

Trilobites from the Rickard Hill facies of the Saugerties Member of the Schoharie Formation, eastern New York (upper Emsian and Lower Devonian) a case study in taphonomy and sequence stratigraphy from glacial erratics

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Article abstract

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ABSTRACT

Glacial erratics belonging to the Rickard Hill facies (RHf) of the Saugerties Member of the Schoharie Formation (upper Emsian: Lower Devonian) occur scattered throughout the Piedmont of northern New Jersey and Lower Hudson Valley of New York. These RHf glacial erratics contain an assemblage of trilobites belonging to: *Anchiopella anchiops*, *Burtonops cristatus*, *Calymene platys*, *Terataspis grandis*, cf. *Trypaulites* sp. and cf. *Coniproetus* sp. This RHf glacial erratic trilobite assemblage consists predominantly of disarticulated cephalons and pygidia that were originally preserved as part of a localized, third-order eustatic sea level lag deposit in the area of the present day Helderberg Mountains region of New York State and subsequently transported in glacially plucked blocks by the Hudson–Champlain Lobe of the Laurentide Ice Sheet southward into New Jersey. Physical and chemical weathering during glacial erosion, transportation and deposition of the RHf glacial erratics has revealed some anatomical features of these trilobites in high detail along with other invertebrates. This unique sequence of weathering reveals additional characteristics that bear upon issues of bathymetric controls on upper Schoharie Formation lithology, trilobite faunal abundance and taphonomy during the upper Emsian (Lower Devonian) of eastern New York State.

RÉSUMÉ

Des éléments erratiques glaciaires faisant partie du faciès de la Rickard Hill (RHf) du Membre Saugerties de la Formation de Schoharie (Emsien supérieur: Dévonien inférieur) sont présents de façon éparse partout à l'intérieur du Piedmont dans le nord du New Jersey et la vallée du cours inférieur de l'Hudson de l'État de New York. Ces éléments renferment un assemblage de trilobites faisant partie des *Anchiopella anchiops*, *Burtonops cristatus*, *Calymene platys* et *Terataspis grandis*, comparables à l'espèce des *Trypaulites* et à l'espèce des *Coniproetus*. Cet assemblage de trilobites des éléments erratiques glaciaires du RHf est principalement constitué de céphalons et de pygidiums ayant originalement été conservés au sein d'une charge de fond localisée, au niveau marin eustatique de troisième ordre, dans le secteur de la région des monts Helderberg actuels de l'État de New York et subséquemment transportés dans des blocs grainelés par l'impact glaciaire du compartiment Hudson-Champlain de l'Inlandsis laurentidien en direction sud vers le New Jersey. L'altération atmosphérique physique et chimique survenue durant l'érosion glaciaire, le transport et la sédimentation des éléments erratiques glaciaires du RHf ont révélé certaines particularités anatomiques des trilobites de façon très détaillée ainsi que d'autres invertébrés. Cette séquence unique d'altération atmosphérique révèle d'autres caractéristiques témoignant d'un contrôle bathymétrique sur la lithologie de la partie supérieure de la Formation de Schoharie, d'une abondance de la faune de trilobites et de la taphonomie durant la période de l'Emsien supérieur (du Dévonien inférieur) dans l'est de l'État de New York.

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INTRODUCTION

Over a century ago, the first occurrence of trilobite fossils in New Jersey glacial erratics was identified approximately 1.5 km north of the city of Paterson by Whitfield and Parsons (1897). Their study described hypostomes and other disarticulated skeletal elements belonging to *Terataspis grandis* (Hall 1861) from glacial erratics of the Schoharie Grit. Since that time, reports of trilobites in New Jersey have been based almost exclusively on in-situ faunas collected in the northwesternmost part of the state and immediately adjacent outcrops in southern New York and eastern Pennsylvania (e.g., Weller 1903; Shimer 1905; Epstein *et al.* 1967; Couri *et al.* 2011).

Recently, an assemblage of fossiliferous glacial erratics containing trilobites was discovered scattered across the northern New Jersey Piedmont and Lower Hudson Valley of New York (Becker and Bartholomew 2013; Becker *et al.* 2016). The occurrence of these trilobite-bearing glacial erratics was traced from outcrops of the Rickard Hill facies (RHf; see below) of the Saugerties Member of the Schoharie Formation (upper Emsian: Lower Devonian) near Clarksville, New York, to the northern New Jersey Piedmont (Fig. 1). The locations along this erratic trail support a nearly due north to south Laurentide Ice Sheet advance and retreat in this part of eastern New York and northern New Jersey, as shown on earlier surficial geologic maps by Stone *et al.* (2002) and Stanford (2003).

In this report we describe the occurrence of 24 trilobite specimens belonging to six different species discovered in RHf glacial erratics since completion of the original account by Becker and Bartholomew (2013). The six forms are: *Anchiopella anchiops* (Woodward 1873), *Burtonops cristatus* (Hall 1861), *Calymene platys* (Green 1832), *Terataspis grandis*, cf. *Trypaulites* sp. and cf. *Coniproetus* sp. Physical and chemical weathering during glacial erosion, transportation and deposition of RHf glacial erratics reveals features of these trilobites and other invertebrate fossils not normally seen in outcrops of the Schoharie Formation. These features provide an opportunity to assess the role of localized bathymetry and topography on trilobite taphonomy during third-order eustatic sea-level cyclicity in the upper Schoharie Formation and RHf (upper Emsian: Lower Devonian) of eastern New York State.

RICKARD HILL FACIES OF THE SCHOHARIE FORMATION: GLACIAL ERRATIC SOURCE REGION AND RECOVERY LOCATIONS

In outcrops, the overall thickness, lithology and fauna of the Schoharie Formation undergo considerable variation between Port Jervis and Cherry Valley, New York. The members of the Schoharie Formation are, from oldest to youngest, Gumaer Island, Aquetuck and Saugerties (Ver Straeten and Brett 2006) (Fig. 2). Exposures of the RHf of the Saugerties Member of the Schoharie Formation identified

in Becker and Bartholomew (2013) occur as a narrow outcrop belt centered near the town of Clarksville (Figs. 1–2). This localized facies belt was originally designated as the Rickard Hill Member of the Schoharie Formation by Johnsen and Southard (1962) and is characterized by a sandy limestone to calcareous sandstone containing brachiopods and prominent cephalopods. Johnsen and Southard (1962) indicated that the Rickard Hill Member ranged in thickness from a thin feather edge near East Springfield to a maximum of 2 m in Schoharie and western Albany counties. More recent study by Ver Straeten and Brett (2006) identified the Rickard Hill Member as a locally developed sandstone facies and recommended its abandonment as a member and its reassignment to the Saugerties Member. We follow Ver Straeten and Brett (2006) in referring to this unit as the Rickard Hill facies (RHf) of the Saugerties Member of the Schoharie Formation.

According to Becker and Bartholomew (2013), the RHf consists of individual beds that range in thickness from a few centimeters to approximately one meter. These beds consist of bluish to medium-gray, exceedingly hard and well-cemented sandy limestone with exterior surfaces weathered light tan to yellow. The contact of the RHf of the Saugerties Member in the Clarksville region with the overlying Edgecliff Member of the Onondaga Formation is sharp and erosional. At this contact there is a distinct lithology change from a highly fossiliferous, pyritic and sandy limestone of the RHf to a finer-grained gray limestone with occasional crinoid and coral fossils of the Edgecliff Member. This striking change in lithology and fossil concentration across the contact horizon is atypical of that seen in other outcrop exposures in eastern New York where the transition between these formations is gradual (e.g., Johnsen and Southard 1962; Brett and Ver Straeten 1994; Ver Straeten 1996; 2007). Although some beds are poorly fossiliferous, much of the RHf contains abundant invertebrate fossils preserved as casts and molds, with the notable preservation of large orthoconic and coiled cephalopods.

