Lithologies, ages, and provenance of clasts in the Ordovician Fincastle Conglomerate, Botetourt County, Virginia, USA

Harvey E. Belkin[1], John E. Repetski[2], Frank T. Dulong[3] and Nelson L. Hickling[4]*
[1]*U.S. Geological Survey (Ret.), 11142 Forest Edge Dr., Reston, VA 20190-4026 USA*
email: harveybelkin@gmail.com
[2]*U.S. Geological Survey, MS 926A, 12201 Sunrise Valley Dr., Reston, VA 20192-0002 USA*
email: jrepetski@usgs.gov
[3]*U.S. Geological Survey, MS 956, 12201 Sunrise Valley Dr., Reston, VA 20192-0002 USA*
email: fdulong@usgs.gov
[4]*U.S. Geological Survey (Ret.), 604 Spring Creek Dr., Ashland, OR 97520 USA*
** Deceased*

ABSTRACT: The Fincastle Conglomerate is an Ordovician polymictic, poorly sorted, matrix- and clast-supported cobble to boulder-rich conglomerate located just north of Fincastle, Botetourt County, VA. At least nine other cobble and boulder conglomerates are located in a similar stratigraphic position from Virginia to Georgia west of the Blue Ridge structural front. All except the Fincastle are dominated (~80%) by carbonate clasts; Fincastle clasts are much more varied and siliceous and it is this clast diversity that provides increased value for provenance and related studies. We have used a multidisciplinary approach that involves conodont analysis, sandstone petrography, in-situ outcrop clast characterization, optical petrography, electron-beam petrography and chemical analysis, and X-ray diffraction to provide data on lithologies, ages, and provenance. The size, roundness, and lithology of 1,656 clasts (> 1 cm) were measured in the field. Although, the clast lithology varies among the studied localities, the average lithology is sandstone and siltstone 12 %, vein quartz 17 %, limestone 31 %, low-grade quartzite/metasandstone 31 %, chert 6 %, and others 3 %. Dolomite, igneous, or high-grade metamorphic rock clasts were not identified in field study or in detailed laboratory analysis. Dolomite rhombs and authigenic albite feldspar were observed in some limestone clasts. Quantitative petrographic data for the Fincastle sandstone clasts indicate tectonic environments from passive margin to transitional continental uplift, but the conglomerate matrix modes have considerably less feldspar and plot in the foreland basin tectonic environment region. Proto-, para-, and euconodonts were identified from clast and matrix, but are long-ranging fauna indicating middle Cambrian to Middle or Late Ordovician ages; color alteration index (CAI) for euconodonts varied from 3 to 3.5. The occurrence of well-rounded clasts including limestone suggests a nearby, high-energy environment, and that transport was rapid enough to preserve limestone before deposition into a foreland basin. The lack of igneous or high-grade metamorphic rocks clasts suggests that the erosional level sampled by the Fincastle Conglomerate did not include the underlying Grenville basement of igneous or high-grade metamorphic rocks.

INTRODUCTION

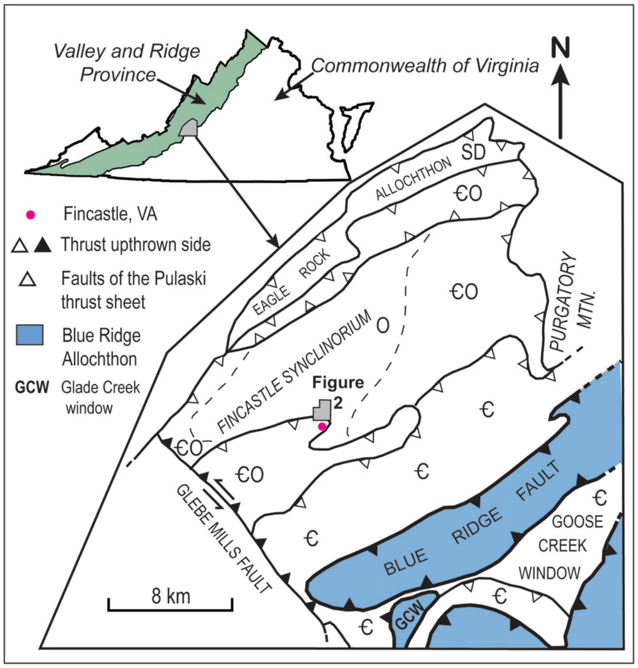
The Ordovician Fincastle Conglomerate is a spectacular polymictic cobble to boulder conglomerate, rare to the Appalachian Valley and Ridge province, in southwestern Virginia. Although limited in outcrop, exposures along a highway have provided convenient stops for many geology field trips (e.g., Cooper 1960; 1969; Cooper et al. 1961; Bartholomew et al. 1982; Rader and Gathright 1986; Haynes and Goggin 1994). Rudaceous deposits, especially polymictic, can provide much information on the degree of erosion, uplift, source region, and depositional setting during transport and accumulation. The cobbles and boulders provide enough sample to adequately characterize their lithology by routine chemical, petrographic, and microbeam studies.

Discussing the Fincastle Conglomerate, Cooper (1969, p. 6-7) said, "This deposit ranks as one of the major stratigraphic discoveries of the twentieth century in the Appalachians. - The cobbles, boulders, pebbles, and smaller clasts in this polymictic conglomerate represents all of the stratigraphic succession at least as low as the Unicoi… - Since the conglomerate is intraformational and so spectacularly polymictic, the conclusion of major rock deformation that was contemporaneous with sedimentation in the Appalachian geosyncline is evident and inescapable." The Fincastle Conglomerate may not live up to Cooper's accolades, but it can provide much information about erosion and depositional conditions in the Ordovician foreland basin and Taconic highlands.

