

# Paleoenvironmental and paleobiogeographic implications of a new Ediacaran body fossil from the Neoproterozoic Carolina Terrane, Stanly County, North Carolina

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Received 21 September 2005; received in revised form 10 July 2006; accepted 12 July 2006

## Abstract

New partial swartpuntioid from Neoproterozoic age rocks of Stanly County, North Carolina, herein assigned to cf. ?*Swartpuntia* sp., along with previously described *Pteridinium carolinaensis*, *Aspidella*, other metazoan trace fossils, and previously reported radiometric ages, suggest Nama Assemblage type affinities for the Carolina Terrane. The new specimen, cf. ?*Swartpuntia* sp., and associated radiometric ages add further information pertaining to proposed geographic linkages between the Carolina Terrane and the Avalon Terrane. This new swartpuntioid may be evolutionarily convergent (in terms of habitat preference) to the infaunal or partially infaunal habitat preferred by other members of the Nama-type Ediacaran biota such as *Pteridinium* and *Rangea*.

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**Keywords:** Ediacaran; *Swartpuntia*; Carolina Terrane; Paleogeography

## 1. Introduction

Reports of fossils from the Carolina Terrane of North Carolina have been limited and not without controversy. The first reported fossil, *Palaeotrochus* Emmons (1856), turned out to be spherulites from rhyolitic flows of the Uwharrie Formation. Conley (1959) found impressions resembling worm burrows in a tuffaceous argillite from an abandoned State Highway quarry, southwest of Aquadale, Stanly County, North Carolina. Stromquist and Sundelius (1969) reported possible coalified algae from Stanly County. In 1973, St. Jean reported a trilo-

bite, *Paradoxides carolinaensis*, which turned out, along with other subsequently described specimens (Teeter, 1983; Gibson et al., 1984; Milton, 1984; Gibson and Teeter, 2001; McMenamin and Weaver, 2002), to be the Ediacaran frond-type fossil *Pteridinium carolinaensis* (St. Jean, 1973). Cloud et al. (1976) reported *Vermiforma antiqua* from Carolina Terrane rocks from the Durham, North Carolina area. However, Seilacher and Meschede (1998) and Seilacher et al. (2000) argued for tectonic, rather than biologic, origins for these specimens. The discovery of another type of trace fossil on the *Vermiforma* slab (McMenamin, 2001), however, supports Cloud's original interpretation of the structures as biogenic.

Gibson (1989) described typical Precambrian ichnofossils from Stanly, County, NC. Finally, Koeppen et al. (1995) reported in an abstract euconodonts, bryozoan zooecial steinkerns and gastropod steinkerns from the

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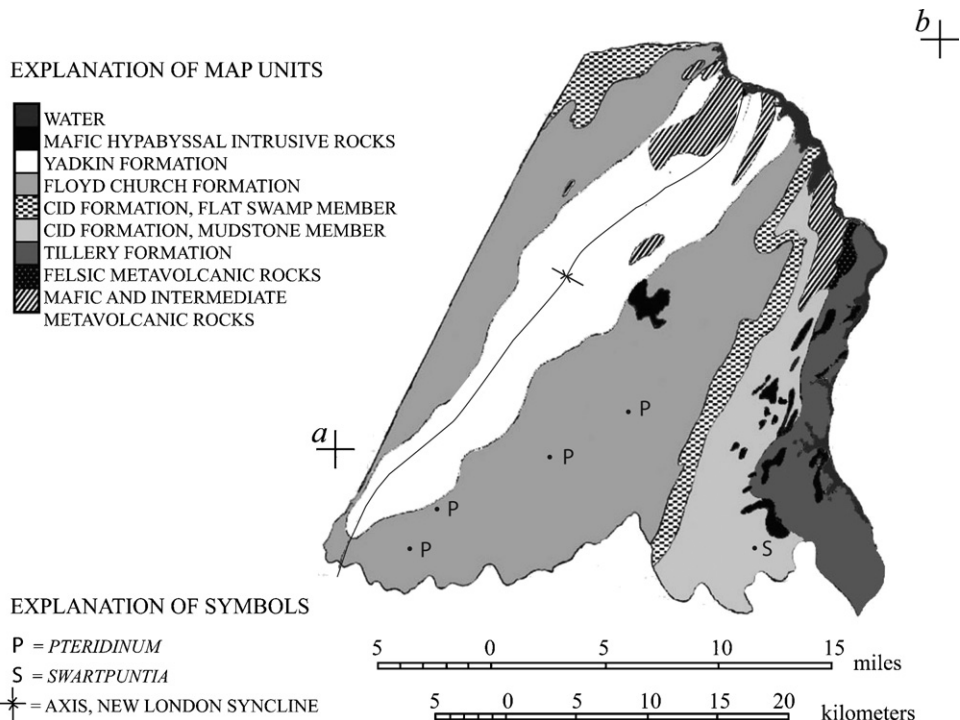


Fig. 1. Geologic map of Stanly County, North Carolina (adapted from Goldsmith et al., 1988) showing *Pteridinium carolinaensis* (adapted from Gibson and Teeter, 2001) and cf. *Swartpuntia* sp. localities. Coordinates are (a) 35° 15'N, 80° 30'W and (b) 35° 30'N, 80° W.