Numerous Paleozoic thrust faults throughout Clarksville have produced extensive jointing within the RHf, which can be also observed within local cave systems (Cooper and Mylroie 2015). Along Route 85 in Clarksville, an excellent outcrop exposure of the RHf occurs, as well as exposures of the Gumaer Island, Aquetuck and Saugerties members of the Schoharie Formation (Fig. 2). Ver Straeten (1996; 2007) provided member assignments, lithologic descriptions, measured sections and sequence stratigraphic interpretations for this exposure. A thrust fault seen in this outcrop offsets these three members and has generated drag folding of the RHf, as seen in Fig. 2. We consider that such thrust faulting has facilitated glacial plucking of the RHf and accelerated physical and chemical erosion of the RHf glacial erratics during transport within the Hudson–Champlain Lobe of the Laurentide Ice Sheet.

RHf glacial erratics containing the trilobites and described

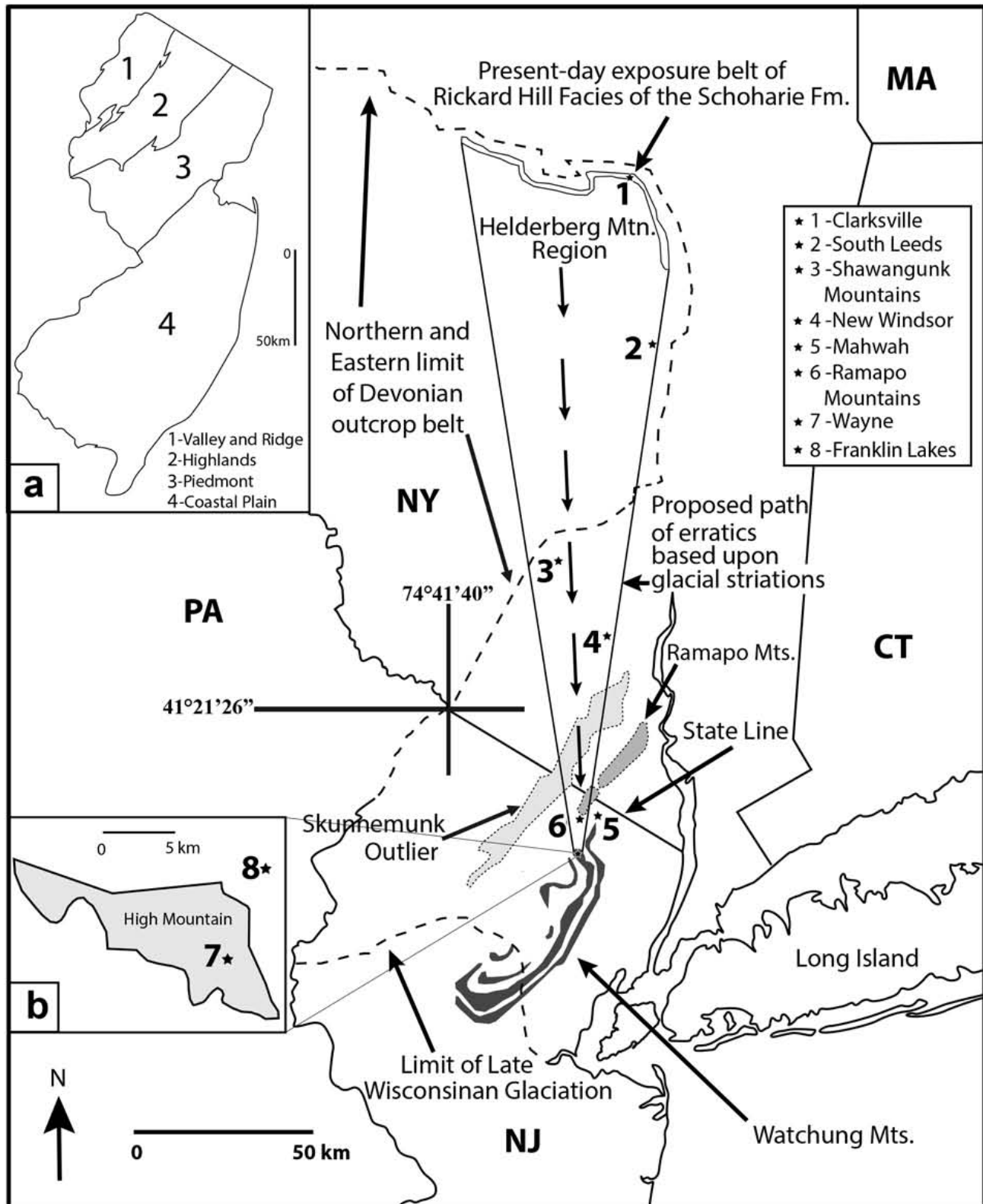


Figure 1. Locality map of the Piedmont and Lower Hudson Valley with proposed path of glacial transport from the Rickard Hill facies (RHf) of the Schoharie Formation, Helderberg Mountains Region, New York. (*1) RHf exposure belt; (*2–*8) fossiliferous erratics described in Becker and Bartholomew (2013); Becker *et al.* (2016) and this report. Inset maps: (a) physiographic provinces of New Jersey and (b) High Mountain region. Note: limit of Wisconsin Glaciation, Skunkemunk Mountains, Ramapo Mountains.