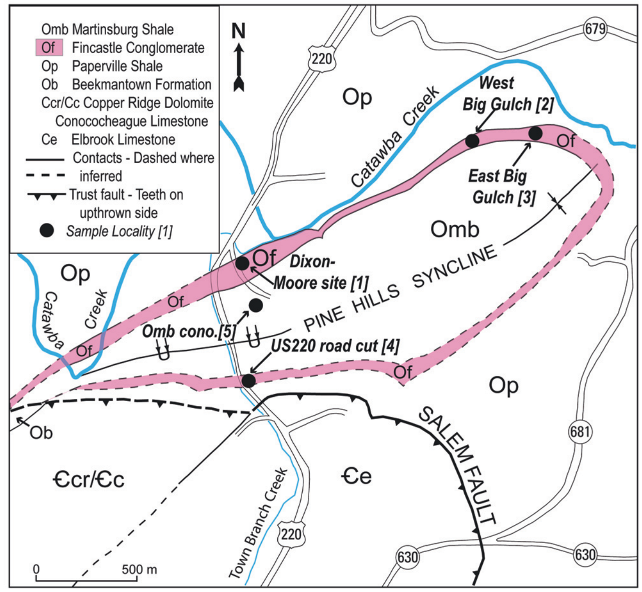
In this study, we present new data on the lithology, mineralogy, chemistry, and conodont paleontology of clasts and matrix from the Fincastle Conglomerate in order to better characterize the clast lithology to help constrain their sources and timing of the conglomerate deposition. A major part of this study was to try to verify the presence of igneous and/or high-grade metamorphic rocks reported in previous studies (e.g., Kellberg and Grant 1956; Karpa 1974). If present, these lithologies in the Fincastle Conglomerate would be important markers for the erosional history of the source highlands.

GEOLOGIC SETTING AND PRIOR STUDIES

The Pine Hills syncline is a complexly folded and thrusted area located in the southwestern Valley and Ridge province of the Virginia Appalachians, where unmetamorphosed siliciclastic and



TEXT-FIGURE 1
Location and schematic geology map that shows the Fincastle Conglomerate study area (text-fig. 2) in the context of the regional geology. € = Cambrian-age Shady, Elbrook and Rome Formations, €O = Upper Cambrian/Lower Ordovician-age carbonates, O = Middle and Upper Ordovician carbonates, sandstones, conglomerates, shales, and calcareous shales, and SD = Silurian sandstones and Devonian shales. Map adapted from Bartholomew (1987).



TEXT-FIGURE 2
Location map of the Fincastle Conglomerate and the Pine Hills approximately 2 km north of Fincastle, Botetourt County, Virginia, The map also shows the location of sample localities referenced in this report; 1-4 from the Fincastle Conglomerate, and 5 from the Martinsburg Formation. Latitude and longitude of the sample locations are given in Table 1. Map modified from Cullather (1992). Note that the thrust fault shown in this illustration is attributed to the Salem thrust, whereas, on text-figure 1, Bartholomew (1987) assigns the fault to the Pulaski thrust.

TABLE 1
Coordinates for sample locations shown in text-fig. 2

Sample sites	Location names	Latitude	Longitude
1	Dixon - Moore site	37° 31.920' N	79° 52.813' W
2	West of Big Gulch	37° 31.284' N	79° 51.995' W
3	East of Big Gulch	37° 31.319' N	79° 51.816' W
4	US 220 road cut	37° 30.621' N	79° 52.780' W
5	Martinsburg conodonts, USGS collection #10654-CO	37° 30.700' N	79° 52.800' W

carbonate Paleozoic strata are part of multiple imbricated, allochthonous thrust sheets that formed in response to continent-continent collision (text-fig. 1). The Pine Hills syncline (text-fig. 2) is part of the Fincastle synclinorium, a downfold of principally Cambrian strata on the Pulaski thrust sheet (Andrews 1952; Nichol 1959; McGuire 1970; Tillman and Lowry 1971; Amato 1974). First described by Woodward (1936, p. 135), the Fincastle Conglomerate is one of at least nine structurally and stratigraphically related Ordovician conglomerates that crop out along a 525 km stretch from Fincastle, Virginia to Cisco, Georgia in the Valley and Ridge province of the southern Appalachians (Cooper 1969). Kellberg and Grant (1956) studied six of these conglomerates, including the Fincastle Conglomerate, and they describe some characteristics among them that indicate a common mode of origin. These include a mid-Ordovician age, a lenticular nature and limited areal extent, poor sorting of the pebbles and cobbles, similar degree of clast rounding, similar percentage of rock types (with the exception of the Fincastle Conglomerate), and proximity to the northwestern boundary of the Blue Ridge thrust front. Three of them are within 2 km of the thrust (Cisco, GA; Etowah and Greenville, TN). The Fincastle Conglomerate lies 18 km northwest of the Blue Ridge front, on the Pulaski thrust sheet.

Subsequent to the detailed study by Kellberg and Grant (1956), the Fincastle Conglomerate has been examined for clast lithology, paleontology, and sedimentary characteristics (e.g., Lowry et al. 1972; Tillman and Lowry 1973; Karpa 1974; Hickling and Belkin 1988; Cullather 1988; 1992; Gao and Eriksson 1991; Eriksson et al. 1994). Recently, detrital zircons from siliciclastic clasts from the Fincastle Conglomerate have been analyzed in order to assess changing provenance with time and isotope composition (Eriksson et al. 2004; Park et al. 2010; Thomas et al. 2014).

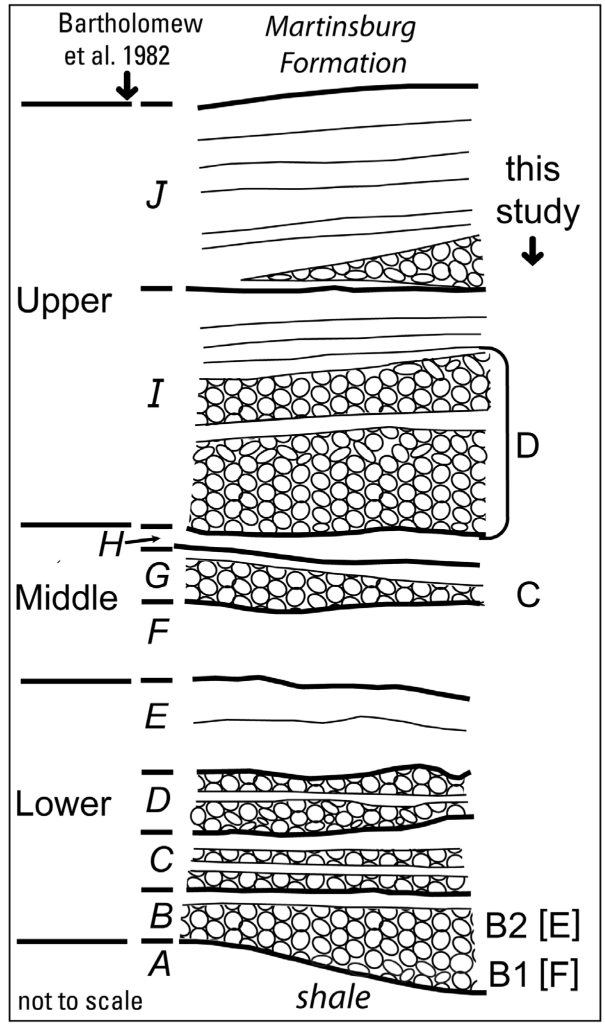
Pohn (2000) suggested that th Fincastle Conglomerate is an indicator of the Roanoke lateral ramp. Apparently, the conglomerate is geographically restricted to the Roanoke lateral ramp and Pohn (2000) proposed that the highland clast source was related to the arriving Taconic trust sheets along the Roanoke lateral ramp. Pohn (2000) also states that 3 of the other 5 conglomerates studied by Kellberg and Grant (1956) lie on a lateral ramp.