Tillery Formation, from a quarry near Asheboro, Stanly County, North Carolina, and euconodonts from the Cid Formation, from the Jacobs Creek Quarry near Denton, Davidson County, North Carolina. Images of these specimens have yet to be published. Recently, Hibbard et al. (2006) reported *Aspidella* from the unnamed mudstone member of the Cid Formation, from Jacobs Creek Quarry near Denton, Davidson Co., North Carolina. These specimens have yet to be formally described. As Ediacaran body fossils from the Carolina Terrane are so few in number, and have been until recently limited to *Pteridinium*, any different Ediacaran body fossil, even if only partially preserved, has great significance.

A new partial Ediacaran specimen, showing two collapsed petaloids, straight petaloidal segments abruptly curving at their distal ends to form a candle-flame shaped termination, with extremely high angles between the petaloids, was found by Tony Furr, on privately owned property, southeast of Cottonville, near Mount Zion Church, Stanly County, North Carolina (Fig. 1). Described herein as cf. *Swartpuntia* sp., this specimen will help refine North Carolina's placement with respect to other Ediacaran faunas worldwide and will add another piece of data to the continued debate over the paleogeographic origin of the Carolina Terrane.

## 2. Geologic setting

The Carolina Terrane extends from southern Virginia southwest to Georgia and is considered to be one of several peri-Gondwanan exotic terranes that accreted to the eastern margin of Laurentia (e.g. Hibbard et al., 2002). Rocks within the Carolina Terrane generally show a lower greenschist-facies grade of regional metamorphism (Gibson and Huntsman, 1988). Stratigraphy of the Carolina Terrane in North Carolina has undergone a series of revisions. In North Carolina, workers have recognized three main stratigraphic units: the Virgilina sequence, the Uwharrie Formation and the Albemarle Group (Conley, 1962; Conley and Bain, 1965; Stromquist and Sundelius, 1969; Seiders, 1978; Milton, 1984). Generalized stratigraphy, radiometric ages and fossil fauna are given in Fig. 2.

Koepfen et al. (1995) reported euconodonts from the unnamed mudstone member of the Cid Formation (Jacobs Creek Quarry, Davidson County, North Carolina) and assigned a late Cambrian or Ordovician age to this unit. Field relations indicate that this unit is stratigraphically lower than the unit containing *Pteridinium carolinaensis*. Recent field work in the unnamed mudstone member of the Cid Formation at Jacobs Creek Quarry has yielded several specimens of the Neoproterozo-

	Formation	Lithology	Radiometric ages	Fossils
<b>Albemarle Group</b>	Yadkin Graywacke	Graywackes and sparse andesitic volcanics (Stromquist and Sundelius, 1969). Sedimentary structures within the lower Yadkin Graywacke suggest shallow marine deposition (Gibson and Teeter, 1984), which appears to grade upward into non-marine facies (Gibson and Teeter, 2001).	540 +/- 7 Ma (Black, 1978, heterolithic tuff)	<b>Ichnofossils</b> <i>Monocraterion</i> sp.
	Floyd Church Formation	Epiclastic mudstone containing lenses of andesites and dacites (Milton, 1984).		<b>Ichnofossils</b> <i>Gordia arcuata?</i> <i>Helminthopsis</i> sp. <i>Neonerites biserialis</i> <i>Neonerites uniserialis</i> <i>Neonerites</i> sp. <i>Planolites beverlyensis</i> <i>Planolites montanus</i> <i>Planolites</i> sp. <i>Syringomorpha nilssoni?</i> <i>Tomaculu m</i> sp. <i>Torrowange a</i> sp. Ichnogenera A & B of Gibson (1989)  <b>Bodyfossils</b> <i>Pteridinium carolinaensis</i>
	Cid Formation Flat Swamp Member	Sequence of felsic, mafic and rare intermediate volcanic rocks (Stromquist and Sundelius, 1969).	540.6 +/- 1.2 Ma (Ingle et al., 2003) 547 +/-2 Ma (Hibbard et al., 2006).	
	Cid Formation Unnamed Mudstone Member	Thinly bedded epiclastic mudstones (Milton, 1984) with thick beds of felsic volcanics and lenses of both felsic and mafic lavas (Conley and Bain, 1965; Seiders, 1978).		<b>Ichnofossils</b> Ichnogenus C of Gibson (1989)  <b>Bodyfossils</b> <i>Cf. Swartpuntia</i> sp. <i>Aspidella</i> sp. Euconodonts (disputed report)
	Tillery Formation	~5,000 feet (~1,500m) of laminated to thinly bedded epiclastic mudstones with minor lenses of volcanoclastic rocks and felsic and mafic lavas (Milton, 1984). Lower part also includes cross-bedded sandstones and sub-aqueous debris flows (Gibson and Teeter, 1984). Upper part is more tuffaceous, with thin water-laid tuff layers, thinly laminated claystone and siltstone (Gibson and Teeter, 1984).		<b>Ichnofossils</b> <i>Monocraterion</i> sp.  <b>Bodyfossils</b> Euconodonts (disputed report)
	Uwharrie Formation	~20,000 feet (6,000 m) of felsic volcanoclastic rocks (Stromquist and Sundelius, 1969). Primarily felsic volcanics, including felsites, tuffs, bedded tuffs and epiclastic conglomerates (Ingram, 1999).	554 +/-15 Ma (Ingle et al., 2003).	
	Virgilina Sequence	Extensive succession of plutonic, volcanic and epiclastic rocks ranging from mafic to felsic in composition (Black, 1980; Rogers, 1982). Volcanics of this sequence are dominantly sub-aqueous pyroclastics interpreted as having been deposited in shallow water (Glover and Sinha, 1973; Green et al., 1982; Harris and Glover, 1988).	Bulk of sequence 633 (+2/-1.5) to 612.4 (+5.2/-1.7) Ma (Wortman et al., 2000). Extrusives 618 +/-3 Ma, intrusives 605 +/- 7.4 Ma (Ingle et al., 2003).	<b>Ichnofossils</b> <i>Vermiforma antiqua</i>