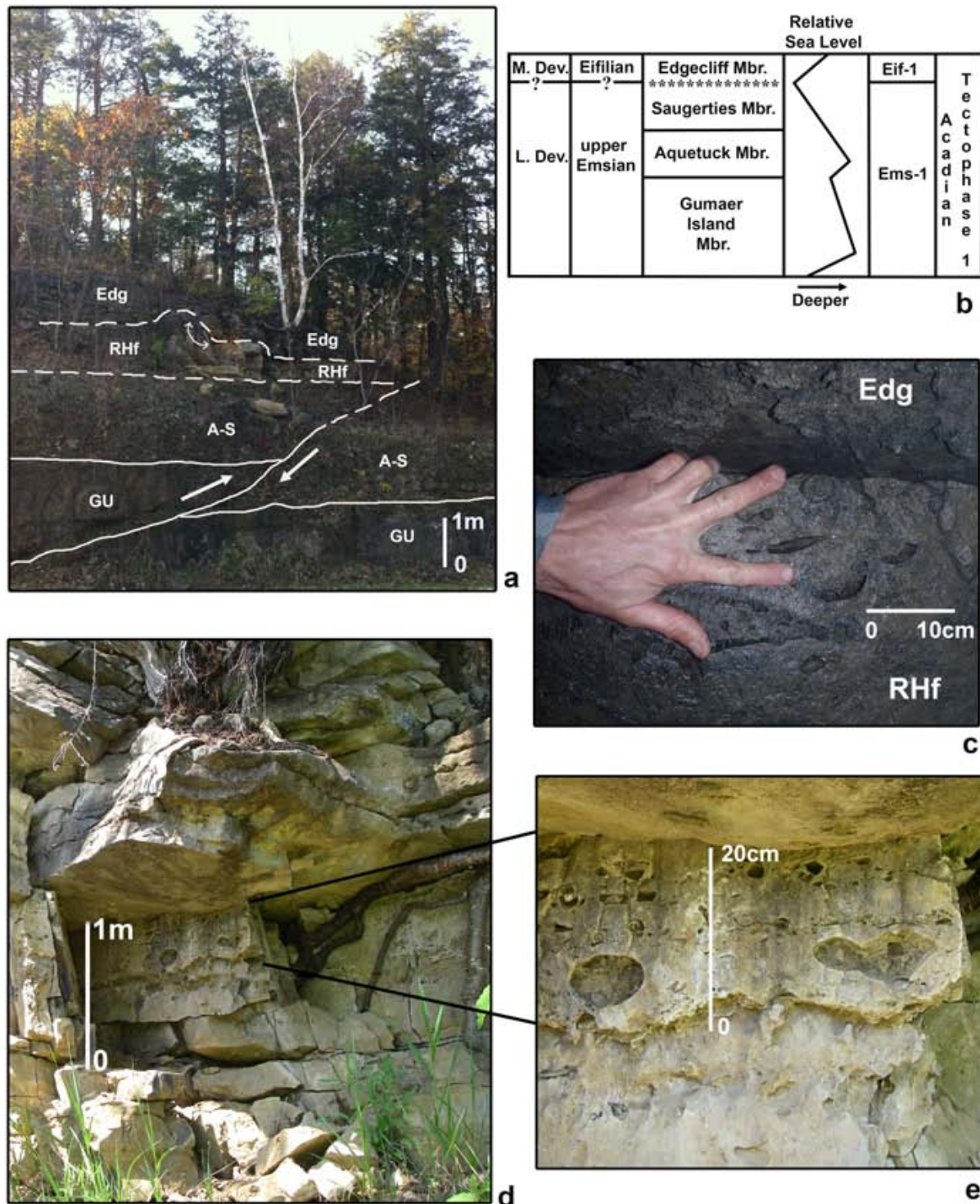


Figure 2. Stratigraphic column with sequence stratigraphy, outcrop exposures and thrust faults in the Rickard Hill facies (RHf), Gumaer Island, Aquetuck and Saugerties members of the Schoharie Formation, Clarksville, New York. (a) Modified from Ver Straeten (2007, fig. 19); (b) Roadcut exposure along Route 85, Clarksville, New York. Note that RHf is dipping to the northwest and drag folded as the result of thrust faulting. Also see Ver Straeten (1996; 2007); (c) Contact and thrust fault between the RHf and Edgecliff Member, Brinley Sump, Clarksville Cave, Clarksville, New York; (d–e) Close-ups of the RHf along Route 85, Clarksville, New York. Note sandy limestone lithology as well as cast and mold preservation of invertebrate fossils. Abbreviations: RHf-Rickard Hill facies; GU- Gumaer Island Member; A-S-Aquetuck and Saugerties members.

in this report were recovered from ground moraines and till deposits within the northern New Jersey Piedmont and Lower Hudson Valley. In these areas, RHf erratics are uncommon and occur scattered among other glacial erratics that typically represent metamorphic and intrusive igneous rocks (Fig. 3). Many of the RHf erratics retain the blocky, jointed bedding seen in outcrop exposures at Clarksville, while others show rounding typical of boulders found in regional ground moraines (Fig. 3). Additionally,

the exterior surfaces of both blocky and rounded erratics exhibit the same weathered light tan to yellow surfaces and characteristic cross-sections of fossil casts and molds present on weathered RHf surfaces at the Clarksville source exposure.

Although some transported RHf blocks may have been weathered prior to glacial plucking, we infer that slow, acidic dissolution of the exceedingly hard and well-cemented sandy limestone during glacial plucking and transport has

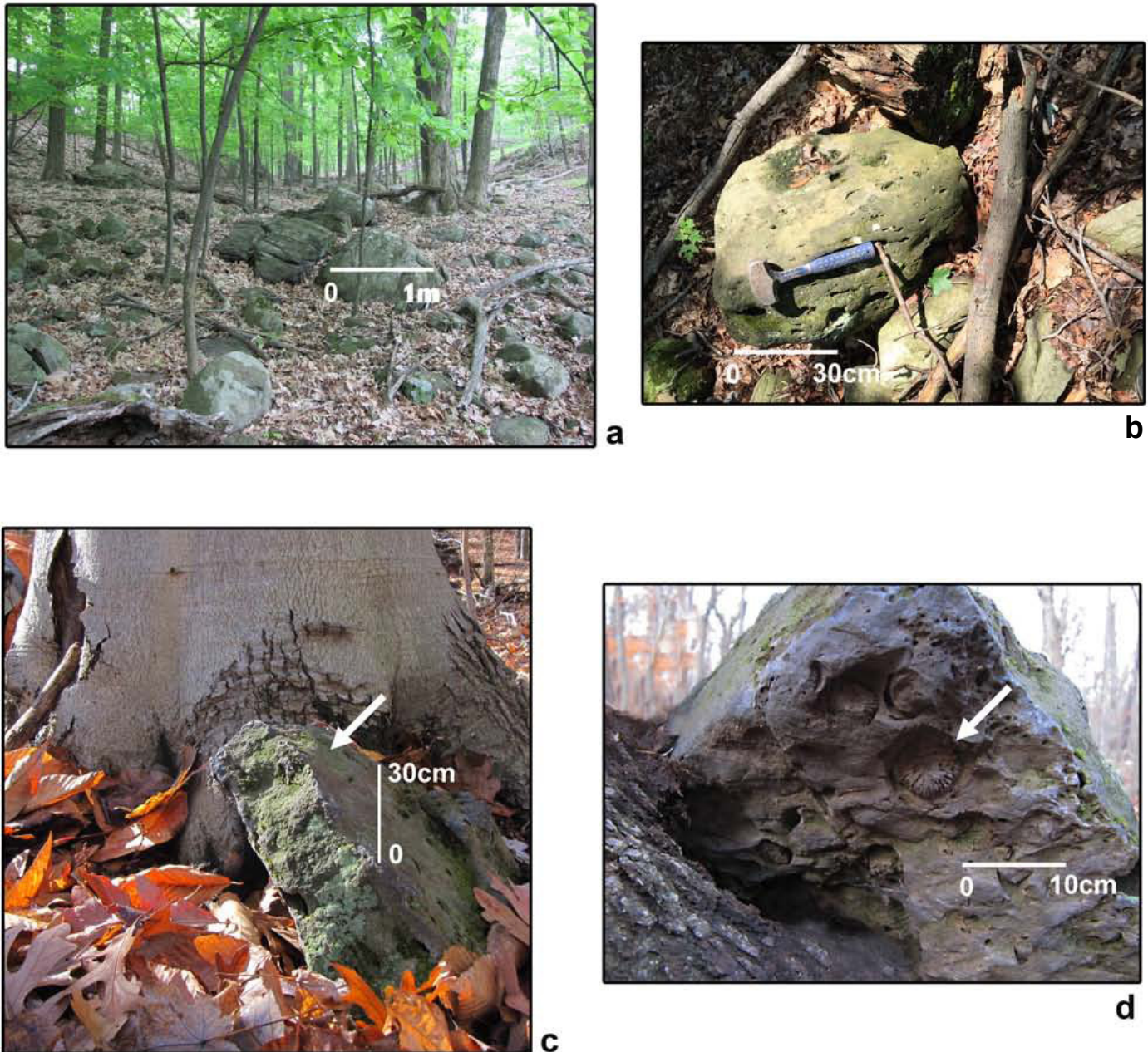


Figure 3. Glacial erratics of the RHf as seen in the northern New Jersey Piedmont, Passaic County, New Jersey. (a) Ground moraine composed mainly of intrusive igneous and metamorphic erratics. (b) Glacial erratic of the RHf found in ground moraine seen in (a); note similarities of fossil casts and molds as well as exterior surface weathering to that seen in Clarksville, New York region. (c) American beech tree growing over RHf glacial erratic. (d) The bark of the red oak tree can be seen in the bottom of the photograph and growing around the RHf erratic. Note rugose coral in cross-section indicated by arrow.

resulted in extensive solutioning of the interior of many boulders, particularly along fossiliferous bedding planes. This has caused the interiors of many boulders to take on the color and fossil preservation features typical of the weathered surfaces. The original bluish to medium-gray, sandy limestone character of the unweathered rock seen in outcrop is not apparent in many of the glacially transported erratics. Additional discussion of the Clarksville source area and the Lower Hudson Valley and northern New Jersey Piedmont recovery locations is available in Becker and Bartholomew (2013) and Becker *et al.* (2016).