FINCASTLE CONGLOMERATE SEDIMENTOLOGY AND STRATIGRAPHIC POSITION

The Fincastle Conglomerate is a composite of conglomeratic lenses and beds up to ~11 m thick separated by shale, siltstone, and sandstone beds in a wide range of thicknesses (Cullather, 1992). The formation has a total thickness of up to 70 m. The matrix of individual conglomerate units is variable from

AGE	FORMATION	
Ordovician	Martinsburg Formation	
	Fincastle Conglomerate	
	Bays/Moccasin ⪤ Paperville/Knobs	
	Botetourt Limestone Lincolnshire Limestone	
	Newmarket Limestone	
	UNCONFORMITY	
	Beekmantown Group	
	Stonehenge Limestone	
Cambrian	Conococheague LS ⪤ Copper Ridge LS Elbrook Limestone	
	Rome Formation	
	Shady Dolomite	
	Erwin Formation	Chilhowee Group
	Hampton Formation	
	Unicoi Formation	
Precambrian	UNCONFORMITY	
	Marshall Metagranite	

TEXT-FIGURE 3
The local stratigraphy in the Fincastle-Roanoke, VA area adapted from Butts (1940), Cullather (1992), and Read and Repetski (2012). Fincastle Conglomerate is shown as a member of the Martinsburg Formation, a position that we favor based on the discussion in the text.



TEXT-FIGURE 4
Schematic stratigraphic column of the Fincastle conglomerate exposed at the Dixon-Moore site after Bartholomew et al. (1982), but drawn (not to scale) without deformation. Only the beds of cobble/boulder conglomerate are shown; shale, sandstone, and pebble conglomerate interlayer beds are not indicated. The heavy lines indicate the major units defined by Bartholomew et al. (1982); the thinner lines indicate boundaries of non-cobble/boulder conglomeratic units. The Bartholomew et al. (1982) classification is shown on the left, sample sections from this study on the right. We have correlated the east of Big Gulch section E with the upper portion of the first conglomerate bed B2 at the Dixon-Moore site and the west of Big Gulch section F with the lower potion of the first conglomerate bed B1 also at the Dixon-Moore site.

siltstone to litharenite composition. A total of eight facies units were recognized by Cullather (1992); (1) matrix-supported granule to boulder conglomerate and coarse-grained pebbly sandstone, (2) clast-supported granule to boulder conglomerate, (3) fine- to medium-grained sandstones (litharenites), (4) laminated to bedded siltstone, (5) massive and finely laminated shale, (6) discontinuously interbedded conglomerate, coarse grained sandstone, and shale, (7) interbedded shale and sandstone, and (8) convolute bedded shale. Cullather (1992) also described various sedimentary structures such as normal and reverse grading, convolute bedding, load casts, loaded flute marks, and intraformational shale clasts; whereas, cross-laminations, ripple marks, and imbrication are very rare.

Gao and Eriksson (1991) examined the strata capping the main conglomerate facies and recognized two facies, (1) bidirectional cross-laminated, very fine grained sandstones, and (2) unidirectional cross-bedded and cross-laminated, medium- to fine-grained sandstones. They suggested these strata represent internal-tide deposits from sea-level rise after the deposition of the coarse conglomerate debris-flow deposits.

The Fincastle Conglomerate and under- and over-lying strata have been assigned to various stratigraphic units since their initial detailed description by Stow and Bierer (1937). Cullather (1992) summarized the different assignments of formation names as follows: (1) in the Athens Formation (Stow and Bierer 1937; Butts 1940; Decker 1952), (2) between the Martinsburg and Athens Formations (Nichol 1959), (3) in the Liberty Hall Formation, but not a distinct member (Cooper 1960), (4) in the Tellico Formation above the Athens Shale (Kellberg and Grant 1956), (5) in the Edinburg Formation (McGuire 1970), 6) a member of the Liberty Hall Formation, (Tillman and Lowry 1971, 1973), (7) a facies of the Bays Formation below the Martinsburg Formation and above the Liberty Hall Formation (Karpa 1974), (8), a distinct formation below the Martinsburg Formation and above the Paperville Shale (Liberty Hall Formation)(Bartholomew et al. 1982), and (9) a member of the Martinsburg Formation above the Paperville Shale (Rader and Gathright 1986; Cullather 1988; 1992). Subsequent to above summary, others have assigned the Fincastle Conglomerate to the

TABLE 2
Summary of clast lithologies (size ≥ 1 cm) as a percentage of the total count as determined on the outcrop

	Sample Locality (Fig. 4) B1	B2	C	D	E	F	Summary This Study	Kellberg and Grant 1956*
number counted	440	264	197	311	222	222	*total* = 1656	
percent of count							*mean*	
sandstone, siltstone	0.9	0.4	74.6	13.6	2.0	2.0	11.7	5.7
vein quartz	15.2	29.2	13.7	18.0	8.0	23.0	17.2	22.1
limestone	43.9	17.0	0	37.0	41.0	31.0	31.2	38.6
quartzite, metasandstone	31.8	42.8	4.6	23.4	38.0	36.0	30.6	29.0
chert	6.6	8.7	0.5	2.6	9.0	7.0	5.9	3.7
other	1.6	1.9	6.6	5.4	2.0	1.0	3.4	0.9
average clast length cm	3.8	5.1	5.6	3.9	4.9	3.8	4.4	

This study - 'other' includes hematitic sandstone and siltstone, limestone and sandstone conglomerate, shale, and jasper

* Kellberg and Grant (1956) measured 2127 fine and coarse (>1 inch) clasts; the comparison data shown is their coarse clast count; data in % of count

following: (1) part of the Bays Formation (Gao and Eriksson 1991), (2) a member of the Martinsburg Formation overlying the Paperville Shale, a Liberty Hall equivalent (Haynes and Goggin 1994), (3) part of the Bays Formation below the Martinsburg Formation and above the Liberty Hall Formation (Eriksson et al. 2004), and (4) a member of the Martinsburg Formation (Park et al. 2010). text-figure 3 shows the local stratigraphy in the Fincastle-Roanoke, VA area; we show the Fincastle Conglomerate as a member of the Martinsburg Formation, a position that we favor based on the discussion below. However, this report does not formally propose this assignment.

