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# Fossil tabulate corals reveal outcrops of Paleozoic sandstones in the Atlantic Coastal Plain Province, Southeastern USA

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## Abstract

The geologic history of the Southeastern United States of America is missing nearly 350-million-years of rocks, sediments, and fossils. This gap defines the Fall Line nonconformity where Upper Ordovician consolidated rocks are directly overlain by Upper Cretaceous unconsolidated sediments of the Atlantic Coastal Plain Province. Here we begin to fill in the missing geologic record by reporting the discovery of fossils of lower-to-middle Paleozoic tabulate corals (Syringophyllidae) in angular, quartz-rich, ferruginous sandstones that crop out in the Carolina Sandhills Physiographic Province that forms the updip margin of the Atlantic Coastal Plain Province near the Fall Line. These fossils of extinct tabulate corals are the first evidence that Paleozoic (Upper Ordovician–Lower Silurian) sandstones crop out amidst the mostly Mesozoic-to-Cenozoic deposits of the Atlantic Coastal Plain Province of the United States of America. This discovery of Paleozoic fossils and strata in a region in which they were previously entirely unknown offers a more complete insight into the geologic history of the Southern Appalachian Mountains Region, Carolina Sandhills and updip margin of the Atlantic Coastal Plain Province and extends the previously identified range of Syringophyllidae in North America.

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## Introduction

No fossils from the Paleozoic have been found in situ in the unconsolidated sediments of the Atlantic Coastal Plain (ACP) Province of the United States of America (USA). The oldest fossils from the ACP are found in the Upper Cretaceous and younger sediments at the updip (inland) margin near the Fall Line (Fig 1A), are floral, non-marine, and represent deposition of terrestrial sediments in an upper-delta plain paleoenvironment along a passive margin [1–10]. In contrast, the metaigneous and metasedimentary rocks of the Piedmont Province north of the Fall Line contain lower Paleozoic, and older, fossils. For example, in the Southern Appalachian Mountains Region (SAMR) (Fig 1A), Upper-to-Middle Ordovician and older invertebrate fossils have been found in North Carolina [11–18], Georgia [19, 20], and South Carolina

confirm they did not have any special access or privileges that other researchers would not have.

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[21–23]. These fossils helped establish temporal constraints of an Upper Ordovician closure of the Iapetus Ocean following accretion of multiple peri-Gondwanan terranes and composite volcanic-arc systems, such as exotic Carolinia, to Neoproterozoic rocks of Laurentia [22, 24–35]. The Fall Line nonconformity, therefore, represents an extensive hiatus in the rock and fossil record from the Lower Silurian to the Lower Cretaceous that has been recognized since at least the 19th century [1–4]. Therefore, it is warranted to report the discovery of fossils from any part of this missing time.

## Geological setting

The Carolina Sandhills Physiographic Province (Fig 1A) is located in the most updip part of the ACP province adjacent to the Fall Line in Georgia, South Carolina (Fig 1B), and North Carolina and encompasses 22,530 square kilometer ($km^2$) and comprises Upper Cretaceous to Quaternary deposits that rest nonconformably on Paleozoic-age rocks of Carolinia, as stated previously [22, 24–31, 33–35] (Fig 2). The thickness of the Upper Cretaceous increases toward the southeast, reaching over 152-m near McBee [37], and extend beneath the sediments of the Inner Coastal Plain at the Orangeburg Scarp. Quaternary-age deposits rest unconformably on the Upper Cretaceous sediments and include the Pinehurst Formation and undifferentiated sediments [36, 38] (Fig 2); the thickness and aerial extent of these sediments ranges from highly variable to absent [39–41]. The lithology of the Upper Cretaceous and Quaternary formations is similar, as the latter is derived from the former. The Upper Cretaceous formations consists of poorly sorted, subangular, medium- to coarse, micaceous (1%), kaolinitic, mature quartz (99%) unconsolidated sand interspersed with lenses of clay and the Quaternary, where present, is considered to represent unconsolidated eolian sand sheets and dunes comprised of reworked Upper Cretaceous material [10, 38, 42].

The Carolina Sandhills are also characterized by sparsely dispersed outcrops of coarse, iron-cemented (ferruginous) sandstones that create some of the highest altitudes across an otherwise mostly flat region [4] (Fig 3A and 3B). Previous workers [1, 2, 42, 43] consider these enigmatic outcrops to represent either a part of the Upper Cretaceous Cane Acre and Coachman or Quaternary Pinehurst formations, based solely on relative stratigraphic position (Fig 2) with persistence explained by resistance to erosion imparted by the iron cementation. One prominent sandstone outcrop, called Sugarloaf Mountain (location shown on Fig 1C), rises more than 45 meters (m) above the surrounding terrain. The thickness of the sandstone beneath the exposed outcrops is not known (Fig 2), although bedrock is no greater than 61 m below land surface [44] and is often exposed in shallow streambeds near the study area. Ferruginous sandstone float can be found at land surface near the outcrops (Fig 3C and 3D) or below land surface entrained in Upper Cretaceous sediments at lower altitudes (Fig 2, Fig 3E and 3F). Though mapped together with Upper Cretaceous and younger sands by former surveys, it appears that these ferruginous sandstone units are lower-to-middle Paleozoic in age and located above younger formations due to reactivation of reverse faults, as demonstrated here.

## Materials and methods

All in situ fossils and fossiliferous float material were discovered at the peak of or adjacent to ferruginous sandstone outcrops, respectively, near the towns of McBee and Patrick in central South Carolina, USA. The generalized locations of the fossiliferous outcrops are labelled 1–6 (Fig 1C). The latitude and longitude of each fossil, either discovered in situ or as float, were recorded in the field by using a hand-held global-positioning system (GPS) device and geospatially referenced using a LiDAR coverage. Fossils found in situ were not removed, although