FIELD TECHNIQUES AND GENERAL DESCRIPTION OF THE ASSEMBLAGE

Trilobites contained in the RHf glacial erratics were collected by hiking a series of transects across the northern New Jersey Piedmont and Lower Hudson Valley, New York, recovery locations with specific focus on larger boulders concentrated in ground moraines and till deposits. All fossils identified and discussed in this study were collected by splitting RHf glacial erratics along fossiliferous bedding plains with standard field tools. Trilobite specimens featured in Figs. 4–9 were removed from the fossiliferous bedding plains of glacial erratics, some erratics weighing as much as 100 kg or more, for laboratory study using standard binocular microscope techniques. Currently, RHf glacial erratics have been recovered in the towns of South Leeds, New Windsor, Mahwah, Franklin Lakes and Wayne as well as the Shawangunk and Ramapo Mountains, (Fig. 1). Locations of individual RHf glacial erratics were documented by a handheld GPS unit. Trilobite specimens discussed here are deposited in the geologic collections of the Department of Environmental Science, William Paterson University.

Based on the features included in Table 1, we have determined that the RHf glacial erratic trilobite assemblage consists of the following species: *Anchiopella anchiops*, *Burtonops cristatus*, *Calymene platys*, *Terataspis grandis*, cf. *Trypaulites* sp. and cf. *Coniproetus* sp. In their comprehensive analysis of trilobites from New York, it is notable that Whiteley *et al.* (2002) indicated that most species found in the Schoharie Formation are known only from incomplete specimens of cephalons and pygidia. Similar conditions of preservation occur in this study, with all 24 specimens included in Figs. 4–9 being incomplete, but preserving enough anatomical details to permit higher-order taxonomic classification. The majority of the best-preserved specimens included in Figs. 4–9 are chemically weathered, sandy limestone casts recovered from the interiors of RHf glacial erratics. A complete list of trilobite species currently known from the Schoharie Formation in New York is included in Whiteley *et al.* (2002).

Examples of diagnostic anatomical features seen in trilobites from RHf glacial erratics include: (1) a large terminal spine in *Anchiopella anchiops* (Fig. 5d); (2) 14 rows

of eye lenses in *Burtonops cristatus*, (Fig. 4i); (3) extensive, spinose and tubercled ornamentation of the cephalon in *Terataspis grandis* (Fig. 6a); (4) a forward expanding glabella in *Calymene platys*, (Fig. 7a); (5) flat pleural ribs in cf. *Trypaulites* sp.; and (6) a distinct pygidial border in cf. *Coniproetus* sp. (Fig. 8b). Three examples of the more delicate thorax regions are also preserved in the RHf glacial erratics (Figs. 7a–b, 9f). The majority of cephalons and pygidia seen in Figs. 4–9 were recovered from different RHf glacial erratics and therefore are unlikely to represent the same individuals. An exception is the pygidium and pygidial spines of *Terataspis grandis* seen in Fig. 6c–d, in which the two specimens were not articulated, but recovered adjacent to one another on the same RHf glacial erratic.

TAPHONOMY OF THE RICKARD HILL FACIES GLACIAL ERRATIC TRILOBITES

The concentration and preservation of trilobites and invertebrate fossils in the RHf, as seen in outcrop and glacial erratics, are unique, unlike those of any identified outside the RHf in the Schoharie Formation throughout its outcrop belt, including well-known Schoharie bedrock localities such as Kingston, Highland Mills and Port Jervis. This outcrop belt extends over 300 km between central and eastern New York, northeastern Pennsylvania and northwestern New Jersey (Johnsen and Southard 1962; Ver Straeten 2007). In addition to the six species of trilobites discussed in this report, as many as 20 species of brachiopods and 15 species of cephalopods have also been identified from RHf glacial erratics (Younger *et al.* 2016; Brembs *et al.* 2015). It is notable that the large cephalopods seen in both RHf outcrop and RHf glacial erratics have not been identified or described from the numerous bioherms found in the Edgecliff Member and along the contact between the Schoharie and Onondaga Formations in eastern New York (e.g., Oliver 1956). It is this distinctive occurrence of cephalopods that not only identifies the source for the glacial erratics, but also reflects a particular set of localized taphonomic conditions within the RHf of the upper Schoharie Formation in the area surrounding Clarksville.

We interpret the taphonomic conditions found in the RHf to be analogous with those seen in some Middle Devonian trilobite assemblages from the Hamilton Group of western New York by Speyer and Brett (1986). Speyer and Brett (1986) defined four facies, or taphofacies, based on diagnostic taphonomic traits of trilobite assemblages and associated invertebrate fossils. In their taphofacies 1A, key features also seen in the RHf glacial erratic trilobite assemblage include: (1) almost entirely disarticulated remains; (2) under-represented thoracic segments; and, (3) disarticulated sclerites that are commonly fragmented. It is also noteworthy that trilobites in this taphofacies commonly occur with tabulate and rugose corals as well as spiriferids, rhynchonellids and strophomenids that were also identified

(text continued on page 279)

Table 1. Features identified in the RHf glacial erratic trilobite assemblages.

RHf Species and References	Cephalon	Thorax	Pygidium	Taphonomic Characteristics
<i>Anchiopella anchiops</i> (Green 1832) (Stumm 1954; Linsley 1994; Whiteley <i>et al.</i> 2002)	triangular-shaped, broad anterior, lateral and posterior borders, slender genal spines form posterior terminus of cephalic border, occipital spine	not identified in RHf glacial erratics	triangle-shaped, typically 8–9 axial rings and 7–8 pairs of rounded, unfurrowed pleural lobes, prominent, upturned terminal spine	genal, occipital and terminal spines typically broken or absent, occurs with other species on same bedding planes (Figs. 4–5; 9)
<i>Burtonops cristatus</i> (Hall 1861) (Linsley 1994; Whiteley <i>et al.</i> 2002)	tumid-shaped, glabella with large, simple tubercles, 14 dorsal ventral eye files, large genal spines	not identified in RHf glacial erratics	not identified in RHf glacial erratics	cephala occurring in broken phragmocone chambers of cephalopods, genal spines broken, occurs with other species on same bedding planes (Figs. 4; 9)
<i>Terrataspis grandis</i> (Hall 1861) (Reimann 1941; 1945; Linsley 1994; Whiteley <i>et al.</i> 2002; Becker <i>et al.</i> 2016)	triangular-shaped, highly ornamented, large genal spines, spinose posterior border, near circular glabella with diagnostic spinose and tubercled ornamentation	not identified in RHf glacial erratics	large spines, diagnostic spinose and tubercled ornamentation	cephalon and pygidial spines delicate, fragmentary and typically broken or absent, partial pygidium and pygidial spines found associated (Fig. 6)
<i>Calymene platys</i> (Green 1832) (Linsley 1994; Whiteley <i>et al.</i> 2002)	semicircular with no genal spines, glabella expanded forward, three glabellar lobes, smooth surfaces	~13 thoracic segments	semicircular with smooth edge	robust exoskeleton segments, near complete specimens recovered (Fig. 7)
cf. <i>Trypaulites</i> sp., (Stumm 1954; Linsley 1994; Whiteley <i>et al.</i> 2002)	not identified in RHf glacial erratics	not identified in RHf glacial erratics	slightly furrowed, flat pleural ribs, axial rings with a post-axial ridge, faint border, surface granules	only pygidium segments recovered (Fig. 8)
cf. <i>Coniproetus</i> sp., (Lieberman 1994; Linsley 1994; Whiteley <i>et al.</i> 2002)	not identified in RHf glacial erratics	not identified in RHf glacial erratics	semicircular, well-developed border, ~10 axial rings	thin exoskeleton, only pygidium segments (Fig. 8)