One caveat the reader should be aware of especially when reviewing past stratigraphic position and age assignments related to the Fincastle Conglomerate and local stratigraphy in comparison to current terminology is that the Mohawkian is now in the Upper Ordovician only (Leslie and Bergström 1995; text-figure 14), and the Cambrian has been divided into four series/epochs (Cohen et al. 2013; version 2017/02). The International Chronostratigraphic epoch names are shown in text-figure 14 to compare to the North American/Laurentian epoch names.

STUDIED FINCASTLE CONGLOMERATE LOCALITIES

The Fincastle Conglomerate has limited areal exposure on two limbs of the overturned Pine Hills syncline (text-fig. 2). We studied and collected samples at four localities (text-fig. 2), the Dixon-Moore site, east and west of Big Gulch, and at the US 220 road cut.

TEXT-FIGURE 5
Back-scattered electron (except G) images of selected clasts.
Note that the gray scale for calcite is different among the images in order to show different textures.

A Sandstone clast FC185 with an adhering coating of matrix (arrow) along the fracture X-Y. Albite (Ab), quartz (Qz), and chlorite (Chl) are the main clast components; TiO_2 is a common phase in the matrix.

B Limestone clast FC16 with an adhering coating of matrix along the corroded edge (arrow) of the clast. Ab = albite, Cal = calcite, and Zrn = zircon.

C The edge of quartzite clast FC124 showing a type 2 calcite vein (Cal) with adhering (arrows) matrix (contains TIO_2). Qz = quartz.

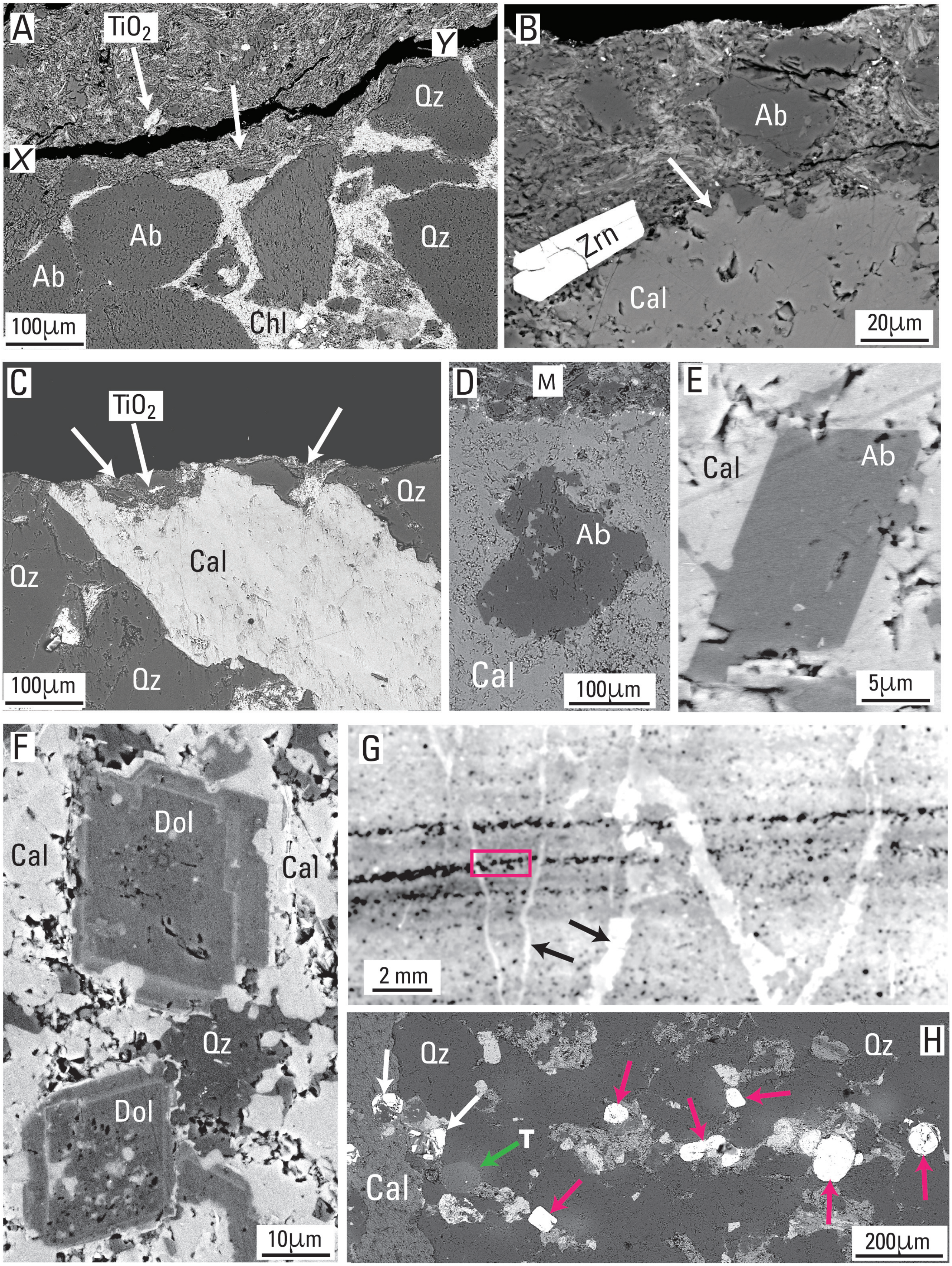
D Subhedral corroded albite (Ab) grain in calcite (Cal); note adhering matrix (M); limestone clast FC145.

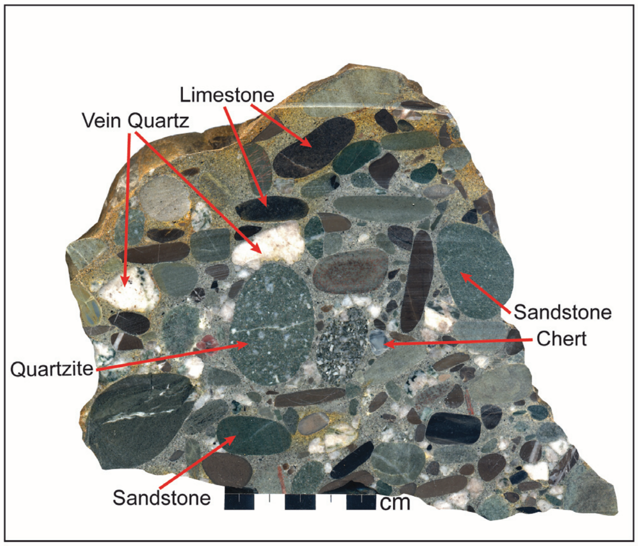
E Limestone clast FC157 with euhedral albite (Ab) in calcite (Cal).