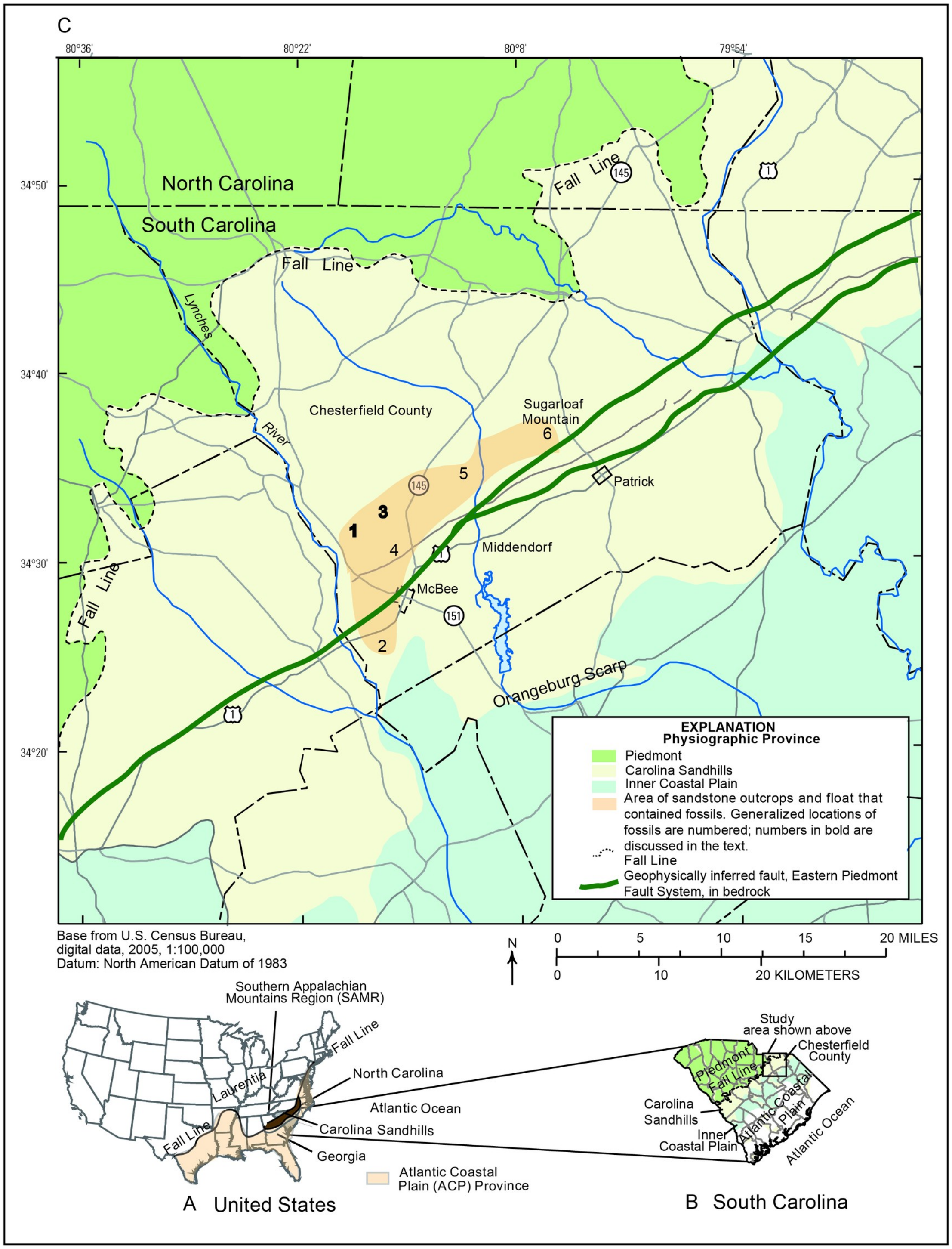

**Fig 1. Maps of the study area in the Southeastern United States of America.** A. Generalized location of Laurentia, the Southern Appalachian Mountains Region, Atlantic Coastal Plain Province, Carolina Sandhills Physiographic Province, the Fall Line, and Georgia, South and North Carolina, Unites States of America (adapted from [36]). B. Enlarged map of South Carolina that depicts the location of the Carolina Sandhills, Fall Line, Piedmont, Atlantic Coastal Plain, and study area in Chesterfield County. C. Enlargement of study area shown in Fig 1B with generalized locations of the Fall Line, Orangeburg Scarp, geophysically inferred faults of the Eastern Piedmont Fault System, and area of fossiliferous, ferruginous sandstone outcrops with generalized fossil localities labelled 1–6 (localities in bold are discussed in the text).

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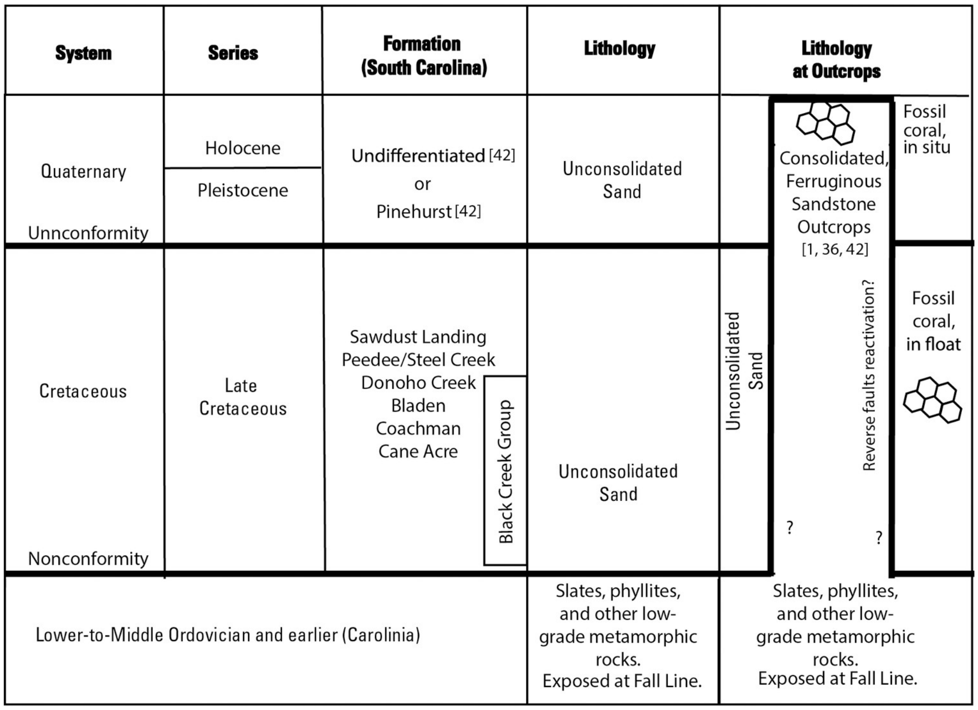

**Fig 2. Diagram showing a generalized geologic section of the study area.** The formation names are those used in South Carolina [36]. The lithology of the unconsolidated Cretaceous sand is presumably penetrated by the lithologic sequence of the fossiliferous, ferruginous sandstone outcrops expressed at land surface, as proposed in the last column.

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fragments were recovered, along with float. The specimens and the locality information are housed at the U.S. Geological Survey (USGS) Caribbean-Florida Water Science Center, 4446 Pet Lane, Suite 108, Lutz, FL, USA. Details of locality information will be made to qualified researchers. No permits were required for the described study, which complied with all relevant regulations. All fossils were discovered by the first author between 2011 and 2018.

