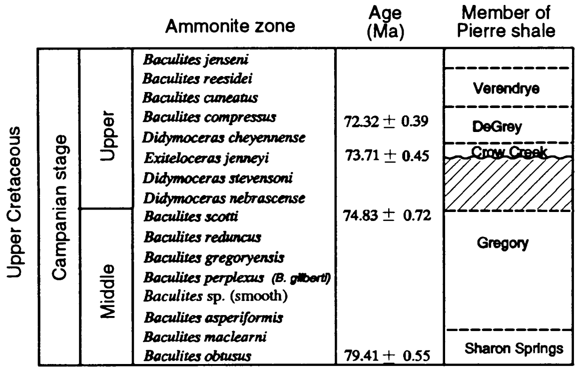

Fig. 3. Western interior Upper Cretaceous Campanian stages, western interior ammonite zones, and the probable positions of the members of part of the Pierre Shale in southeastern South Dakota. The diagram is generalized from outcrops near Chamberlain, South Dakota, where the Crow Creek Member rests unconformably on the Gregory Member. Ages are from (*24*).

erations given above suggest that the Manson impact occurred during a normal paleomagnetic chron, possibly in chron 33N or in a brief normal in 32R (32R.1N).

The Crow Creek Member, which consists of 2 to 3 m of marl, has received considerable attention because of an anomalous lithologic feature (*23*). This member contains at its base a locally cross-bedded siltstone 15 to 20 cm thick or a concentration of sand grains and rip-up shale clasts as large as 4.5 cm. The sand grains and shale clasts increase in size and abundance from west to east in southeastern South Dakota (*23*, *26*). The provenance of the sand grains, some as large as 2.8 mm, in an otherwise shale-dominated sequence has puzzled geologists for more than 40 years. The abrupt appearance of sand granules supports the argument for a sudden change in depositional conditions or source. Just as interesting is the fact that the Crow Creek Member rests disconformably on successively older beds of the Pierre Shale from northwest (Chamberlain) to southeast (Yankton) along the Missouri River toward the MIS. A few kilometers west of Yankton, the Crow Creek overlies about 2 to 3 m of organic-rich shale of the Sharon Springs Member (*26*).

We searched for mineralogic evidence that is diagnostic of an impact in the basal part of the Crow Creek Member at three places in southeastern South Dakota: a site in Black Dog Township, Lyman County, about 20 km southwest of Chamberlain, and two sites (*27*) in Yankton County (House of Mary Shrine and an abandoned limestone quarry, 11 and 6 km west of Yankton, respectively). The acid-insoluble residue of the samples from these sites consists chiefly of quartz and minor feldspar and mica. A few percent of the quartz and feldspar (microcline and plagioclase) grains contain multiple intersecting sets of planar lamellae (Fig. 4) identical to those in shocked mineral grains from rocks at known impact structures. Many of the shocked quartz grains also exhibit pronounced shock-mosaic texture. Shocked lithic fragments composed of quartz and feldspar also were identified. The presence of shock lamellae in well-rounded quartz grains suggests that these grains were derived from a sedimentary target rock. A few rounded, shock-metamorphosed zircon crystals were recovered from heavy-mineral concentrates of the insoluble residue of the marl.

The largest shocked mineral grains in the basal Crow Creek marl at the two Yankton County sites were 2.3 mm and 1.7 mm. These sites are about 250 km from the MIS. In contrast, the largest shocked mineral grains from the basal sandstone of the Crow Creek in Lyman County, 200 km west of Yankton County, were only 0.6 mm. The unusually large size of the shocked mineral grains in Yankton County implies that they came from a nearby source, such as the MIS.

Further study of stratigraphic relations in shale directly below the layer of Manson impact ejecta may provide a key to understanding (i) the puzzling absence of three ammonite zones above the zone of *E. jenneyi* at the Red Bird section in eastern Wyoming (*22*) and (ii) the origin of regional unconformities above the zone of *E. jenneyi* and below the Teapot Sandstone Member of the Mesaverde Formation and Pine Ridge Sandstone of the Mesaverde Group in central Wyoming (*28*). An impact-triggered tsunami could account, in part, for some of these anomalous stratigraphic and biostratigraphic relations.