F Limestone clast FC157 with zoned dolomite rhombs (Dol) in calcite; irregularly shaped quartz (Qz) is late stage.

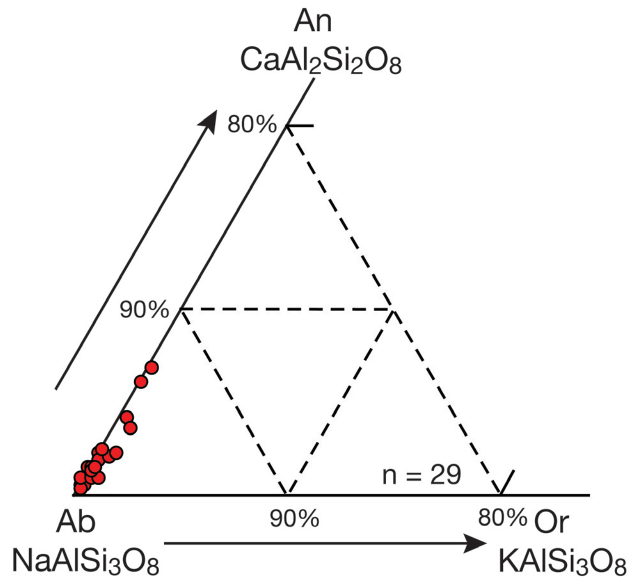
G Transmitted light image of a metasandstone (sample FC154) showing layers of dark minerals oriented left to right. Rectangle indicates the area enlarged in H. Arrows point to type 2 calcite veins, the thick and thin white bands of the image.

H Enlarged portion of G showing that most of the heavy mineral suite comprising the dark layers are zircon (red arrows) and less common tourmaline (T - green arrow). A type 2 calcite (Cal) vein has fractured the zircons indicated by the two white arrows on the left. Qz = quartz.


A
TiO2
Y
Qz
X
Ab
Qz
Ab
Chl
100μm
B
Ab
Zrn
Cal
20μm
C
TiO2
Qz
Cal
Qz
Qz
100μm
D
M
Ab
Cal
100μm
E
Cal
Ab
5μm
F
Dol
Cal
Cal
Qz
Dol
10μm
G
2 mm
H
Qz
Qz
T
Cal
200μm



TEXT-FIGURE 6
Image of a cut slab of Fincastle Conglomerate from the Dixon-Moore site (text-fig. 2, locality 1). This is a sample of conglomerate D (this study; conglomerate *I* of Bartholomew et al. 1982) from the Dixon-Moore site (text-fig. 3). Note clasts - limestone, vein quartz, chert, sandstone, and quartzite. The upper part of the slab was at the surface and has been weathered and stained brown by hydrated iron oxides.



TEXT-FIGURE 7
Albite corner of the An-Ab-Or ternary (mole%) showing that the authigenic plagioclase is nearly pure albite with some Ca variability; EPMA quantitative data.

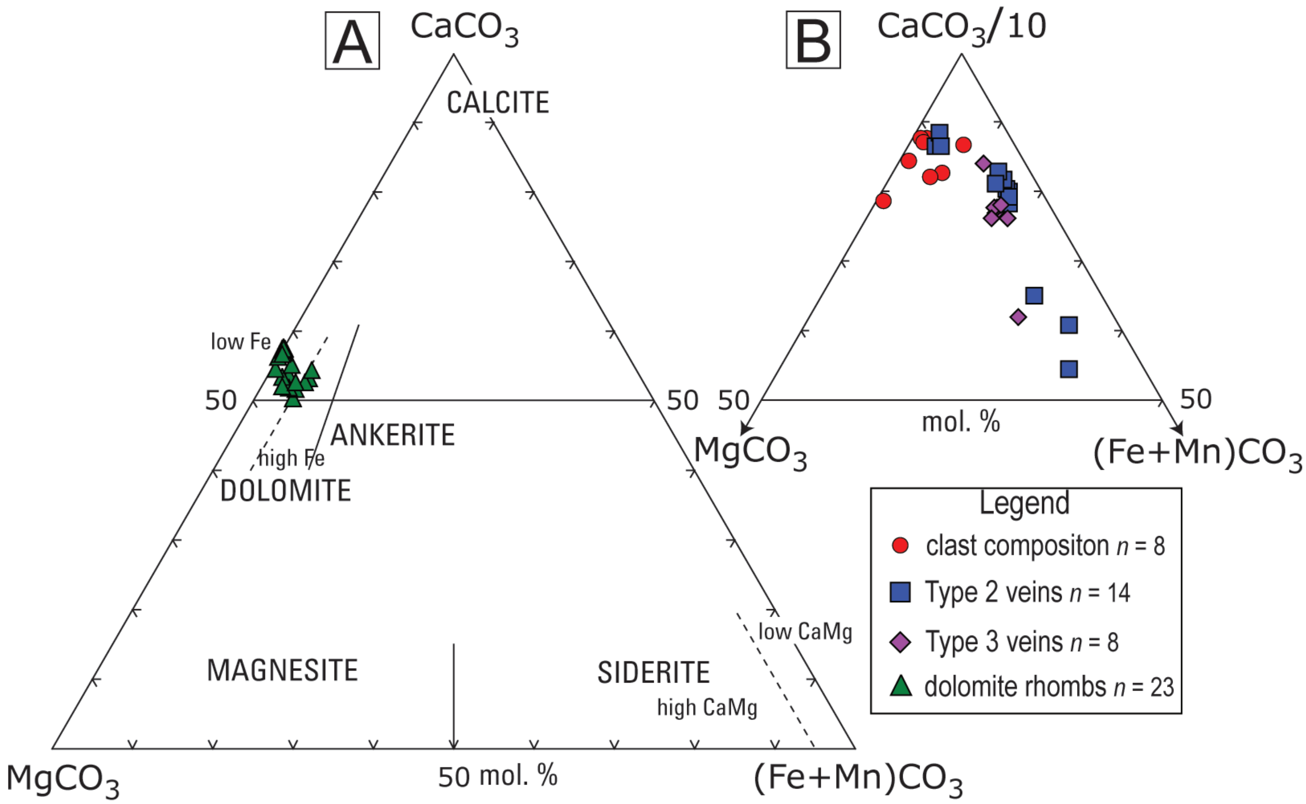
Clast counts were taken in the field at three locations, Dixon-Moore site, a former quarry [1], west [2] and east [3] of Big Gulch (text-fig.2, Table 1). The positions of our sampling sites, B1, B2, C, D, E, and F, relative to the conglomerate stratigraphy mapped by Bartholomew et al. (1982) are shown in schematic form in text-figure 4. The schematic strata configuration for the Dixon-Moore site shown in text-figure 4 was drawn in 1982 and the actual exposure has changed and continues to change as the outcrop weathers and slumps, and heavy equipment use continues intermittently for excavation of unstable sections. Therefore, clast counts that were taken before and after our counts may be somewhat different as the outcrop surface changes. Furthermore, in 1974 the Fincastle Conglomerate exposures changed relative to earlier studies with new road cuts along US 220, and a quarry opened in 1982 - the Dixon-Moore site. Additional samples, but no clast counts, were taken for chemistry and paleontology at the US 220 road cut (text-fig. 2). Butts (1940) shows a picture (Plate 28A, p. 129) of the former US 220 Fincastle Conglomerate outcrop prior to its 1974 change.