Fig. 2. Generalized stratigraphic column showing formations contained within the Carolina Terrane, radiometric ages and fossil faunas. Dashed lines represent gradational boundaries between units. Wavy line indicates an unconformity. Trace fossil data from Gibson (1989), Euconodont data from Koeppen et al. (1995), *Pteridinium carolinensis* data from Gibson and Teeter (2001), and *Aspidella* data from Hibbard et al. (2006).

zoic genus *Aspidella* (Hibbard et al., 2006). It is possible there is a structural discontinuity between this unit and overlying units (Koeppen et al., 1995; Gibson and Teeter, 2001; Hibbard et al., 2002). Gibson and Teeter (2001) suggested that the Ugly Creek Thrust described by Dockal and Huntsman (1990) could account for this. However, the proposed thrust faults (Dockal and Huntsman, 1990) were predicated on the identification of turbidites, and on models incorporating grain size distribution, bed thickness and internal sedimentary structure. All of these assumptions, including the characterization of the units as turbidites, were called into question by Butler and Secor (1991). Field mapping at 1:250,000 scale (Goldsmith et al., 1988) and at the 1:24,000 scale (Ingram, 1999) showed no evidence of these proposed faults. Recent work suggests that there are unrecognized unconformable inliers of younger strata deformed within the sequence (Hibbard et al., 2002). Hibbard et al. (2006) suggest three possibilities; Jacobs Creek Quarry may contain rocks of both Neoproterozoic and Paleozoic age, but their interrelationship has not been recognized; any Paleozoic rocks would represent small outliers (stratigraphic or structural) on the Neoproterozoic strata; or reports of Paleozoic fossils from the quarry are erroneous.

The partial specimen of cf. *?Swartpuntia* sp. was found on private property, from surface deposits weathered out of a nearby exposed bank, southeast of Cottonville, near Mount Zion Church, Stanly County, North Carolina. The specimen was found near an outcrop of fine-laminated siltstone. No evidence of soft-sediment deformation or slumping was observed.

The top layer of the hand specimen shows a vertical fracture associated with waviness in the underlying laminations, suggesting differential compaction of the siltstone laminae and associated microfaulting (Fig. 3). The rock consists of interstratified siltstone laminae, <1–4 mm thick, distinguished by differences in iron oxide content (Fig. 4). The darker laminae may have held larger amounts of clay or organic matter that led to enhanced precipitation of iron oxide minerals. Whether these darker layers are due to microbial mat influence, or to size and shape sorting in a unidirectional current, is not certain.

In thin section (Fig. 5), the rock consists of two populations of quartz that form an unusual mixture. Quartz type 1 (about 80–85% of the rock) consists of equigranular grains, typical size 20  $\mu\text{m}$  in diameter with long contacts between grains. The grains are monocrystalline but many grains show numerous fractures that are less straight than is typical for impact-shocked quartz. Partly because of the fracturing, the grains



Fig. 3. Thin section view of fossil-bearing siltstone showing soft-sediment faulting and fracture filling by a thin silt wedge. The image is in presumed proper stratigraphic orientation, so the fracture evidently formed above the underlying beds. Width of view 13.5 mm.

appear cloudy to dark even when far from cross-polar extinction.

Quartz type 2 (about 15–20% of the rock) consists of lath-shaped grains, typically 2  $\mu\text{m}$   $\times$  10  $\mu\text{m}$  in size. The grains are monocrystalline, but many have undulose extinction, suggesting derivation from a metamorphic rock type. Whether or not the elongate shapes of the grains are associated with the metamorphism is not known.

The oxides appear clotted and reddish to light orange under cross-polars. Feldspars, clays and accessory minerals are rare to absent. Cathodoluminescence analysis reveals rare, tiny grains of what are probably potassium feldspar (blue luminescence) and orange luminescence

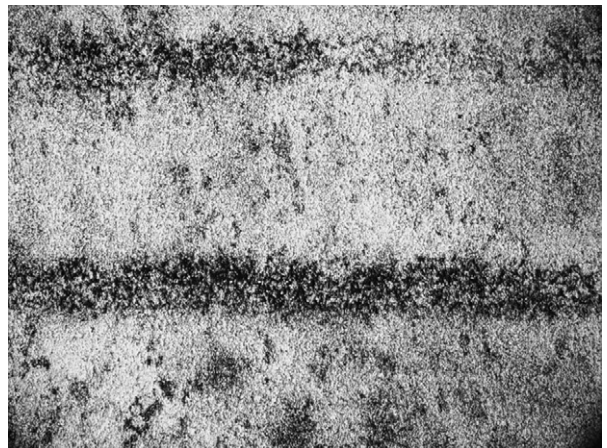


Fig. 4. Enlarged view of oxide laminae in siltstone specimen. The oxide laminae have relatively sharp bases and these are presumed to be the bedding soles. Width of view 8 mm.