Each fossil hand specimen or fragment was examined by using a Leica M205C stereomicroscope (20.5:1 zoom and objective Planapo 0.63x.) illuminated with a Leica LED5000 ring light (80/40). Standard thin sections (30 micrometers (μm), 26 x 46 millimeters (mm)) of representative fossils were prepared (Burnham Petrographics, LLC, Rathdrum, ID). Digital images were made with a Leica M205C integrated 5 Mpixels digital microscope camera (DFC450) and Leica LAS Montage Software. Systematic description and classification follow Hill [45]. The color of iron cementation and morphology of sediment cemented to the fossils are evaluated to understand possible post-burial diagenesis ranging from cementation to low-grade metamorphism.

## Results and discussion

Specimens in hand (Fig 4A–4D) and thin section (Fig 4E–4G) indicate the fossil corals are characterized by complete tabulae. Although poorly preserved and with no visible septa, the tabulae unequivocally indicate the specimens represent tabulate corals. These skeletal features also demonstrate that the specimens are not hematite nodules or septarian concretions.

The ceroid and polygonal corallites range between 2 and 5 mm (Fig 4A–4G) with horizontal tabulae and no visible septa (Fig 4C and 4G) and strongly resemble corals of the Order Sarcinulida, family Syringophyllidae [45]. Syringophyllidae ranged from the Late Ordovician to

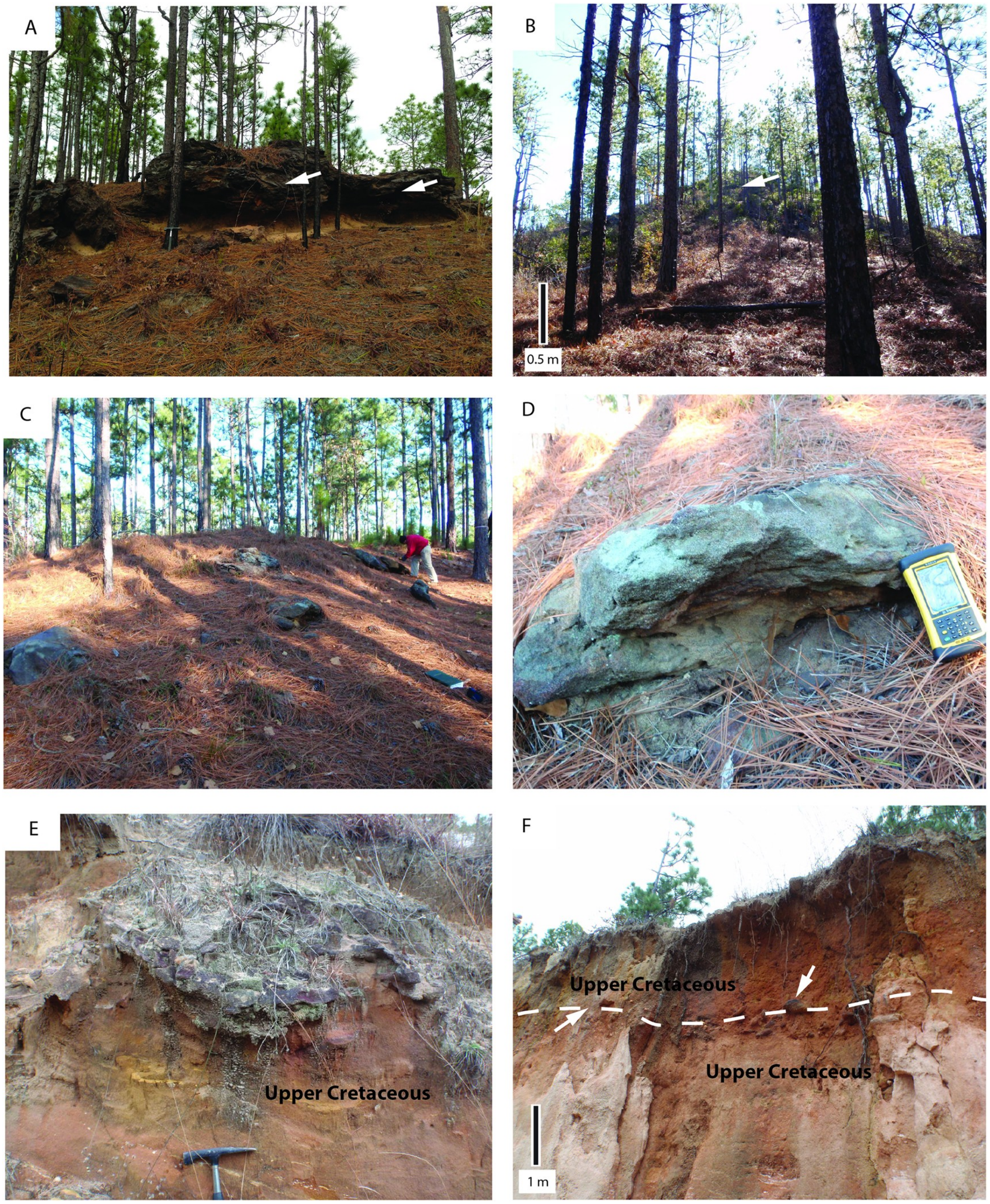

**Fig 3. Photographs of ferruginous sandstone outcrops and float.** A. Outcrop (labelled no. 1, Fig 1C; arrow points to generalized locations of in situ fossils). Hammer shown for scale. B. Outcrop (labelled no. 6, Fig 1C; arrow points to generalized locations of in situ fossils). C. Float (near outcrop labelled no. 4, Fig 1C). Person shown for scale. D. Float (near outcrop labelled no. 4, Fig 1C). GPS device shown for scale. E. Float (near outcrop labelled no. 2, Fig 1C). Hammer shown for scale. F. Float buried by Upper Cretaceous sediments (near outcrop labelled no. 2; Fig 1C).

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Early Silurian [45]. The absence of mural pores (Fig 4C and 4G), presence of semicircular corallites in longitudinal thin section (Fig 4E and 4F), and separation of groups of corallites from neighboring groups by longitudinal lacunae (Fig 4E and 4F) tentatively suggest an attribution