METHODS

Field identification was done only on clasts equal to or more than 1 cm in long dimension. Smaller clasts were difficult to distinguish from the larger matrix grains and those smaller than 1 cm present significant uncertainties in field lithologic identification at that scale. Dilute (10%) hydrochloric acid was used for carbonate identification with careful application such that calcite veins in siliceous or carbonate clasts were not inadvertently tested. Dolomite clasts are similar in appearance to limestone clasts, but being less soluble the standard field method of applying HCl to a powdered surface serves to differentiate the two lithologies (Prothero and Schwab 2013).

Quantitative electron microprobe analyses (EPMA) of carbonate and feldspar were obtained with a JEOL JXA-8900R five spectrometer, fully automated electron microprobe using wavelength-dispersive X-ray spectrometry at the U.S. Geological Survey in Reston, VA. The samples were examined optically and by scanning electron microscope (SEM) back-scattered electron imaging to define points for analysis. Analyses were made at 15 keV accelerating voltage, 10 or 20 nA probe current, and counting times of 10 or 20 s on peak, using a 5 of 20 µm probe spot. Natural standard in-house and Smithsonian supplied reference materials were used. The analyses were corrected for electron beam/matrix effects, and instrumental drift and deadtime using a Phi-Rho-Z (CITZAF, Armstrong 1995) algorithm as supplied with the JEOL JXA-8900R electron microprobe. Relative accuracy of the analyses, based upon comparison between measured and published compositions of standard reference materials, is ~1-2 % for oxide concentration >1 wt. % and ~5-10% for oxide concentrations <1 wt.%.

Powdered (<73 µm) bulk carbonate clast samples were prepared as 25 mm pressed-pellets for X-ray diffraction semi-quantitative analysis. A PANalytical X-ray diffractometer operating at 45 kilovolts and 40 milliamps with fixed slits (incident-divergence 1/8° and antiscatter 1/4° and diffracted- antiscatter 1/8°) was used to scan the samples from 5 to 65° two-theta counting for what is the equivalent of 60 seconds every 0.017° two-theta with copper radiation. A computer program was used to process the X-ray spectrum and estimate the proportions of major, minor, and trace mineral phases (Hosterman and Dulong 1989). The (002) kaolinite and (004) chlorite peaks at high 24 and low 25 degrees two-theta respectively were examined graphically in order to determine their relative amounts if present (Biscaye 1964). Detection limits ranged from 1 to 5% as a function of intrinsic crystallinity.



TEXT-FIGURE 8
Mineral chemistry from EPMA. A- Molar composition (%) of dolomite rhombs in limestone clasts FC145 and FC157. B - Carbonate composition of clasts, Type 2, and Type 3 veins. Note that the apex, $CaCO_3$, has been divided by 10, before normalization. Representative data are shown in Tables 7 and 8.

Fourteen carbonate clasts and pieces of matrix were selected for sample preparation for conodont study using standard methods of crushing, buffered acetic acid dissolution, heavy liquid separation and hand picking (Collinson 1963).

RESULTS

Clast composition and diversity

Clast counts and sizes

Separate clast population counts were made of each of the three major conglomerate units exposed in the quarry face at the Dixon-Moore site and at Big Gulch east and west (text-fig. 2). The stratigraphic column shown in text-figure 4 is taken from Bartholomew et al. (1982); it shows their first (lower) conglomerate made up of units B thru E, second (middle) conglomerate units F thru H, and the third (upper) conglomerate as units I and J. The clast counts at the Dixon-Moore site were made on units B, G, and I. Unit B was subdivided into B1, lower part and B2, upper part and counted separately. Additional counts were made on the stratigraphic equivalent of sub-units B1 and B2 at Big Gulch east and west (text-fig. 2).

The following provides the details of the locations of the clast counts. At location 1 (text-fig. 2): B1 – just above the shale-conglomerate contact at the bottom of Town Branch Creek; B2 – the upper portion of the first conglomerate, approximately 2 m stratigraphically above site B1; C – the second major conglomerate unit, and D – the uppermost conglomerate unit at the Dixon-Moore site. At location 3: E – east of Big Gulch about 10 m above base level, contact with shale not observed; we correlate E with B2. At location 2: F – west of Big Gulch about 2 m above shale contact; we correlate sample F stratigraphically with B1. Karpa (1974) defines a lithologic boundary separating the US 220 and Dixon-Moore Site units with the much thicker section at Big Gulch, although sedimentation was contemporaneous. Cullather (1992) suggests that the thicker section at Big Gulch is the result of tectonic thickening. Cullather (1992) also presents photographs of typical Fincastle Conglomerate lithologies and detailed measured stratigraphic sections. As noted above, the photographed outcrops and measured sections have changed due to slumping, erosion, and excavation.