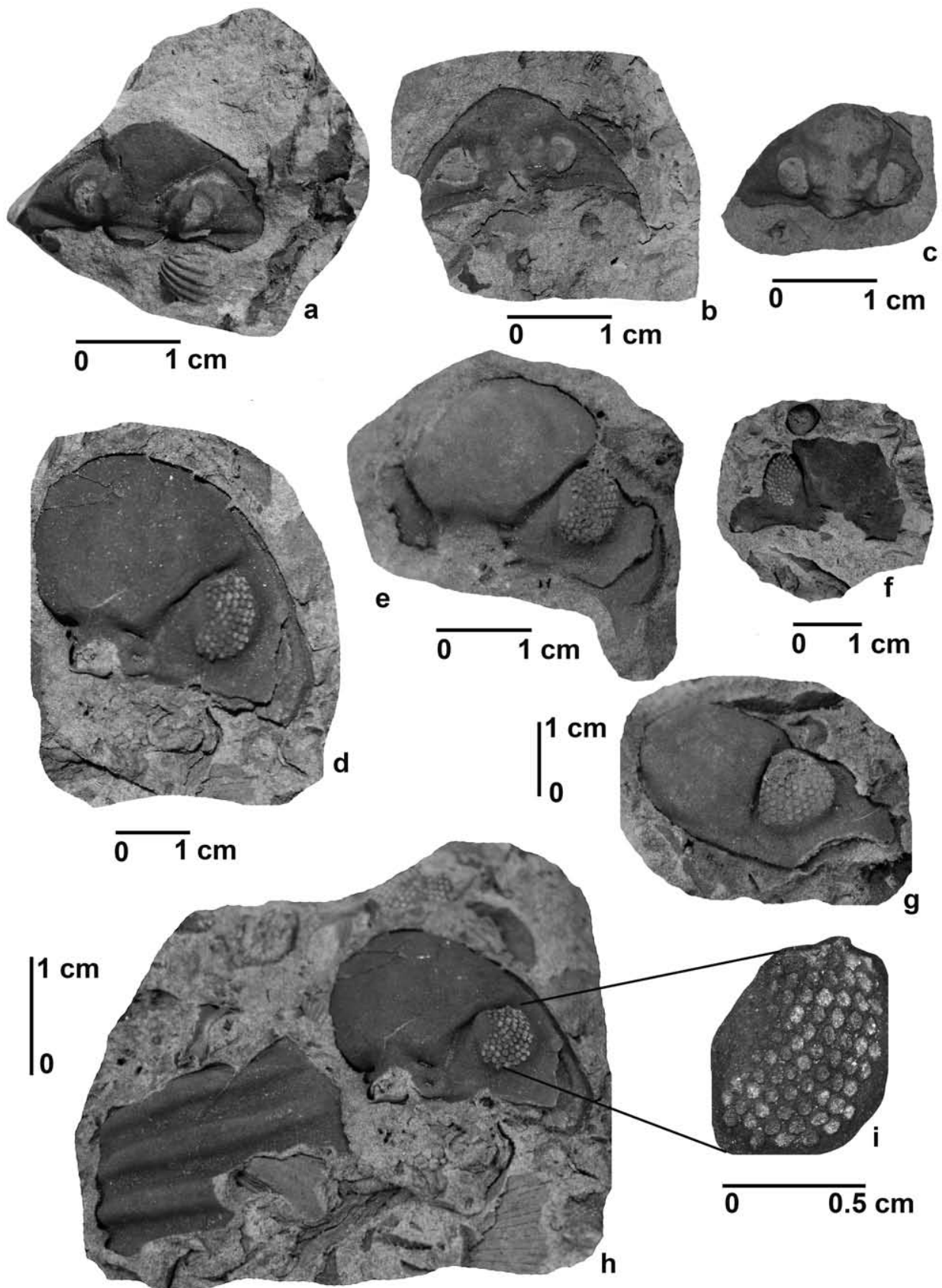


Figure 4. *Anchiopella anchiops* and *Burtonops cristatus* cephalon casts from RHf glacial erratics. (a–c): *Anchiopella anchiops* and (d–i): *Burtonops cristatus*. Note distinct shape of glabella and diagnostic fourteen rows of eye lenses seen in (i).

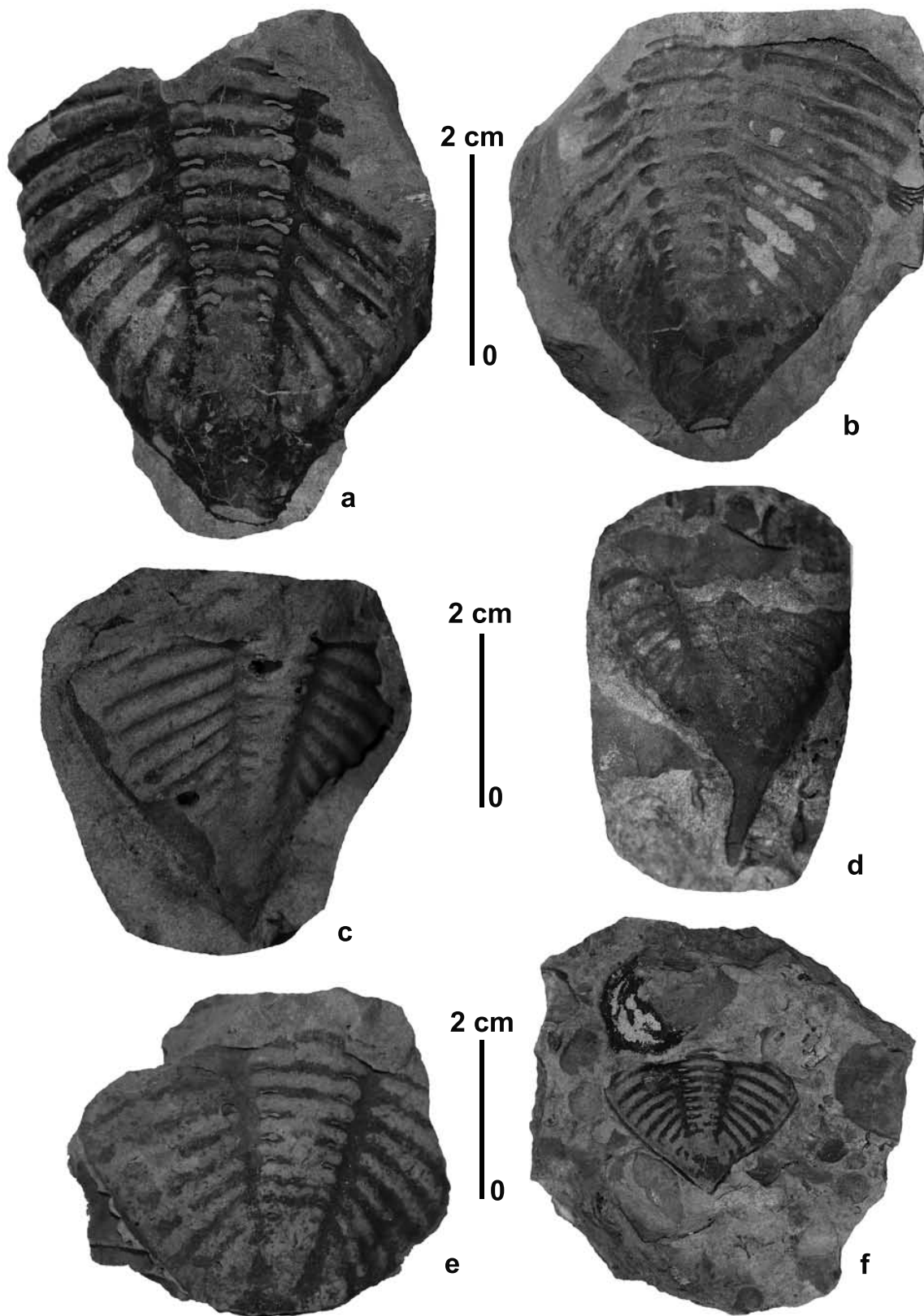


Figure 5. *Anchiopella anchiops* pygidia casts (a, c–d) and mold (b) from RHf glacial erratics. Note diagnostic terminal spine in (d) indicated by arrow.