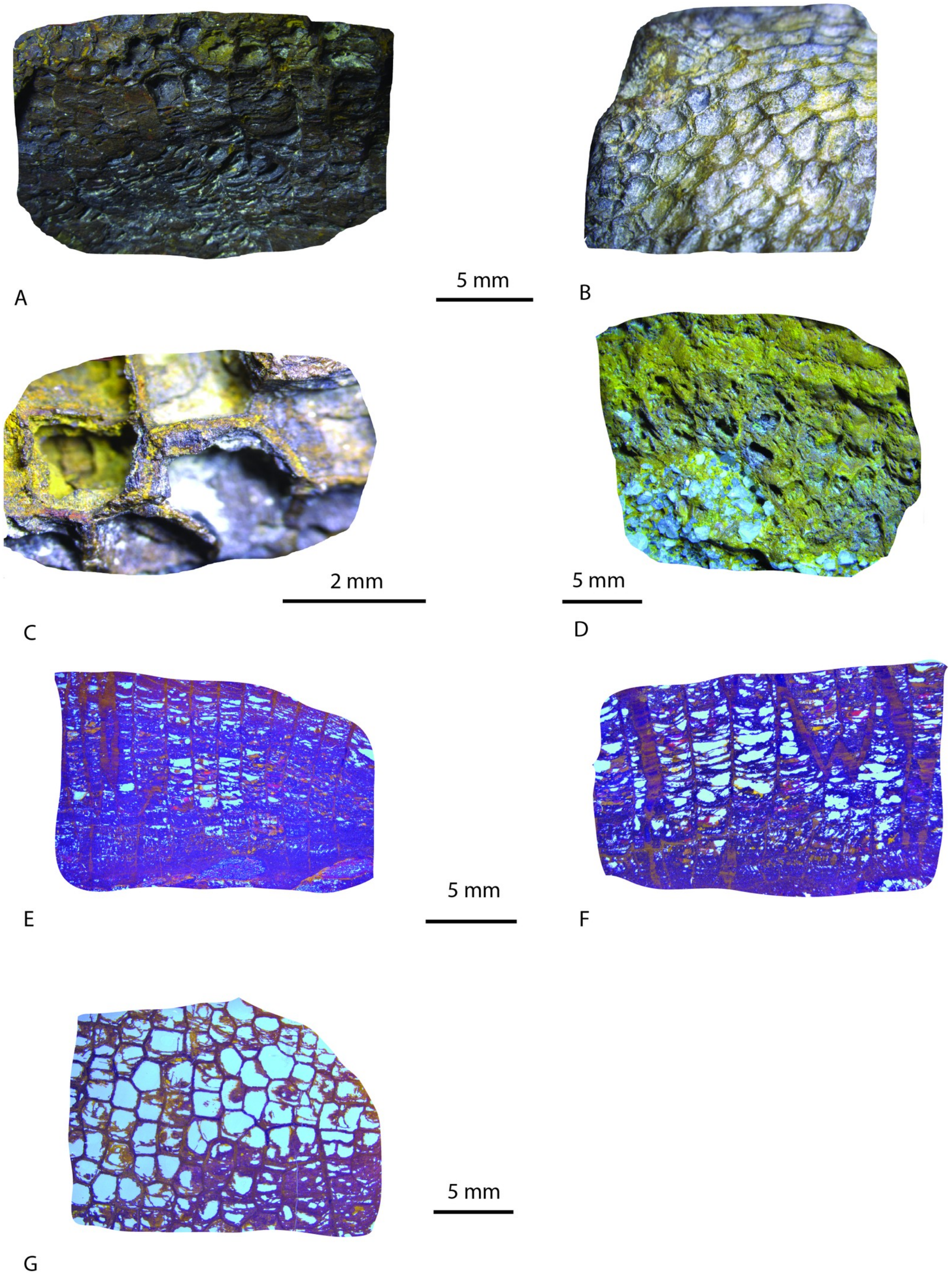

**Fig 4. Photographs of tabulate coral fossil hand specimens and thin sections.** A. Fragment, massive, hemispherical corallum of polygonal corallites, variable diameters 2 to 3 mm, tabulae numerous, convex, individual corallite budding present, USGSSC-001 (outcrop labelled no. 3, Fig 1C) (×5). B. Fragment, massive corallum, corallites polygonal, variable diameters from 2 to 3 mm, tabulae numerous, convex (funnel-shaped) upward toward calical surface, USGSSC-002 (outcrop labelled no. 3, Fig 1C) (×5). C. Corallum showing separate, unshared calice walls and thecal contact as limonite pseudomorphs of hematite, USGSSC-003 (outcrop labelled no. 3, Fig 1C) (×20). D. Fragment, in situ, massive, corallum of polygonal corallites, variable diameters 2 to 3 mm, large, angular, unsorted quartz grains cemented to material, USGSSC-004 (outcrop labelled no. 1, Fig 1C) (×5). E. Longitudinal section of specimen shown in Fig 4B, corallites, 2 to 3 mm, with complete tabulae. Compares favorably to that shown for *Baikitolites sp*. in Hill [45], Fig 343, 2b, p. F527) (×5). F. Longitudinal section of specimen shown in Fig 4A, corallites, 2 to 3 mm, with complete tabulae. Budding apparent in Fig 4A visible (×5). G. Transverse section of specimen shown in Fig 4A, showing distinct five- to six-sided, "honeycomb-shaped" polygonal calice, closely packed corallites, diameters up to 3 mm. Compares favorably to that shown for *Baikitolites sp*. in Hill [45], Fig 343, 2b, p. F527) (×5). Microstructures were not observed in any specimen.

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to the genus *Baikitolites sp*. [46]; if confirmed, this would be the first record of *Baikitolites sp*. outside of central Asia [47, 48] where association is Late Ordovician. The lack of microstructures precluded a more specific assignment beyond genus; however, the use of microstructures in tabulate systematics is disputable [49, 50]. The systematic paleontology of the fossils is provided herein:

## Systematic paleontology

This is the first occurrence of any tabulate coral in the study area, and the first record of the family Syringophyllidae east of the Appalachian Plateau and Valley and Ridge Provinces.

Class ANTHOZOA [51]
Subclass TABULATA [52]
Order SARCINULIDA
Family SYRINGOPHYLLIDAE [53]
**Genus? *Baikitolites sp*. [46]**
Fig 4A–4D

**Material.** 4 poorly preserved, iron-epigenized specimens as shown (Fig 4A–4D), collected as in situ fragments and float as shown of Fig 3A–3F. Additional specimens not shown were located in situ or as float at Localities 2 and 4–6 (Fig 1C), but the best-preserved specimens are described herein and used to provide thin sections. All fossils found consist of iron (hematite) replacement with partial limonite pseudomorphs after hematite. No organic matter, calcite, or siderite are present which precluded analyses by carbon-isotopic methods; any siderite or glauconite originally present had been mineralized to iron hydroxides. Chemical composition awaits further analyses, although even petrographic evaluation may not reduce uncertainties surrounding post-burial processes as it permits inspection of the last cementation process at the expense of any previous ones. Microfacies present is weak, or is not primary, having been diagenetically changed, almost exclusively, due to transition from goethite to hematite followed by, in some instances, limonite pseudomorphs after hematite (Fig 4C and 4D). Coarse, angular quartz grains were cemented by hematite to the inner and outer part of some of the recovered material (Fig 4D). These quartz grains are larger and more angular than the subangular quartz that comprises the unconsolidated Upper Cretaceous and younger formations in the study area.