Our laser-fusion $^{40}Ar/^{39}Ar$ apparent age of 73.8 ± 0.3 Ma for a sanidine clast from a melt layer of the MIS is more rational than incremental-heating $^{40}Ar/^{39}Ar$ ages of 64 to 65 Ma for shock-metamorphosed microcline from the same structure obtained by Kunk and colleagues (*11*) because the Crow Creek Member of the Pierre Shale contains shock-metamorphosed minerals that were probably derived from the MIS. This formation is sandwiched between isotopically dated ammonite zones (*24*), and the inferred numerical age for the Crow Creek Member is in accord with our proposed isotopic age for the MIS.

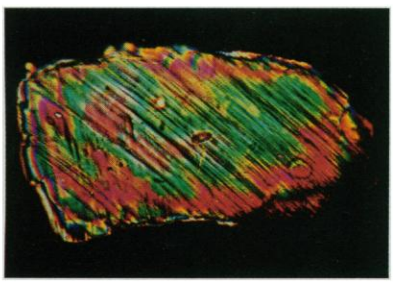

Fig. 4. Shocked quartz grain 0.55 mm long from marl at the base of the Crow Creek Member of the Pierre Shale at the House of Mary Shrine site, 11 km west of Yankton, South Dakota. The grain has six sets of shock lamellae, but only two sets are visible in this orientation. Photographed with plane-polarized light.

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18. The procedures used to date samples were described in (*16–19*), including the reactor fluence characteristics, irradiation scheme, and methods for the measurement of corrections for interfering argon isotopes. Fragments (0.2 to 0.4 mm) of sanidine from a clast at the 114.2-m level of the M-1 core were sealed in aluminum foil cups, and the flattened, pancake-like packet was sandwiched between similar packets of the fluence-monitor mineral, sanidine of the Taylor Creek Rhyolite. The packets were arranged in a vertical stack and loaded into a quartz tube that was irradiated (2.4 × 10^{18} neutrons cm^{-3} s^{-1}) for 24 hours in the core of the U.S. Geological Survey's Training Reactor, Isotopes General Atomic reactor. Irradiated samples were loaded into wells in a copper disk and placed in the sample chamber. Under ultrahigh vacuum, the samples were melted

with a 5-W, continuous argon-ion laser. Only one fragment of the sanidine melted to a clear glass bead (93Z0406, Table 1). Nevertheless, radiogenic argon yields were appreciable (1.23×10^{-13} to 5.13×10^{-13} mol). Most fragments were heated with the laser for less than 1 s, but a few were heated for 5 min. Reheating of the sanidine (93Z0408 and 93Z0411, Table 1) showed that most of the argon was expelled during the initial 1-s heating episode. The neutron fluence within the radiation package was measured by the analysis of five to seven lots of sanidine crystals of each fluence-monitor packet. Each age determination of the sanidine from the M-1 core hole was made by the melting of single fragments (~0.3 mg). For additional internal calibration, 12 K-T boundary tektites from Beloc, Haiti, were irradiated in the same package, and they yielded a weighted mean age of 64.6 ± 0.1 Ma at the 95% confidence level for the standard error of the mean. This $^{40}Ar/^{39}Ar$ age is nearly identical to that of K-T tektites (64.5 Ma) reported in (*6*). The gas released from the samples was cleaned with Zr-Al and Zr-V-Fe getters, and the isotopic composition of the argon released was analyzed with an ultra-sensitive, rare-gas mass spectrometer. Ages were calculated with the use of the decay constants of R. H. Steiger and E. Jäger [*Earth Planet. Sci. Lett.* **36**, 359 (1977)].
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Mississippian Fossils from Southern Appalachian Metamorphic Rocks and Their Implications for Late Paleozoic Tectonic Evolution

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Fossils of *Periastron reticulatum* Unger emended. Beck recovered from the Erin Slate of the Talladega slate belt of Alabama establish that these rocks have a Mississippian (Kinderhookian-Tournaisian) age. The Talladega slate belt, the southwestern extension of the western Blue Ridge belt, was interpreted to have been affected by regional dynamothermal metamorphism and coeval deformation as a result of the Acadian orogeny. This fossil find indicates that metamorphism and deformation of the Talladega belt occurred after the Early Carboniferous (Alleghanian), requiring a reevaluation of tectonic interpretations of the southernmost Appalachians.