Fig. 5. Cross-polar photomicrographic view of fossil-bearing siltstone. Two populations of grains are present, larger (and darker) quartz grains and smaller, elongate, and lighter-appearing elongate grains. Width of view 400  $\mu\text{m}$ .

grains of similar size and rarity that may represent carbonate grains.

The possible depositional environment for this rock is not unambiguous, but based on the primarily quartzose nature of the siltstone, we interpret this rock as deposited in a marine environment not greatly distant from sources of sediment (Figs. 5.3 and 5.5 in Brice et al., 2001). The interstratification of oxide-rich and oxide-poor laminae suggests that deposition was episodic. Thus we interpret deposition as occurring in relatively quiet water below storm wave base (50 m; Dalrymple and Cummings, 2006) in pulses associated with sediment mobilization and unidirectional transport on what might be considered a shelf-margin delta (Dalrymple and Cummings, 2006). This might help explain the rarity of feldspar, as the amount of feldspar drops off dramatically in the offshore direction in siltstones deposited offshore from a delta front (Brice et al., 2001). Organic matter possibly associated with the dark, oxide-rich laminae may represent deltaic input of fine organic debris. Metamorphism of quartz type 2 is consistent with evidence for a deformational event that predates the Appalachian orogenic cycle (Hibbard and Samson, 1995).

Based on locality (Fig. 1), comparison of the specimen and adjacent outcrop, and rock type (Fig. 2), it is likely that cf. *?Swartpuntia* sp. comes from the unnamed mudstone member of the Cid Formation, stratigraphically much lower than *Pteridinium carolinaensis*.

### 3. Radiometric ages

Radiometric ages for Carolina Terrane rocks are given in Fig. 2. Early isotopic studies indicated that the

Albemarle Group was Early Cambrian. A  $540 \pm 7$  Ma Rb/Sr whole rock age was obtained from mafic volcanics in the Yadkin Formation (Black, 1978). However, Butler and Secor (1991) identified the source rock as a heterolithic tuff, sericitized prior to metamorphism. Uncertainties in the origin of the lithic fragments render this date equivocal.

Recent absolute age dating shows the Albemarle Group to be near the Cambrian-Neoproterozoic boundary ( $542.0 \pm 0.3$  Ma, Amthor et al., 2003). Ingle et al. (2003) used both TIMS and SHRIMP methods to analyze zircons from this study area in the Carolina Terrane. The presence of inherited zircons and the use of the lower-precision SHRIMP instrumentation resulted in analytical error such that most of the units overlap in age (Ingle et al., 2003). Cf. *?Swartpuntia* sp., described herein, was discovered in the unnamed member of the Cid Formation. A dacite from this unit yields an age of  $542 \pm 14$  Ma (Ingle et al., 2003). The overlying unit is the Flat Swamp member of the Cid Formation, for which more precise dates were measured,  $540.6 \pm 1.2$  Ma (Ingle et al., 2003) and  $547 \pm 2$  Ma (Hibbard et al., 2006). Consideration of the analytical error in the most recent date (Hibbard et al., 2006) gives an age bracket of 545–556 Ma for the rocks containing cf. *?Swartpuntia* sp.

Problems with inherited zircons were particularly acute with the andesite from the overlying Floyd Church Formation, resulting in a large error of the measurement. The age of the Floyd Church Formation can be better constrained by the lower limit of the higher precision age of the underlying Flat Swamp member as less than 541.8 Ma. *Pteridinium carolinaensis* is found from the Floyd Church Formation, so this age range indicates Late Neoproterozoic to Early Cambrian.

### 4. Ediacaran assemblage types

Ediacaran fossils are known from approximately thirty localities on five different continents (Narbonne, 2005). Their systematic affinities have been debated again and again with little consensus (Glaessner, 1984; Jenkins, 1985, 1992; McMenamin, 1986; Seilacher, 1989; Gehling, 1991; Fedonkin, 1992, 2003; Dewel, 2000; Dzik, 2002; Grazhdankin and Seilacher, 2002). Recent work seems to suggest that there are both animals and large protists in the Ediacaran assemblage (Jenkins et al., 2004; McMenamin, 2004). Even though systematic affinities of Ediacaran organisms have yet to be fully understood, the distribution patterns of these enigmatic fossils have been used in discussions of paleogeographic reconstructions (McMenamin, 1982; Donovan, 1987; Waggoner, 1999; Hagadorn and Waggoner, 2000), and