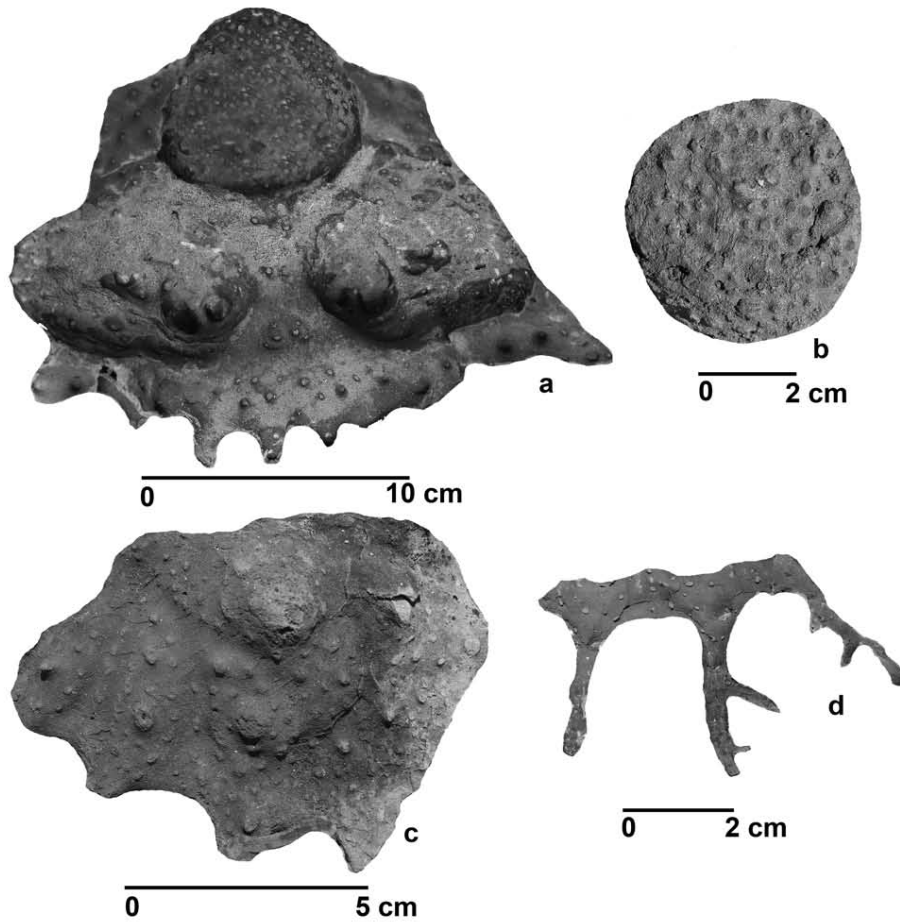


Figure 6. *Terataspis grandis* cephalon (a — mold), glabella (b — cast), pygidium (c — cast) and pygidium spines (d — cast) from RHf glacial erratics. Note distinct spinose and node ornamentations. Specimens (c–d) were not articulated, but recovered adjacent to one another on the same RHf glacial erratic.

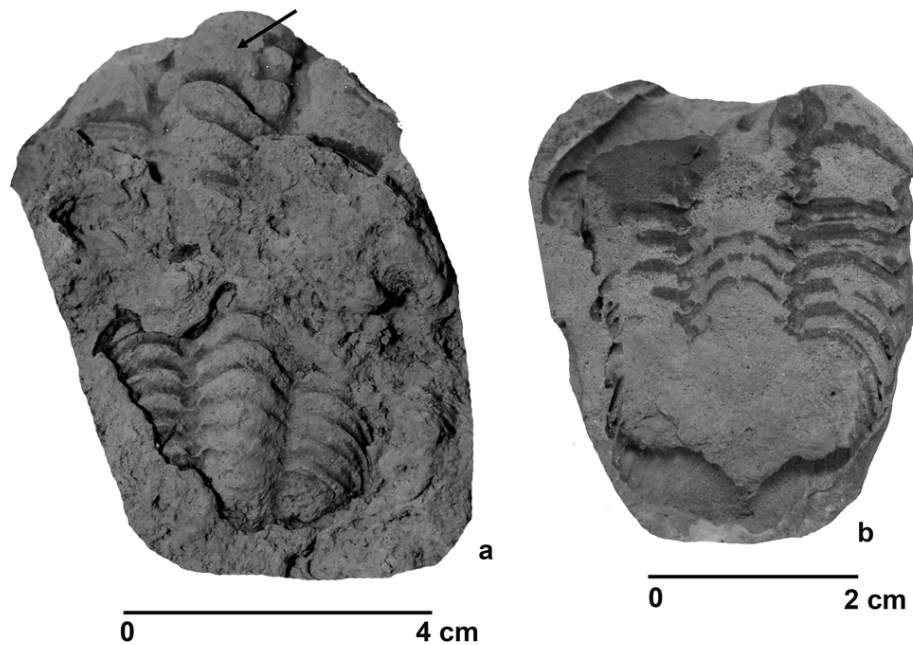


Figure 7. Near complete *Calymene platys* trilobite casts (a–b) from glacial erratics of the RHf. Note distinct forward expanding glabella in (a) indicated by arrow.

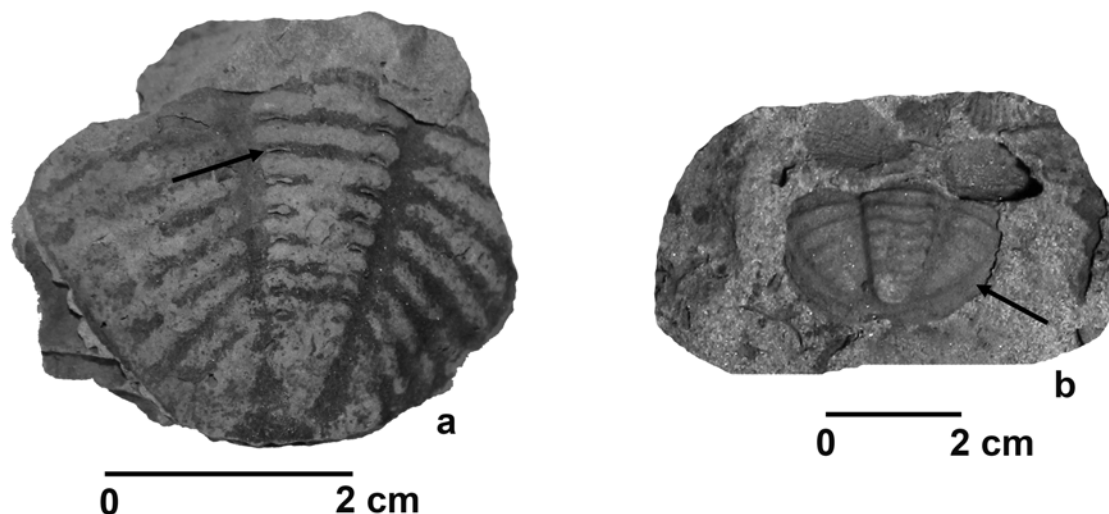


Figure 8. Pygidia casts of (a) cf. *Trypaulites* sp. and (b) cf. *Coniproetus* sp. from RHf glacial erratics. Note flat pleural ribs in (a) and pygidial border in (b) indicated by arrows.

in RHf glacial erratics by Becker and Bartholomew (2013). Speyer and Brett (1986) further indicated that taphofacies 1A represented environmental conditions near normal wave base with current agitation, multiple reworking events and lag accumulation.