**Material locality.** Locality numbers correspond to those shown on Fig 1C. Locality 1 is the peak of a sandstone outcrop exposed at an altitude of about 153 m above the North American Vertical Datum of 1988 (NAVD 88) located northwest of McBee (Fig 1C). Locality 3 is a road cut at an altitude of about 138 m above NAVD 88 along an unimproved public road north of McBee. Additional specimens were located in situ or as float at Localities 2, 4–6 (Fig 1C). The widespread distribution of the material dispels concerns of a potential non-geologic source of the material, such as non-native fill.

**Description.** Coralla hemispherical (when shape is visible, Fig 4A) or of unknown geometry (in fragments, Fig 4C), cerioid, composed of polygonal corallites, 2–3 mm in diameter. Tabulae numerous, flat or convex, complete and incomplete. Walls even, thin. Septal apparatus not observed. Connecting pores not observed. Microstructures not observed. Budding extracalicular (Fig 4F).

## Discussion

The material described here seems to be most similar to *Baikitolites sp*., however it differs from both species *B. alveolitoides* [46] and *B. magnus* [54] by presence of numerous incomplete tabulae. The species described here differs from the latter species by smaller corallite diameters (sometimes up to 5.5 mm, usually smaller [54]). The material presented here is also somewhat similar to *Saffordophyllum* (Tabulata: *Palaeofavositinae*), Late Ordovician in North America [45] from which it differs by absence of pores. The absence of septal apparatus may be caused by diagenesis. The poor preservation of the skeletal elements, epigenetized in iron (hydro) oxides, precludes a more formal identification.

The association of the fossil tabulate coral with coarse, angular sand (Fig 4G) at the outcrops and in float is rare [55, 56] and, therefore, most likely records the depositional event(s) that buried the corals rather than the original growth substrate. The angular sand and lack of large clasts indicate erosion of a proximal granitic highland, such as the southernmost part of the Taconic or Salinic highlands (Fig 5). For example, paleogeographic reconstructions of the Late Ordovician indicate the study area was likely characterized by a narrow, high-energy shelf that would have had significant siliciclastic input from the highlands as sea levels fell [57, 58]. Because delicate skeletal features such as tabulae were preserved, and angular sand grains were found inside and outside of the fossils, indicate the corals were buried rapidly, and locally. Moreover, transport of the fossils, and entombing sand, from distant sources such as the westernmost part of the Allegheny Plateau some 480 kilometers to the northwest would have necessarily obliterated delicate skeletal features and required seaways which are not known to have existed (Fig 5). Moreover, there are no sandstones to the north of the Fall Line. In fact, the rocks to the north of the study site and Fall Line are phyllites of Middle Cambrian to Middle Ordovician age, are not Upper Ordovician to Lower Silurian, and no fossil invertebrates have been found there. Moreover, the current altitude of the Piedmont north of the Fall Line is considerably lower than the study site, as well as most of the ACP.

The source of the iron for fossilization and cementation is subject to speculation because iron supplies to Pre-Cambrian and Paleozoic-age marine sediments has been a matter of considerable debate [60, 61]. For example, assuming the initial source of iron is from the weathering of proximal, ferromag-rich granitic sources, any siderite ($FeCO_3$) present at deposition would have been mineralized to goethite and, subsequent to subaerial exposure, hematite. Additional supplies of iron could have been derived from contact metamorphism via pluton emplacement at shallow depths during subsequent orogenies. The transition between diagenesis and metamorphism is gradual and no isothermal boundary can be applied [62]. In any case, it may be possible that other near-shore, biotic or abiotic, components of the Lower Paleozoic exist in the Carolina Sandhills, but are either buried, eroded, or have been mineralized to iron oxides/hydroxides, as has been observed in the Silurian Clinton ironstones [63].

The tectonic feature likely responsible for the uplift of the Paleozoic fossiliferous sandstone could be related to reactivation of the Paleozoic Eastern Piedmont Fault System (EPFS) [64, 65] during the Late Cretaceous-Cenozoic. The EPFS comprises multiple geophysically inferred faults (prominent elongate magnetic anomalies related to ductile deformation during the Paleozoic) beneath most of the ACP sediments in Georgia, South Carolina, and North Carolina, including beneath the study area [65] (Fig 1C). The location of the inferred fault generally coincides with the surface location of the fossiliferous sandstones. The best example of post-Cretaceous reactivation of the EPFS along the Fall Line in South Carolina is the Belair Fault near Augusta, GA. The Belair Fault comprises a series of reverse faults that vertically offset the Upper Cretaceous sediments up to 40 m since the Late Cretaceous [66]. Vertical offsets, most likely from en echelon reverse faulting, as large as 213 m have been reported [67]. In these areas, Piedmont rocks have faulted over ACP strata along high angle reverse faults and is evidenced by brittle deformation [66–68]. In fact, the very linearity of the Fall Line along the length of the ACP has been suggested as evidence of such Cenozoic tectonism [69].

Following post-Cretaceous uplift, the iron-epigenetized corals most likely were then re-covered by fluvial sediments during the Late Cretaceous when sea level was higher than the