Assemblage type	Characteristic fauna	Paleoenvironments	Localities	Age ranges
Nama	Mineralized and agglutinated taxa: <i>Cloudina</i> , <i>Archaeichnium</i> , <i>Namacalathus</i>  Endemic frond-like fossils: <i>Ernieetta</i> and <i>Swartpuntia</i>	Distributary-mouth bar shoal	Kuibis Gr., Namibia South China British Columbia, Canada Schwartzrand Gr., Namibia Mojave Desert, USA	543.1 Ma ~543 Ma
White Sea	Bilaterally symmetrical forms: dickinsoniids, <i>Kimberella</i> , <i>Spriggina</i>  Annulated concentric forms: <i>Kullinga</i> and <i>Ovatoscutum</i>  Most known triradially symmetric forms: <i>Tribrachidium</i>	Prodelta or low-energy shore face	Wernecke Mts., NW Canada Ural Mts., Russia Finmark, Norway Olenek Uplift, Siberia Central Australia Lower Mbr., Ediacara, Australia Mbr. I, Winter Coast, Russia Podolia, Ukraine Sumer Coast, Russia Mbr. 11, Winter Coast, Russia Mbr. 9, Winter Coast Russia Main Mbr., Ediacara, Australia	~550 Ma  555.3 Ma 551 Ma
Avalon	Lobate “medusoid” <i>Ivesia</i>  Unique frond-like fossils: <i>Bradgatia</i>  Unnamed spindle	Deeper water, slope apron	Sekwi Brook, NW Canada Charnwood Forest, England Mistaken Point, Newfoundland Briscol Fm., Newfoundland	~550 Ma 559 Ma 565 Ma >565 Ma

Fig. 6. Ediacaran assemblage types (adapted from data in Gehling, 2001; Waggoner, 2003; Grazhdankin, 2004).

more recently for interpreting paleoenvironments, paleoecology and taphonomy (Grazhdankin and Ivantsov, 1996; Gehling, 2001; Clapham and Narbonne, 2002; Waggoner, 2003; Grazhdankin, 2004; Narbonne, 2005).

Recent studies by Waggoner (1999, 2003), Gehling (2001) and Grazhdankin (2004) have divided the global Ediacaran fauna into three environmentally and age related assemblage types: Avalon, White Sea and Nama. Characteristics of the each of the assemblage types are given in Fig. 6.

The Ediacaran frond-like fossils *Pteridinium carolinaensis* have been known from Stanly County, south-central, North Carolina, for nearly 3 decades (St. Jean, 1973; Teeter, 1983; Gibson et al., 1984; Milton, 1984; Gibson and Teeter, 2001; McMenamin and Weaver, 2002), reported from the stratigraphically higher Floyd Church member of the Albemarle Group. However, as *Pteridinium* was the only Ediacaran body fossil reported from the Carolina Terrane, North Carolina's Ediacaran fauna did not fit the models for Ediacaran assemblage types described by Waggoner (1999, 2003), Gehling (2001) and Grazhdankin (2004). Even with *Pteridinium* as the only body fossil from North Carolina, Waggoner (1999) (his Fig. 4) shows North Carolina being equally or slightly more closely related to the Nama Assemblage than to the Avalon Assemblage.

Recent discovery of cf. ?*Swartpuntia* sp. from the mudstone member of the Cid Formation now sheds some light on the appropriate placement of the North Carolina Ediacaran biota. As discussed above, the most precise data of Ingle et al. (2003) constrain an age of less than 541.8 for the Floyd Church Formation from which other previously reported specimens of *Pteridinium carolinaensis* (St. Jean, 1973; Teeter, 1983; Gibson et al., 1984; Milton, 1984; Gibson and Teeter, 2001; McMenamin and Weaver, 2002) were found. The data of Hibbard et al. (2006) give an age range of 545–556 Ma for the unnamed mudstone member of the Cid Formation from which cf. ?*Swartpuntia* sp. was recovered. These ages, which are strikingly younger than those reported for the Avalon Assemblage (Fig. 6), along with *Pteridinium*, which is not known from the Avalon Assemblage, and the presence of a swartpuntioid, characteristic of the Nama Assemblage, suggest that North Carolina's Ediacaran fauna has greater affinity with the Nama Assemblage than with the Avalon Assemblage (Fig. 7).

## 5. Taphonomy

Though the existence of these distinct assemblages is widely accepted, their interpretation remains controversial (Narbonne, 2005). Although some researchers

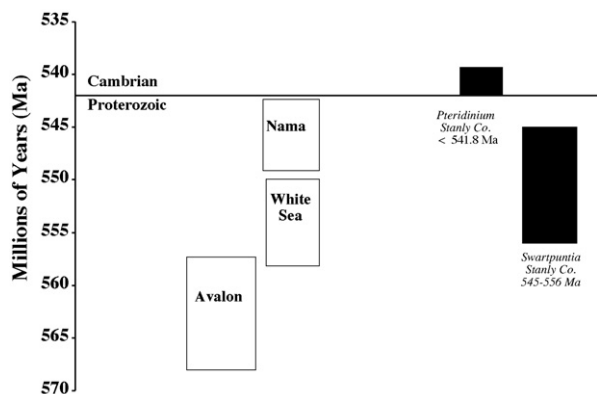


Fig. 7. Isotopic ages of North Carolina Ediacarans in relation to isotopic ages of the three Ediacaran assemblage types (adapted from data in Waggoner, 2003; Ingle et al., 2003).

argue that assemblage types do not reflect biogeography (Waggoner, 1999, 2003; Grazhdankin, 2004), the hypothesized paleobiogeographic link between Australian and White Sea Ediacaran biotas (McMenamin, 1982) has survived all tests to date. Faunal succession does appear to have some influence on assemblage types (Waggoner, 2003), but this apparent temporal control may equally reflect a coincidental association of volcanism (Narbonne, 2005). Grazhdankin (2004) speculated that environments played a major role in controlling assemblage types, but purely environmental control does not explain why a deeper-water assemblage from northwestern Canada is interpreted as a White Sea, not an Avalonian Assemblage (Waggoner, 2003). Recent studies by Narbonne (2005) propose that taphonomy is a major influence on the nature and composition of Ediacaran assemblages.