The Talladega belt is the westernmost crystalline thrust sheet in the southernmost exposed Appalachians and lies between the foreland fold-thrust belt to the northwest and the eastern Blue Ridge to the southeast (Fig. 1). Southeast-dipping, post-metamorphic fault systems form both upper and lower boundaries. Low-grade metasedimentary and metavolcanic rocks are interpreted to range from Late Precambrian to Devonian in age, on the basis of radiometric determinations and lithostratigraphic and biostratigraphic correlations with fossiliferous units in the foreland (*1*). Fossiliferous units include the Cambrian Jumbo Dolomite (*2*), the Silurian–Early Devonian Lay Dam Formation (*2*), the Early Devonian Jemison Chert (*2–4*), and the controversial Erin Slate that has been argued as either Early Devonian (*2*) or "probably Pennsylvanian" (*5*). Metasedimentary rocks in the Talladega belt contain no evidence of polymetamorphism (*6*). The time of dynamothermal metamorphism has been interpreted to be Devonian, coeval with Acadian orogenesis, on the basis of K-Ar whole rock ages on slate and the presence of an Early Devonian megafaunal assemblage from chert (Jemison Chert) near the stratigraphic top of the sequence (*6, 7*). An early 20th-century report of "probable" Pennsylvanian plant fossils from the Erin Slate (*5*), which overlies the Jemison, has been questioned because of the inability of subsequent investigators to replicate previous material. This inconsistency has led to the conclusion that these Carboniferous fossils are exotic (*2*).

In its type area, the Erin Slate is a variably deformed black slate that stratigraphically overlies the Cheaha Quartzite across a gradational contact and underlies the Chulafinnee Schist (Fig. 2). The upper contact with the Chulafinnee is interpreted as a thrust fault (*8*). The interpretation of the Erin-Chulafinnee contact as gradational and conformable; the discovery of the fossil *Veryhachium*, a long-ranging (Silurian to Carboniferous) marine acritarch from the Erin Slate; and the correlation of the Chulafinnee with the Jemison Chert (*9*) have

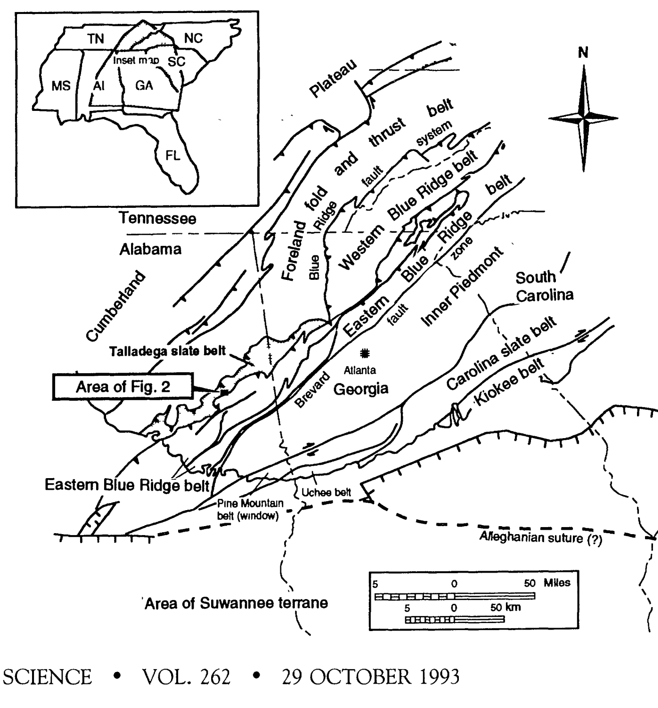

Fig. 1. Generalized tectonic map of the southern Appalachians [modified from (*8*) and (*29*)].

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