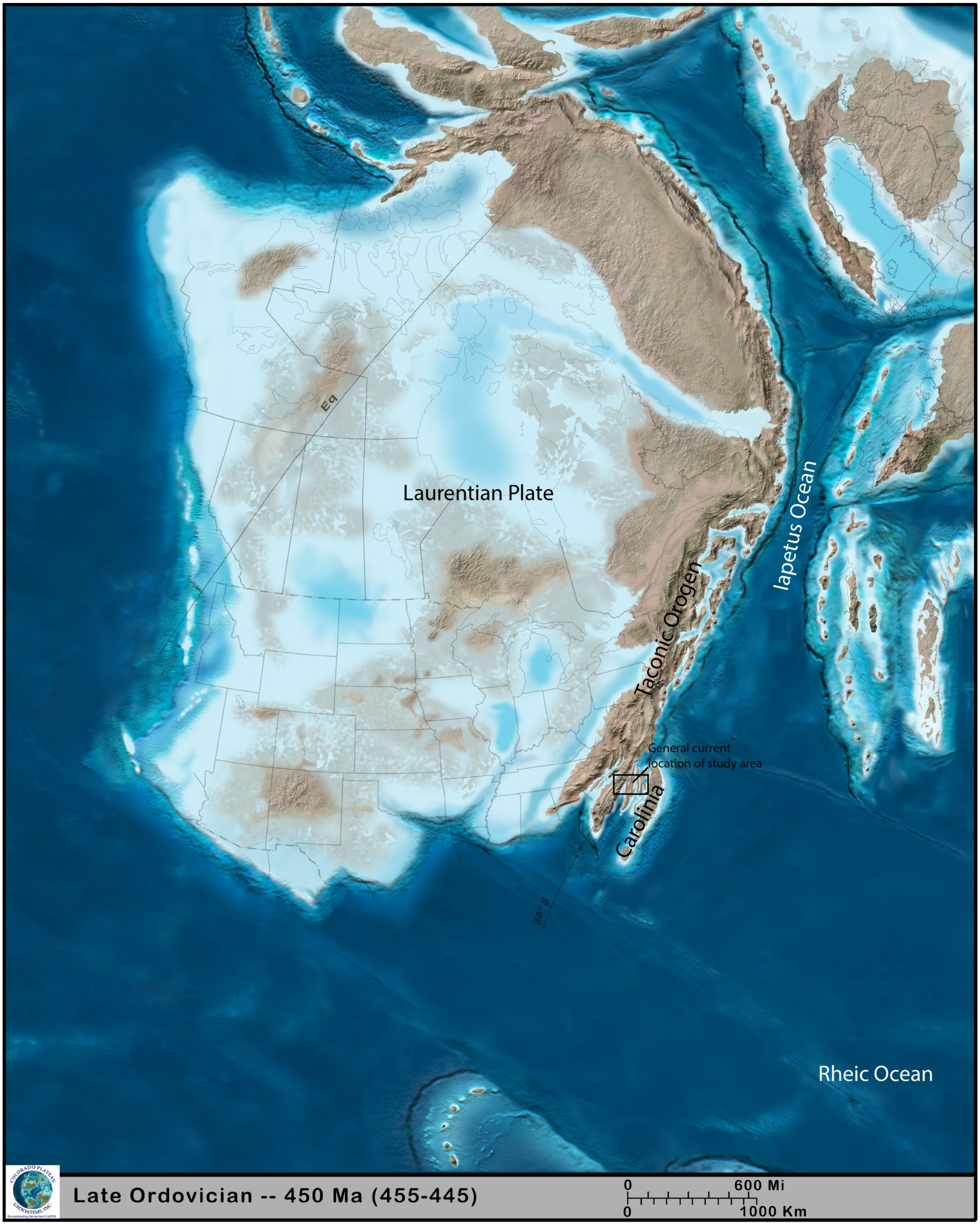

**Fig 5. Paleogeographic reconstruction of Laurentia during the Upper Ordovician (450 Ma).** Probable location of the study site is shown as square (modified with permission from [59]).

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Silurian [57]. Such deposition would provide for the veneer of sediments that drapes the flanks and bases of most outcrops as described by Sloan [2]. Subsequent re-exposure of most of the outcrops occurred only after sea levels decreased following the Cretaceous and subsequent weathering. Such weathering would also explain the location of fossiliferous float at land surface on the slopes of or near the base of some outcrops (Fig 3C–3E); the float material is composed of the same consolidated, ferruginous sandstone as found at the peaks of the outcrops. Fossiliferous float is also found in a somewhat continuous layer in Upper Cretaceous sediment at depths of 1 to 2 m below land surface (Fig 3F) at short distances from the outcrops and is characterized by the same large, angular, iron-cemented quartz grains that comprise the outcrops.

## Conclusions

This discovery of lower-to-middle Paleozoic tabulate coral fossils in ferruginous sandstones that crop out amidst the much younger Carolina Sandhills of the ACP should provide impetus for the recreation of paleolandmasses and potential linkages to the cause of such rapid burial, perhaps as may be related to the Ordovician-Silurian extinction event, as this initial work documents rapid coral burial as evidenced by fossil association with angular sand grains. The fossils extend the distribution of the Syringophyllidae into North America where they were not previously recognized or recorded. Additional field and laboratory work would facilitate further resolution of the geologic history of the SAMR and ACP in the Southeastern USA to an extent similar to the more fossiliferous strata of Avalonia in the Northern Appalachians.

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## Author Contributions

**Conceptualization:** James E. Landmeyer.

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**Formal analysis:** James E. Landmeyer.

**Investigation:** James E. Landmeyer.

**Methodology:** James E. Landmeyer.

**Project administration:** James E. Landmeyer.

**Validation:** Mikołaj K. Zapalski.

**Writing – original draft:** James E. Landmeyer.

**Writing – review & editing:** Francis Tourneur, Julien Denayer, Mikołaj K. Zapalski.

## References

1. Tuomey, M. Report on the Geology of South Carolina. 1848. Printed and published for the state by A.S. Johnson, Columbia, SC.
2. Sloan, E. A preliminary report on the clays of South Carolina. 1904; S.C. Geological Survey, Series 4, Bulletin 1: 171.