## 6. Paleogeography

Over the past several decades there has been much debate over the geographic origin of the Carolina Terrane. Hibbard et al. (2002), in their extensive discussion of age, origin and deformational history of the Carolina Terrane state that one of the first-order outstanding problems is the affinity of the fossil fauna, as it relates to paleogeographic setting. Thus it is important to examine the possible implications of the discovery of cf. *Swartpuntia* sp. from Stanly County, North Carolina, regarding the biogeographic origin of the Carolina Terrane.

Most workers agree that the Carolina Terrane is exotic with respect to Laurentia and considered it to be peri-Gondwanan in origin (Hibbard et al., 2002). The simplest evidence is that the Carolina Terrane was forming in a convergent marginal setting at the same time

the eastern edge of Laurentia (present coordinates) was accumulating passive margin sediments (e.g. Shervais et al., 1996). Other evidence that the Carolina Terrane is exotic with respect to Laurentia include: gross geological evolution similar to that of other peri-Gondwanan terranes throughout the North Atlantic region (Secor et al., 1983; Nance and Murphy, 1996), the southern part of the Carolina Terrane (near Batesburg, South Carolina) contains an “Acado-Baltic” trilobite fauna that is considered to be exotic to Laurentia, but similar to Gondwanan faunas (Samson et al., 1990; McMenamin, 2002; McMenamin and Weaver, 2002, 2004), and areas within the terrane record a deformational event that predates the Appalachian orogenic cycle (Hibbard and Samson, 1995; Dennis and Wright, 1997; Barker et al., 1997). Although Landing (1996) subsequently suggested that “Acado-Baltic” be discontinued as it grouped dissimilar faunas, this does not change the interpretation of the Carolina faunas as exotic to Laurentia.

Though it is generally agreed that the Carolina Terrane is exotic with respect to Laurentia, its geographic origins are still debated. Williams and Hatcher (1983) and Hatcher et al. (1990) proposed that the Carolina Terrane is one of the pieces of the disrupted Avalon Terrane. Dextral translation of the Grenvillian Goochland Terrane from a position much farther north in the orogen, followed by reaccrction, has been proposed (Bartholomew and Tollo, 2004), presumably similar to the transport of the Carolina Terrane from a more northerly Avalonian source. Association of the Carolina Terrane with the Avalon Terrane is based on broad similarities in timing of magmatism, lithology and faunas distinct from those of Laurentia (Secor et al., 1983; Gibson et al., 1984; Samson et al., 1990; McMenamin and Weaver, 2002, 2004; Ingle et al., 2003). The Carolina Terrane and Avalon also appear to have docked with Laurentia at roughly the same time (Hibbard, 2000), although widespread consensus on the time of Carolina docking is lacking (see Hibbard et al., 2002, for review).

Conclusions regarding the geochemical affinities of the Carolina Terrane section in this study area continue to evolve. Mueller et al. (1996) inferred from U-Pb and Nd-Sm data that there was a Mesoproterozoic component, possibly Grenvillian, to the later volcanic rocks of the Carolina Terrane. The “Grenvillian” component was later reinterpreted as Orinoquian (Ingle et al., 2003), the “Grenvillian” timing resulting from Laurentian-Amazonian interaction that produced the ca. 1 Ga Grenville Orogeny. Juxtaposition of the Goochland Terrane with the Carolina Terrane offers another source of a “Grenvillian” component (Hibbard and Samson, 1995). Some authors group Avalon with Carolina based

on broadly contemporaneous and long-lived magmatism, provenance near Amazonia or Baltica, faunas exotic to Laurentia, and termination in a Cambrian platform sequence (Ingle et al., 2003; Keppie et al., 2003).

When considered in detail, the similarities between Avalon and Carolina Terranes do not persist. Uranium-lead zircon dates and Nd isotopic character suggest that earliest Carolina Terrane rocks of the Virgilina group were built on juvenile oceanic crust (Wortman et al., 2000). Wortman et al. (2000) concluded that Avalon and Carolina should be considered as separate entities. Samson et al. (1995) compared detrital and xenocrystic zircons from Avalon and Carolina Terranes and concluded that the two should be considered as having different basements. Samson (2004) noted that the timing of magmatism for the Carolina Terrane spanned 633–547 Ma, while there were two distinct phases of magmatism in Avalon, 630–600 and 570–550 Ma. More recent proposals suggest that the Carolina Terrane is more closely related to the Gander Terrane, inboard of Avalon in eastern Canada (Hibbard and van Staal, 2004).

The inherited zircons that plagued determination of U-Pb crystallization ages for the Albemarle Group (Ingle et al., 2003) yield dates that match events in the Amazon Craton. Earlier work based on detrital zircon dates and Nd isotopic data suggested the same for the Avalon Terrane (Nance and Murphy, 1996). Later data show that the Cambrian rocks of the Carolina Terrane contain 2.3–2.0 Ga detrital zircons, sourced in Western Gondwana, probably the West African shield (Samson, 2004). Zircons of this age are missing within Avalon. This suggests that the Carolina Terrane moved away from the Amazon shield and towards the West African Craton (Samson et al., 2001) during the time period in question here.