The long dimension of each of 1,656 clasts was measured and the lithic type identified after breaking the weathered surface. We attempted to randomize our sampling, but sometimes portions of the outcrop surface were not equally accessible. Table 2 gives the clast lithologic diversity data and average size and compares it with Kellberg and Grant (1956) who had similar results. The average clast size was 4.4 cm for all lithologies and the largest clast found in this study was a 21 cm sandstone from the conglomerate at Big Gulch west. Karpa (1974) reports a sandstone clast 43 cm in length in the middle conglomerate at Big Gulch, and Cooper (1960) found a siliceous clast 46 cm in length. The average clast long dimension for the major lithologic groups measured in this study is: sandstone and siltstone = 5.55 cm, metasandstone and

TABLE 3
Fincastle Conglomerate clast roundness data.

conglomerate unit (Fig.4)	number counted		normalized to 100%			
B1	n =		RS	RF	OS	OF
	8	sandstone & siltstone	0	25	13	63
	70	vein quartz	11	1	87	0
	30	chert	0	17	67	17
	173	limestone	0	5	12	83
	139	quartzite & metasandstone	0	9	50	40
B2	n =		RS	RF	OS	OF
	1	sandstone & siltstone	0	0	100	0
	58	vein quartz	7	0	91	2
	23	chert	0	9	43	48
	47	limestone	0	4	11	85
	102	quartzite & metasandstone	1	1	77	21
C	n =		RS	RF	OS	OF
	145	sandstone & siltstone	2	5	59	34
	26	vein quartz	0	12	88	0
	1	chert	0	0	0	100
	0	limestone	0	0	0	0
	9	quartzite & metasandstone	11	0	67	22
D	n =		RS	RF	OS	OF
	42	sandstone & siltstone	19	10	21	50
	58	vein quartz	74	12	10	3
	9	chert	89	0	0	11
	114	limestone	6	5	19	69
	80	quartzite & metasandstone	28	20	25	28
E	n =		RS	RF	OS	OF
	8	sandstone & siltstone	0	0	88	13
	16	vein quartz	0	0	94	6
	20	chert	0	0	65	35
	89	limestone	0	1	28	71
	84	quartzite & metasandstone	0	2	75	23
F	n =		RS	RF	OS	OF
	7	sandstone & siltstone	0	57	0	43
	56	vein quartz	70	5	21	4
	16	chert	0	0	31	69
	73	limestone	0	1	14	85
	77	quartzite & metasandstone	10	6	55	29

RS = round spheroid, RF = round flat, OS = oval spheroid, OF = oval flat

quartzite = 5.55 cm, limestone = 3.75 cm, vein quartz = 3.54 cm, and chert = 1.70 cm.

Clast lithic types were identified on the outcrop and by necessity we used a simple lithologic classification scheme. Sandstone, for example, can be classified into a plethora of names, but our field name was just sandstone to which we added siltstone. Siliciclastic clasts very difficult to break were called quartzite/metasandstone. Sandstone and siltstone are combined into one class. In the field it was not possible to distinguish clasts composed of fine sand from coarse silt; the division is 0.063 mm (International scale). The remaining lithologic classification used is: vein quartz, limestone, and chert. The 'others' class includes mostly clasts of limestone and sandstone conglomerate, hematitic sandstone and siltstone, shale, and rare jasper (1 clast). We were particularly interested in the reports of dolomite and augen gneiss (Karpa 1974) and greenstone (Kellberg and Grant 1956) found in the Fincastle Conglomerate, and carefully looked for these types, but we found none.

Clast roundness

As part of the field examination, we classified each clast into one of four groups: round spheroid, round flat, oval spheroid, and oval flat combining a description of shape (or form) and roundness (the sharpness of the corners and edges). This classification was useful in the field, especially on flat outcrop surfaces. Early in our field investigation, we recognized that the Fincastle Conglomerate clasts, in general, are well rounded and very angular to sub-angular classifications (e.g., Benn and Ballantyne 1993) were not needed. Furthermore, to establish more detailed roundness parameters would have entailed extensive clast collections and was beyond the scope of this study.

Table 3 gives the field roundness data associated with the clast lithology identification. Limestone clasts, especially those of chocolate brown color (5YR 2/2 to 5 YR 3/4), siltstone and shale were flattened shapes, whereas, the siliciclastic clasts, sandstone, metasandstone and quartzite, tended to be more spherical in shape, and it appears both shapes resulted from the geometry of their original bedding and/or jointing and fracture characteristics. Vein quartz and chert were the least rounded. Clasts smaller (< 1 cm) than our studied criterion were more angular as were the quartz and feldspar fragments in the matrix.

Clast petrography and chemistry

The collected clasts were usually separated from the matrix either by weathering, where the clasts collect at the bottom of the outcrop, or by hand or hammer with little or moderate effort. Commonly, the clast has a discontinuous adhering matrix coating of varying thickness. Freshly dislodged clasts sometimes had a brown stain (see below) that usually washed off with scrubbing. Hickling and Belkin (1988) suggested that this adhering discontinuous matrix coating might be similar to a desert varnish although they found the coating not Mn-bearing as is typically found in modern desert varnish. Text-figures 5a and 5b show that some matrix is commonly attached to the clast, albeit discontinuously, when the clast is separated from the outcrop. Text-figure 5c shows small pockets of matrix attached in pockets where a calcite vein was eroded during transport. The variable composition of the clast coating reported by Hickling and Belkin (1988) is compatible with the small-scale compositional variability one would expect in a relatively coarse-grained immature matrix. We suggest that the coatings described by Hickling and Belkin (1988) are fragments of matrix adhering to the clast. However, their conclusion that the clasts represent resedimented alluvial fan material sourced from arid environments is not precluded.

The conglomerates are both clast and matrix supported as a function of their relative proportions (cf. Cullather 1988, 1992). Text-figure 6 shows a slab from the Dixon-Moore site [conglomerate D, our study] showing a clast-supported portion of the conglomerate. Also shown are typical examples of limestone, sandstone, quartzite, and vein quartz clasts. Note that the upper portion of the slab is weathered and brown-stained as a result of accumulation of hydrated iron oxides.

TABLE 4
Representative modal analysis of Fincastle Conglomerate sandstone clasts.