3. Berry E.W. The Upper Cretaceous and Eocene floras of South Carolina and Georgia. U.S. Geological Survey Professional Paper. 1914; 84: 200.
4. Cooke C.W. Geology of the Coastal Plain of South Carolina. U.S. Geological Survey Bulletin. 1936; 867: 196.
5. Dorf E. Critical analysis of Cretaceous stratigraphy and paleobotany of Atlantic Coastal Plain. American Association of Petroleum Geologists Bulletin. 1952; 36: 2162–2184.
6. Howe J.T., Howard A.S. Fossil locations in South Carolina. 1978. Museum Bulletin Number 3. South Carolina State Museum, IRM Printing Services, Columbia, SC.
7. Goldstein A. Distribution of Paleozoic corals in the United States. Mid-America Paleontological Society Digest. 1985; March.
8. Wait, R.L., Davis, M.E. Configuration and hydrology of the pre-Cretaceous rocks underlying the Southeastern Coastal Plain aquifer system. U. S. Geological Survey Water-Resources Investigations Report 86–4010. 1986.
9. Prowell D.C., Christopher R.A., Waters K.E., Nix S.K. The chrono- and lithostratigraphic significance of the Type Section of the Middendorf Formation, Chesterfield County, South Carolina. Southeastern Geology. 2003; 42: 47–66.
10. Fitzwater, B.A. Swezey, C.S., Whittecar, G.R., Garrity, C.P., Mahan, S.A. Geologic mapping of the Middendorf and Patrick Quadrangles, Chesterfield County, South Carolina. The Geological Society of America, Southeastern Section, 63rd Annual Meeting, April 10–11, 2014, Blacksburg, VA. Geological Society of America Abstracts with Programs. 2014; 46: 82.
11. Conley J.F. Geology of the Albemarle quadrangle, North Carolina. Geological Society of America Bulletin. 1959; 70: 1760.
12. St. Jean, J. A new Cambrian trilobite from the Piedmont of North Carolina. American Journal of Science. 1973; 273-A: 196–216.
13. Cloud P., Wright J., Glover L. III. Traces of animal life from 620-million-year-old rocks in North Carolina. American Scientist. 1976; 64: 396–406.
14. Gibson G.G., Teeter S.A., Fendokin M.A. Ediacarian fossils from the Carolina slate belt, Stanly County, North Carolina. Geology. 1984; 12: 387–390.
15. Koeppen R., Repetski J., Waery D. Microfossil assemblages indicate Ordovician or Late Cambrian age for Tilley Formation and mudstone member of Cid Formation, Carolina Slate Belt, North Carolina. Geological Society of America Abstracts with Programs. 1995; 27: A397.
16. Offield, T.W., Sutphin, D.M. Revised stratigraphic and tectonic framework of the Carolina Slate Belt from southern Virginia to the South Carolina–Georgia border (with observations bearing on the origin of the slate-belt gold deposits. U.S. Geological Survey Open-File Report 99–2. 1999.
17. Hibbard J., McMenamin M.A.S., Pollock J., Weaver P.G., Tacker R.C., Miller B.V., et al. Significance of a new Ediacaran fossil find in the Carolina Terrane of North Carolina. Geological Society of America Abstracts with Programs. 2006b; 38: 91.
18. Weaver P.G., Tacker R.C., McMenamin M.A.S., Webb R.A. Ediacaran body fossils of South-Central North Carolina-Review and analysis of a Neoproterozoic-Early Cambrian Fauna. Geological Society of America Abstracts with Programs. 2006; 38: 550.
19. Maher H.D., Palmer A.R., Secor D.T., Snoke A.W. New trilobite locality in the Piedmont of South Carolina, and its regional implications. Geology. 1981; 9: 34–36.
20. Allen A.T., Lester J.G. Contributions to the paleontology of northwestern Georgia. Georgia Geological Survey Bulletin. 1954; 62: plate 18, f.1.
21. Bourland W.C., Rigby J.K. Sponge spicules from early Paleozoic rocks of the Carolina Slate Belt. Geological Society of America Special Paper. 1982; 191: 125–132.
22. Secor D.T. Jr., Samson S.L., Snoke A.W., Palmer A.R. Confirmation of the Carolina Slate Belt as an Exotic Terrane. Science. 1983; 221: 649–650. https://doi.org/10.1126/science.221.4611.649 PMID: 17787733
23. Samson S., Palmer A.R., Robison R.A., Secor D.T. Jr. Biogeographical significance of Cambrian trilobites from the Carolina Slate belt. Geological Society of America Bulletin. 1990; 102: 1459–1470.
24. Williams H., Hatcher R.D. Jr. Suspect terranes and accretionary history of the Appalachian orogen. Geology. 1982; 10: 530–36.
25. Secor D.T. Jr., Snoke A.W., Bramlett K.W., Costello O.P., and Kimbrell O.P. Character of the Alleghenian orogeny in the southern Appalachians-Part I. Alleghenian deformation in the eastern Piedmont of South Carolina. Geological Society of America Bulletin. 1986; 97: 1319–1328.
26. Vick H.K., Channell J.E.T., Opdyke N.D. Ordovician docking of the Carolina Slate Belt–Paleomagnetic data. Tectonics. 1987; 6: 573–585.

**27.** Dennis A.J., Shervais J.W. The Carolina terrane in northwestern South Carolina–Insights into the development of an evolving island arc. Geological Society of America Special Paper. 1996; 304: 237–256.

**28.** Dennis A.J., Wright J.E. Middle and late Paleozoic monazite U-Pb ages, Inner Piedmont, South Carolina. Geological Society of America Abstracts with Program. 1997; 29:12.

**29.** Hibbard J. Docking Carolina–Mid-Paleozoic accretion in the southern Appalachians. Geology. 2000; 28: 127–130.

**30.** Hibbard J.P., Stoddard E.F., Secor D.T., Dennis A.J. The Carolina Zone-Overview of Neoproterozoic to Early Paleozoic peri-Gondwanan terranes along the eastern Flank of the southern Appalachians. Earth Science Reviews. 2002; 57: 299–339.

**31.** Murphy J.B., Pisarevsky S.A., Nance R.D., Keppie J.D. Neoproterozoic–Early Paleozoic evolution of peri-Gondwanan terranes–Implications for Laurentia-Gondwana connections. International Journal of Earth Science. 2004; 93: 659–682.

**32.** Murphy J.B., Keppie J.D. The Acadian Orogeny in the Northern Appalachians. International Geology Review. 2005; 47: 663–687.

**33.** Hibbard, J.P., van Staal, C.R., Rankin, D.W., Williams, H. Lithotectonic map of the Appalachian orogen (South), Canada-United States of America. Geological Survey of Canada Map. 2006a; 02096A: 2 sheets, scale 1:1,500,000.

**34.** Hibbard J.P., van Staal C.R., Rankin D.G. Comparative analysis of the geological evolution of the northern and southern Appalachian orogen–Late Ordovician-Permian. In: Tollo R.P., Bartholomew M.J., Hibbard J.P., and Karabinos P.M., editors. From Rodinia to Pangea; The lithotectonic record of the Appalachian Region. Geological Society of America Memoirs. 2010; 206: 51–69.

**35.** Hibbard J.P., Miller B.V., Hames W.E., Standard I.D., Allen J.S., Lavallee S.B., et al. Kinematics, U-Pb geochronology, and 40Ar/39Ar thermochronology of the Gold Hill shear zone, North Carolina–The Cherokee orogeny in Carolinia, Southern Appalachians. Geological Society of America Bulletin. 2012; 124: 643–656.

**36.** Campbell B.G., Coes A.L. Groundwater availability in the Atlantic Coastal Plain of North and South Carolina. U.S. Geological Survey Professional Paper. 2010; 1773: 241,7 pls.

**37.** Campbell, B.G., Landmeyer, J.E. Groundwater availability in the Crouch Branch and McQueen Branch aquifers, Chesterfield County, South Carolina, 1900–2012. U.S. Geological Survey Scientific Investigations Report 2014–5050. 2014; 68.

**38.** Swezey C.S., Schultz A.P., González W.A., Bernhardt C.E., Doar W.R. III, Garrity C.P., et al. Quaternary eolian dunes in the Savannah River valley, Jasper County, South Carolina, USA. Quaternary Research. 2013; http://dx.doi.org/10.1016/j.yqres.2013.06.007.

**39.** Woollen I., Colquhoun D.J., Nieuwenhuise D.V. The Upper Cretaceous rocks of the Great Peedee River Valley–A guide prepared for the 1978 Carolina-Clemson Field Excursion, April 22, 1978. University of South Carolina. 1978; 33.

**40.** Nystrom P.G. Jr., Willoughby R.H., Price L.K. 12. Cretaceous and Tertiary stratigraphy of the Upper Coastal Plain, South Carolina. In: Horton J.W. Jr., Zullo V.A., editors. The Geology of the Carolinas. Carolina Geological Society Fiftieth Anniversary Volume. 1991; 221–250.