While the main phase arc phases in both the Avalon and Carolina Terranes are broadly similar in age and composition, the histories prior to and after the arcs appear to be different (Hibbard et al., 2002). Hibbard and van Staal (2004) note that the Avalonian arc system ended in the late Neoproterozoic and was succeeded by a robust Cambrian-Silurian platform sequence. The Carolina arc terminated during the late Neoproterozoic in an arc–arc collision; only a thin Middle Cambrian clastic sequence is preserved above the arc sequences (Hibbard et al., 2002; Hibbard and van Staal, 2004). The Carolina Terrane deformed in the Ordovician-Silurian while the Avalon Terrane deformed in the Early Devonian (Hibbard and van Staal, 2004).

Details of isotope geochemistry and timing of geological events support the conclusion that Avalon and

Carolina Terranes are distinct entities and underscore the conclusion that the two terranes contain distinct fossil assemblages, affirming the results of earlier studies (Secor et al., 1983). There is some question as to the significance of the distinctions in relation to paleogeographic reconstructions (Hibbard et al., 2002). It is likely that Avalon and Carolina were paleogeographically distinct entities in the Neoproterozoic but it is possible they may have traveled together prior to accretion (Hibbard et al., 2002).

The discovery of cf. *?Swartpuntia* sp. from Carolina Terrane rocks from Stanly, County, North Carolina, and our assignment of the North Carolina Ediacaran fauna as more closely related to the Nama Assemblage type than the Avalon Assemblage type may place constraints on the paleogeographic origin of the Carolina Terrane. Paleoenvironments are somewhat latitudinally controlled, but observed faunal distribution patterns may also be a function of taphonomy so that resolution of exact biogeographic affinities appears to be more complex than originally thought. More Ediacaran specimens are needed before their usefulness in paleogeographic reconstructions can be fully assessed (Waggoner, 1999).

## 7. Systematic paleontology

The specimen described herein is housed in the collections of the North Carolina Museum of Natural Sciences (NCSM).

Genus *?SWARTPUNTIA* (Narbonne et al., 1997)

Cf. *?SWARTPUNTIA* sp.

### 7.1. Description

Fragment of multifoliate frond, showing two collapsed petaloids, straight petaloidal segments abruptly curving at their distal ends to form a candle-flame shaped termination with high angles between the petaloids.

The pneu-structure of the fronds is collapsed. On the lower frond the rigid vertical walls of each pneu-tube projects downward, suggesting that, in the petaloid parallel to bedding, the pneu-tubes were collapsed from below, not from above. Two of the pneu-tubes on the proximal edge of this specimen had the rigid wall between them collapse completely, giving the two tubes the appearance of a single tube of double width.

There is a faint suggestion, at the juncture of the two vanes, of a thickened and possibly nodular central axis.



Fig. 8. Cf. ?*Swartpuntia* sp. from the Carolina Slate Belt. Two vanes visible, angle between vanes  $83^\circ$  as measured parallel to vane segments.

## 7.2. Material examined

One partial specimen (NCSM 9581).

## 7.3. Occurrence

Unnamed mudstone member Cid Formation, Albe-marle Group, Stanly County, North Carolina (UTM coordinates 17S 0576952/3893792  $\pm$  2.7 m).

## 7.4. Discussion

The specimen preserved here consists of two fronds of a once multi-frond organism (Fig. 8). The less-well preserved frond projects vertically into the strata above the lower frond, which is prostrate on a bedding sole surface (Fig. 9). There is a faint suggestion of a central

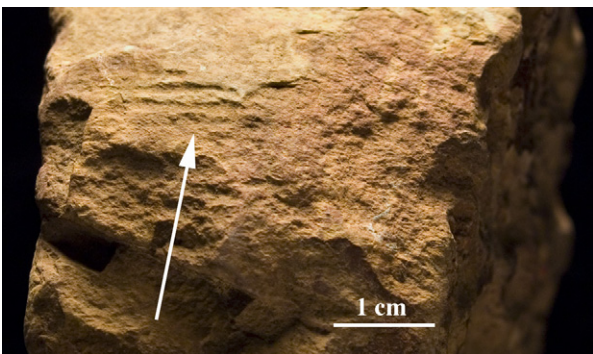


Fig. 9. Cf. ?*Swartpuntia* sp. Enlarged view, arrow indicates vertical vane. Laminar bedding visible on right-hand side of image.



Fig. 10. Cf. ?*Swartpuntia* sp. Enlarged view of horizontal (and better-preserved) vane. Bent tube or segment terminations are visible.

axis. However, it cannot be unambiguously identified as a stalk.

The planar nature of the vanes/fronds in this specimen, the multiple vanes joining at slightly less than a  $90^\circ$  angle, and the straight nature of the pneu-tubes all combine to indicate that this specimen most resembles the genus *Swartpuntia*. Other similar Ediacaran body fossils would include *Dickinsonia* and *Pteridinium*. However, *Dickinsonia* would have petaloids all in a single plane, and *Pteridinium* would show curving in both in the sub-horizontal fronds and in the individual pneu-tubes. Dickinsoniids are known to show three-dimensional features due to folding during burial (Dzik and Ivantsov, 2002). However, the laminar bedding in the hand sample does not show any convolutions that would indicate folding of the specimen. The tube terminations (Fig. 10) are not unlike those of *Swartpuntia gerssi*, but the new specimen is too incomplete to permit a confident genus or species assignment.