Additional support for similarities between taphofacies 1A of Speyer and Brett (1986) and a lag deposit origin for trilobites and other invertebrates occurring in the RHf glacial erratics can be seen in Figs. 9–10. Along more extensive fossiliferous bedding planes: (1) cephalata and pygidia from two different species, *Anchiopella anchiops* and *Burtonops cristatus* are preserved adjacent to one another (Figs. 9d–e); and (2) cephalata and pygidia of indeterminate species of trilobite are oriented in multiple directions with sclerite orientations as convex up and convex down (Figs. 10a–b). In other examples: (1) broken phragmocone chambers of cephalopods are filled with sediment and cephalata from phacopids (Figs. 9a–c); and, (2) large cephalopods that show preferred orientations occur, along with indeterminate species of trilobites (Figs. 10a–c). Furthermore, lag deposits in New York also commonly preserve *Calymene platys* and associated body segments due to a robust exoskeleton (Whiteley *et al.* 2002). During this study, two nearly complete specimens of this trilobite species were recovered in RHf glacial erratics (Figs. 7a–b). None of the other trilobites in our assemblage are preserved as whole specimens.

In some instances, the exoskeletons of invertebrates in RHf glacial erratics may have formed temporary shelly hardgrounds, as indicated by: (1) borings and bryozoan encrustation on brachiopod valves (Figs. 10d–e); and (2) algal accumulations that have encrusted brachiopod valves (Fig. 10f). Brett (1995) indicated that these types of hardgrounds and skeletal accumulations are typical at bedding surfaces and discontinuities during sea level

rise and sediment starvation. These stratigraphic and paleontological characteristics are also seen in the RHf of the Clarksville region and in RHf glacial erratics from the Lower Hudson Valley and northern New Jersey Piedmont (Figs. 2–3).

SEQUENCE STRATIGRAPHY AND RHf LAG DEPOSIT FORMATION

The original sequence-stratigraphic framework for the transition between the Schoharie and Onondaga formations was compiled by Brett and Ver Straeten (1994) and in subsequent publications, including Ver Straeten (1996; 2007) and Brett *et al.* (2009; 2011). In eastern New York, the transition between the Saugerties Member of the Schoharie Formation and Edgecliff Member of the Onondaga Formation is gradational and relatively conformable (e.g., Goldring and Flower 1942; Oliver 1956; Johnsen and Southard 1962; Brett and Ver Straeten 1994; Ver Straeten 1996; 2007). However, in central and western New York, Ver Straeten (1996) identified the sub-Edgecliff Member unconformity, which locally becomes amalgamated with the pre-Schoharie and Wallbridge unconformities. It is noteworthy that in the present study the localized RHf containing the trilobites and other invertebrates occurs within the transition between eastern and central New York (Fig. 1).

According to Ver Straeten (2007, fig. 19), the contact between the uppermost Schoharie and lowermost Onondaga formations, as well as the Saugerties and Edgecliff members, delineates the third-order eustatic sea-level sequence boundary between the Emsian Cycle 5 and Eifelian Cycle 1 (Fig. 2). This contact also occurs along the maximum regressive surface of Acadian Tectophase 1, as identified by Ver Straeten (2007), and along a regional

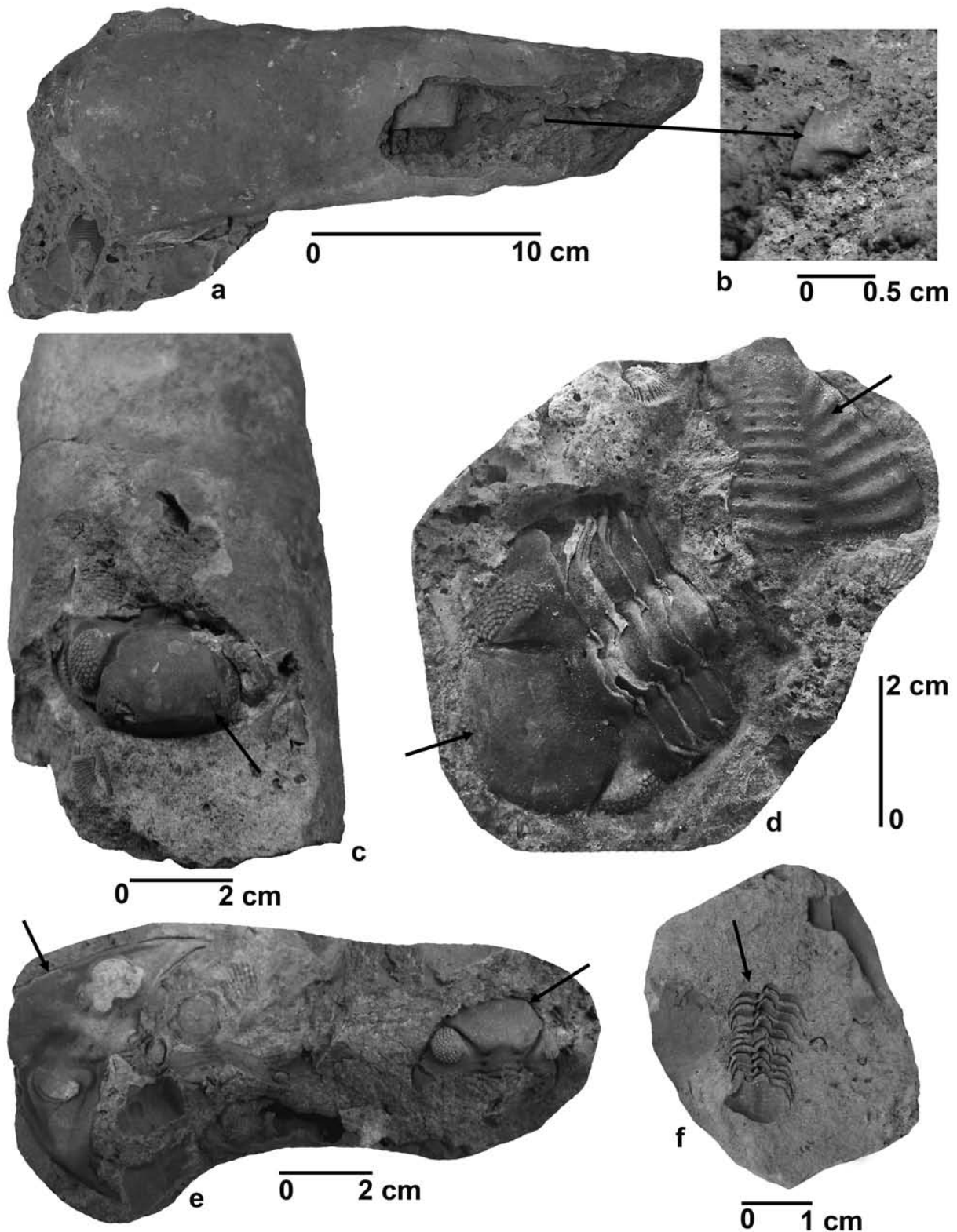


Figure 9. Taphonomic and paleontological features seen in RHf glacial erratics. (a) Cephalon of *Burtonops cristatus* preserved in the broken phragmocone chambers of cephalopod. (b) Close up of *Burtonops cristatus* preserved in the broken phragmocone chambers seen in (a) and indicated by arrow. (c) Cephalon of *Burtonops cristatus* preserved in broken phragmocone chambers of cephalopod of indicated by arrow. (d–e) Cephalon and pygidia from *Anchiopella anchiops* and *Burtonops cristatus* preserved on same bedding planes indicated by arrows. (f) Disarticulated thorax region from an indeterminate trilobite species indicated by arrow.