**41.** Soller, D.R., Mills, H.H. 17. Surficial geology and geomorphology. In: The Geology of the Carolinas, Carolina Geological Society Fiftieth Anniversary Volume, Horton, J.W., Jr., and Zullo, V.A. editors, 1991; 290–308.

**42.** Swezey C.S., Fitzwater B.A., Whittecar G.R., Mahan S.A., Garrity C.P., González W.A., et al. The Carolina Sandhills–Quaternary eolian sand sheets and dunes along the updip margin of the Atlantic Coastal Plain province, southeastern United States. Quaternary Research. 2016; 86: 271–286.

**43.** Bell, H., III, Butler, J.R., Howell, D.E., Wheeler, W.H.Geology of the Piedmont and Coastal Plain near Pageland, South Carolina and Wadesboro, North Carolina. Carolina Geological Society Guidebook for 1974 Annual Meeting. 1974; 1–16.

**44.** Campbell, B.G., Voytek, E.B. Bedrock topography of the McBee, South Carolina, area, based on bedrock altitudes from geologic borings and analysis of ambient seismic noise by the horizontal-to-vertical spectral-ratio method, as Appendix 1. In: Campbell, B.G. Landmeyer, J.E. (2014a) Groundwater availability in the Crouch Branch and McQueen Branch aquifers, Chesterfield County, South Carolina, 1900–2012. U.S. Geological Survey Scientific Investigations Report 2014–5050. 2014; 68.

**45.** Hill D. Treatise on Invertebrate Paleontology, Part F- Coelenterata, Supplement 1-Rugosa and Tabulata, volume 1, 2009. University of Kansas Paleontological Institute. 1981; 743.

**46.** Sokolov B. S. Palaeozoic tabulates of the European part of USSR Vol. 1, Introduction: General problems of systematics and evolution of the tabulates. Trudy Vsesoyuznogo Neftyanogo Nauchno-Issledovatel'skogo Geologo-Razvedochnogo Instituta (VNIGRI). Novaya Seriya. 1955; 85: 1–527.

**47.** Khaiznikova K.B. Evolution of Paleozoic corals of the Verkhoyansk Mountains. Acta Paleontologica Polonica. 1980; 25: 5675–570.

**48.** Bondarenko O.B., Ulitina L.M. Ordovician corals of the Siberian and Mongolian basins: Taxonomic diversity, morphogenesis, and occurrence. Paleontological Journal. 2009; 43: 1439–1457.

**49.** Oekentorp K. The microstructure concept-coral research in the conflict of controversial opinions. Bulletin of Geosciences. 2007; 82: 95–97.

**50.** Zapalski M.K. Tabulate corals from the Givetian and Frasnian of the southern region of the Holy Cross Mountains (Poland). Special Papers in Palaeontology. 2012; 87: 1–100.

**51.** Ehrenberg C.G. Dritter Beitrag zur Erkenntniss grosser Organisation in der Richtung des kleinsten Raumes. Abhandlungen der Königlichen Akademie der Wissenschaften zu Berlin. 1834; 1833: 145–336, pls I-XIII.

**52.** Milne-Edwards H., Haime J. A monograph of the British fossil corals. Palaeontographical Society. 1850; 322.

**53.** Roemer C.F. Lethaea geognostica, Theil 1: Lethaea palaeozoica. E. Schweizerbart, Stuttgart. 1883; 544.

**54.** Sokolov B.S., Tesakov J.I. Tabulyaty paleozoya Sibiri [Paleozoic Tabulata of Siberia]. Akademiya Nauk SSSR, Sibirskoe Otdelenie, Institut Geologii i geofiziki. 1963; 1–188. Moscov–Leningrad.

**55.** Oliver W.A., Hecht W.S. Well-preserved favositid corals in the Oriskany Sandstone (Lower Devonian) of New York: in Landing Ed, ed., Studies in stratigraphy and paleontology in honor of Donald W. Fisher. New York State Museum Bulletin. 1994; 481: 265–287.

**56.** Cook A.G. 1994. Sedimentology and depositional environments of the Middle Devonian Big Bend Arkose and Burdekin Formation, Fanning River Group, Burdekin Subprovince, North Queensland, Australia. Memoirs of the Queensland Museum. 1994; 38: 53–91.

**57.** Haq B.U., Shutter S.R. A chronology of Paleozoic seal-level changes. Science. 2008; 322: 64–68. https://doi.org/10.1126/science.1161648 PMID: 18832639

**58.** Brachert T.C., Forst M.H., Pais J.J., Legoinha P., Reijmer J.J.G. Lowstand carbonates, highstand sandstones? Sedimentary Geology. 2003; 155: 1–12.

**59.** Blakey R.L. Ordovician paleogeography of North America. Colorado Plateau Geosystems, Arizona, USA. 2019; http://cpgeosystems.com/paleomaps.html

**60.** Kimberley M.M. Origin of oolitic iron formations. Journal of Sedimentary Petrology. 1979; 49: 0111–0132.

**61.** Kimberley M.M. Exhalative origins of iron formations. Ore Geology Reviews. 1989; 5: 13–145.

**62.** Arkai, P., Sassi, F.P., Desmons, J. Very low-to low-grade metamorphic rocks-Recommendations by the IUGS Subcommission of the systematics of metamorphic rocks.

**63.** Cotter E., Link J.E. Deposition and diagenesis of Clinton ironstones (Silurian) in the Appalachian Foreland Basin of Pennsylvania. Geological Society of America Bulletin. 1993; 105: 911–922.

**64.** Hatcher R.D. Jr., Howell D.E., Talwani P. Eastern Piedmont fault system: Speculations on its extent. Geology. 1977; 5: 636–640.

**65.** Maybin A.H. III. Structural features of South Carolina. South Carolina Department of Natural Resources Geological Survey Map. 1998.

**66.** Prowell D.C., O'Connor B.J. Belair fault zone: Evidence of Tertiary fault displacement in eastern Georgia. Geology. 1978; 6: 681–684.

**67.** Faye R.E., Prowell D.C. Effects of Late Cretaceous and Cenozoic faulting on the geology and hydrology of the Coastal Plain near the Savannah River, Georgia and South Carolina. U. S. Geological Survey Open-File Report 82–156. 1982; 73 p.

**68.** Nystrom P.G. Jr. Late Cretaceous-Cenozoic brittle faulting beneath the western South Carolina Coastal Plain: Reactivation of the Eastern Piedmont Fault System. South Carolina. Geological Society of America Abstracts with Programs. 2005; 38: 74.

**69.** Prowell, D.C., O'Connor, B.J., Rubin, M. Preliminary evidence for Holocene movement along the Belair Fault Zone near Augusta, Georgia. U.S. Geological Survey Open-File Report 75–680. 1975.