The possibility that this specimen represents an unusual preservational state of *Pteridinium* needs to be considered here. Species of *Pteridinium* (*P. simplex*, *P.*

*carolinaensis*) show varying degrees of flexibility and in many cases a tendency to stretch. The specimen assigned here to cf. ?*Swartpuntia* sp. has straight vanes with a stiffness and rigidity, combined with straightness of the individual partitions, that is atypical for *Pteridinium* but characteristic for *Swartpuntia*. This specimen could actually represent an unusual specimen of *Pteridinium*, but we consider this possibility to be unlikely both because of the morphological differences and because of the fact that this specimen occurs significantly down section from the strata that bear *P. carolinaensis*.

Yet another possibility that needs to be considered is that the specimen considered here represents a fossil of an undescribed type of Ediacaran fossil. This is a distinct possibility, for two reasons. First, the three dimensional preservation of this specimen is atypical for *Swartpuntia*, which is usually preserved as vanes all flattened together. Second, the paleontology of the Ediacaran biota is still in its infancy and we should expect to find previously unrecognized taxa as research proceeds. Nevertheless, the morphology of the new specimen is, in our opinion, close enough to genus *Swartpuntia* (and sufficiently unlike any other described Ediacaran biota genus) to permit comparison at the genus level. In particular, there is a slight waviness to the (otherwise rather straight) ridges (i.e., the rigid walls separating the collapsed tubes) in the new specimen that is seen in *S. germsi* but not other Ediacaran biota frondose species.

We interpret the new specimen as having been buried not by an event sand but by progressive burial by inter-stratified siltstone laminae. This raises the possibility that the organism lived and grew within the sediment, as has been suggested for Ediacaran species such as *Pteridinium simplex* and *Rangaea schneiderhoehni* from Namibia (Grazhdankin and Seilacher, 2005). Thus it is entirely possible that our new organism lived buried within, or more likely, partly buried within the sediments that preserved it. This mode of preservation is very similar to that proposed for a specimen of *Pteridinium* from Namibia (McMenamin, 1998, Fig. 5.3). The sessile, infaunal habitat proposed for *Pteridinium* and *Rangaea* (Grazhdankin and Seilacher, 2005) is in distinct contrast to the presumed epifaunal habitat of *S. germsi*. Nevertheless, Grazhdankin and Seilacher (2005) were so impressed with the differences between *Pteridinium* and *Rangaea* that they considered their infaunal habitat similarities to be the result of evolutionary convergence in these two presumably unrelated organisms. Therefore, we consider our new specimen to represent an (undescribed) taxon comparable to *Swartpuntia* that also, by convergent evolution, had begun to occupy a semi-infaunal habitat.

The biological affinities of *Swartpuntia* (and for that matter *Pteridinium*) are caught up in the general controversy surrounding the systematic affinities of Ediacarans. A case can be made that forms such as dickinsoniids, sprigginids, yorgiids and vendiids should be assigned to a eumetazoan stem-group sometimes called the Proarticulata. If this is indeed the case, and these organisms really do represent early segmented animals, then swartpuntiids and *Pteridinium* could very well belong to this same metazoan plexus. This suggestion is far from certain, however, and it is still possible that *Swartpuntia*, *Pteridinium* and especially *Rangaea* belong to a group that is only distantly related, or perhaps not related at all, to the eumetazoa. Striking convergences in habitat preference have already been noted for *Pteridinium*, *Rangaea*, and our new swartpuntiid, and it is likely that other types of convergences are present among the members of the Ediacaran biota. This new fossil may represent a swartpuntiid that is evolutionarily convergent (in terms of habitat preference) to the infaunal or partially infaunal habitat preferred by *Pteridinium* and *Rangaea*. If it could be shown that swartpuntiids are members of the Proarticulata (and indeed, Narbonne et al., 1997, propose an evolutionary link between *Swartpuntia* and *Dickinsonia*), then we may furthermore see in the new specimen a habitat convergence between the proarticulate and non-proarticulate (i.e., Vendozoan or Petalonamid) Ediacaran taxa.

## 8. Conclusions

The discovery of cf. ?*Swartpuntia* sp. from the Cid Formation, Stanly County, North Carolina, combined with the best available radiometric ages for this interval, indicate that the North Carolina Ediacaran fauna is more closely related to other Nama Assemblage types worldwide, than it is to the Avalon Assemblage. Further studies and specimens are also needed to determine what role, if any, the Ediacaran fauna will play in determining the precise paleogeographic history of the Carolina Terrane. At this point geochemical and paleontologic data support the hypothesis that the Carolina Terrane is distinct from Avalon.

## Acknowledgments

We are extremely grateful to Tony Furr for donating the specimen described in the study and to Richard Olsen (Aurora Fossil Museum) and Vince Schneider (NCSM) for their help in procuring this specimen, and to Gerard J. Marchand for thin sectioning the sample. We are grateful for the professional photographic assistance of Charles

Brown (Charles Brown Photography, Raleigh, NC). We are also very grateful to Janet Edgerton (NCSM) for her bibliographic assistance and to Dr. James Hibbard (NC State University) for discussion and insightful comments, and to Tamara Moore (NCSM) for her assistance with Fig. 1.

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