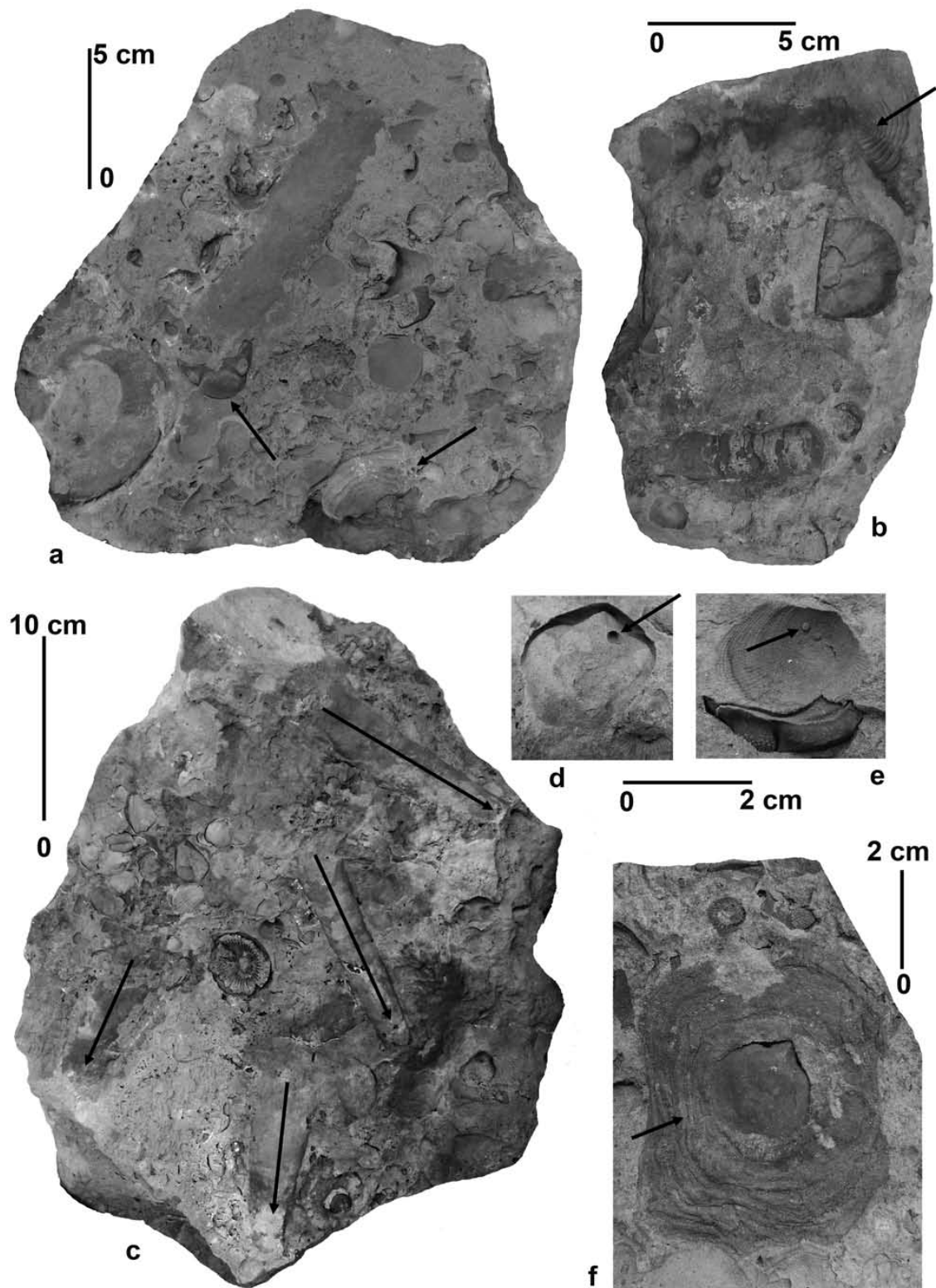


Figure 10. Taphonomic and paleontological features seen in RHf glacial erratics. (a–b) Cephalon and pygidium from indeterminate species of trilobites with sclerite orientations as convex up and convex down indicated by arrows. (c) Cephalopods with hydrodynamically orientated body chambers as indicated by arrows. (d) Boring on brachiopod valve near hinge indicated by arrow. (e) Bryozoan growth on interior of brachiopod valve indicated by arrow and deposited on an indeterminate species of trilobite cephalon. (f) Algal accumulation encrusting brachiopod valve indicated by arrow.

unconformity in New York (Brett *et al.* 2011). Based on conodont biostratigraphy, this contact also coincides approximately with the uppermost Emsian and thus the boundary between the Lower and Middle Devonian (Kendall *et al.* 1983; Brett *et al.* 2009). According to Brett *et al.* (2009) and based on the estimates of Kaufman (2006), the Schoharie Formation was deposited over an interval of about 5 to 8 million years.

Based on the sequence stratigraphy and taphonomy discussed above, we interpret the RHf lag deposit to have accumulated initially during third-order sea-level regression in Emsian Cycle 5 of Ver Straeten (2007), and as part of a shallowing-upward cycle bounded below and above by the sub-Aquetuck and sub-Edgecliff unconformities. Trilobites and other invertebrate fauna would have been concentrated during exhumation and reburial events where localized wave base was capable of eroding into the shallow shelf platform in this area of eastern New York. Subsequent third-order sea-level transgression in Eifelian Cycle 1 of Ver Straeten (2007) would have resulted in preservation of the sandy limestone beds and the RHf lag deposit containing the trilobites and other invertebrates. The role of third-order sea-level cyclicity in the formation of this localized lag deposit is further reinforced by: (1) the sharp, erosional contact and distinct lithological change between the 1-m-thick RHf and underlying Saugerties Member (Fig. 2); (2) the fragmentary nature and random orientations of trilobites and other invertebrates (Figs. 4–10); and (3) hydrodynamic orientation of the larger cephalopods and inclusion of trilobite cephalons in broken phragmocone chambers of cephalopods (Figs. 9a–c).

Lag deposits similar to the RHf have also been identified in the Upper Ordovician Trenton Group and Middle Devonian Hamilton Group of New York (Brett 1995; Brett and Baird 1986; 1996). Basal transgressive beds commonly show shell concentrations with long-term time averaging, mineralization (including pyrite casts) above the maximum flooding surface, and concentration of nautiloids directly above an erosional disconformity (see Brett 1995). These additional basal transgressive and taphonomic features are also preserved in the RHf and suggest that this localized facies may in fact belong to the basalmost Edgecliff Member of the Onondaga Formation and initial transgression during Eifelian Cycle 1 of Ver Straeten (2007).

In the Helderberg Mountains region of New York, the Devonian outcrop belt bends sharply to the west near Albany, with the Taconic Mountains to the east and the Low Mountains and Western Hills of the Adirondack Mountains to the north. We interpret the discontinuous nature of the RHf in eastern New York as reflecting this shift in overall strike and dip along the Helderberg Escarpment and as representing a shallower-water shelf setting relative to other outcrops of the Saugerties Member of the Schoharie Formation seen in Kingston, Highland Mills and Port Jervis. The localized concentration and abundance of trilobites and other invertebrate fossils in

the RHf reflects these bathymetric controls on wave and current activity across this shallower-water setting. To the southeast and west of the RHf outcrop belt, the notable absence of fossil concentration and the gradational contact between the Schoharie and Onondaga formations indicates that deposition took place well below normal wave base and within deeper parts of the basin. Widespread changes in water depth in equivalent strata across the Appalachian Basin are also observed across the Schoharie-Onondaga transition and are related to an uplifted peripheral bulge in Acadian Tectophase 1, as identified by Ver Straeten (2007).

It is also significant that the RHf may have originally extended to the east to the Hudson River Gorge but if so was removed by glaciation of the Hudson-Champlain Lobe of the Laurentide Ice Sheet (see Sirkin and Bokuniewicz 2006). RHf glacial erratics containing the trilobites and other invertebrates described in this report, as well as those of Becker and Bartholomew (2013) and Becker *et al.* (2016), were likely part of this original eastward extension of the outcrop belt, which has been subsequently eroded, transported and deposited as far south as the northern New Jersey Piedmont.

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