Sandstone classification =	1	2	2	2	2	3	3	3	3	4	4
Sample	FC20	FC84	FC1	FC3	FC83	FC29	FC23	FC2	FC27	FC86	FC87
Quartz	60.8	86.3	83.3	60.4	80.6	71.4	73.5	65.1	60.9	45.3	47.9
meta-Quartz	0.9	8.0	2.9	5.3	1.6	4.2	1.3	0.9	5.2	1.4	2.6
Chert	1.1	0.0	4.2	7.7	0.4	1.3	0.4	0.9	1.0	0.0	0.0
Feldspar	0.5	0.9	7.1	8.3	9.8	18.8	18.9	22.5	24.6	30.0	39.6
Lithic (sedimentary)	35.1	2.7	1.0	4.3	2.1	1.2	2.8	3.0	4.6	4.5	6.3
Lithic (metamorphic)	0.0	0.0	0.0	4.7	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Lithic (carbonate)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.0	0.0	0.0
Muscovite	0.0	1.6	0.0	3.6	1.8	0.5	0.9	1.3	0.4	6.0	1.0
Biotite	0.0	0.0	0.2	0.0	1.0	0.0	0.0	0.4	0.0	3.8	1.0
Chlorite	1.3	0.4	1.0	4.9	2.6	2.0	2.2	3.3	3.1	8.9	1.6
Tourmaline	0.1	TR	0.3	0.8	0.1	0.1	0.0	TR	0.1	0.1	TR
Zircon	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Matrix	7.3	7.8	16.4	49.3	16.7	2.4	18.5	15.1	7.5	14.5	9.3
Cement	0.0	15.6	0.0	0.0	3.9	0.3	0.0	14.7	0.0	1.5	29.1
Framework grains	92.7	76.6	83.6	50.7	79.4	97.3	81.5	70.2	92.5	84.0	61.6

Modal analysis based on 1000 counts; Data in volume %
Sandstone classification - 1 = lithic arenite, 2 = quartz arenite, 3 = subfeldspathic arenite, 4 = felspathic arenite
TR = trace

Carbonate clasts and veins: petrography and chemistry

Carbonate clast texture and composition

The textures of the limestone clasts varied widely and we described as pelletal, micritic, intraclastal, and sparry. Scattered euhedral to subhedral authigenic albite crystals were noted in many limestone clasts (text-figs. 5D, 5E). By the 1880s, euhedral feldspars in limestone had been documented as being authigenic (Daly 1917 and references therein). EPMA data shows that these authigenic crystals are nearly end member albite with slight differences in Ca content (text-fig. 7). Pure end member composition is typical of albite forming in limestones during diagenesis (Rais et al. 2008) or from exposure to hydrothermal fluids (Spötl et al. 1999).

Kellberg and Grant (1956) discussed the presence or absence of dolomite clasts as an indicator of source region for these conglomerates; our field clast identification did not detect dolomite. We selected representative carbonate clasts for powder X-ray diffraction and EPMA procedures to confirm our field identification. Table 6 shows that based on X-ray diffraction, all of our tested carbonate clasts are calcite with variable amounts of quartz. Minor amounts of ankerite/dolomite, siderite, sulfide and feldspar were also identified.

Representative EPMA data of the carbonate clasts (Table 7) also show that calcite is the major carbonate species with minor amounts of magnesite ($MgCO_3$), siderite ($FeCO_3$), and rhodocrosite ($MnCO_3$) components; strontianite ($SrCO_3$) was usually at or below detection limit. Two carbonate clasts, FC145 and FC157, contained scattered subhedral to euhedral zoned calcian dolomite crystals with slightly iron-rich rims (text-fig. 5F). EPMA data (text-fig. 8A) show that most of the dolomite is nonstoichiometric, with a maximum 57 mole% $CaCO_3$. However, no significant differences were observed among the carbonate clasts from the various units in terms of bulk carbonate chemistry (text-fig. 8B).

Carbonate veins

Various sizes of quartz and calcite veins are present in a variety of generations both in the clasts and the matrix. We classified the vein occurrences into three types: type 1 - veins in grains that comprised the clast protolith, type 2 - veins forming before the protolith eroded to form the clast, and type 3 - veins forming after conglomerate lithification (text-fig. 9). Type 3 veins may intersect a clast or just transect the matrix. Kellberg and Grant (1956) and Karpa (1974) described two sets of filled veinlets and both commented that they found compositional differences associated with their occurrence; calcite veins in the matrix versus quartz veins in the clasts. We examined Fincastle Conglomerate veins in the field, in kilogram hand samples, and in individual clast thin sections. We found in our sampling, in contrast to Karpa (1974) and Kellberg and Grant (1956), that quartz veins were less common and were observed only in siliceous clasts as type 1 or 2 veins. In our sampling, carbonate veins were more common and were observed in both siliceous and carbonate clasts (text-figs. 5C, 5D, and 5G). Calcite veins that transected the matrix ranged in thickness from <1 to 7 mm and are discontinuous. The EPMA compositional data (text-fig. 8B, Table 8), for carbonate vein types 2 and 3, are essentially calcite with minor amounts of $MgCO_3$, $FeCO_3$, $MnCO_3$, and $SrCO_3$.

Text-figure 10 shows a slab cut from a sample collected at locality 4 (US 220 road cut; text-fig. 2), from the overturned limb of the Pine Hills syncline. In comparison to samples from the Dixon-Moore site on the upright limb (see text-fig. 6), type 3 veining is much more common in the overturned limb where intense shear and extension were operative.

Sandstone petrography and classification

Representative siliciclastic clasts were selected from all the studied conglomerate units for thin section petrography and modal analysis (Table 4). Additionally, matrix samples (Table 5) were analyzed modally in an attempt to characterize their components, but we recognize the limitation that some fine-grained matrix material was beyond resolution with the polarizing microscopic.

TABLE 5
Representative modal analysis of Fincastle Conglomerate matrix.

Sandstone classification =	1	1	1	2	2
Sample	FC8	FC31	FC13	FC72	FC9
Quartz	56.2	66.9	55.0	43.4	51.6
meta-Quartz	19.5	8.6	5.7	0.0	3.3
Chert	6.3	1.0	2.0	0.0	5.0
Feldspar	3.4	5.2	5.7	1.8	4.3
Lithic (sedimentary)	2.9	15.4	13.7	8.8	9.2
Lithic (metamorphic)	4.0	1.9	0.0	0.0	14.2
Lithic (carbonate)	6.0	1.0	5.7	40.8	8.8
Muscovite	1.1	0.0	0.3	2.4	1.3
Biotite	0.0	0.0	0.0	0.0	0.0
Chlorite	0.6	0.0	11.9	2.8	2.3
Tourmaline	TR	0.0	0.0	0.0	0.0
Zircon	0.0	0.0	0.0	0.0	0.0
Matrix	65.2	68.9	64.8	49.8	60.0
Cement	0	0	0	0	0
Framework grains	34.8	31.1	35.2	50.2	40.0

Modal analysis based on 1000 counts; Data in volume %
Sandstone classification - 1 = sublithic arenite, 2 = lithic arenite
TR = trace

Text-figure 11 shows the sandstone classification based on point counts of quartz (Q), feldspar (F), and lithic (L) framework grains. Most of the sandstones are quartz and subfeldspathic arenites, with the higher feldspar content sandstones in the feldspathic arenite field. Two feldspar-poor sandstones classify in the lithic arenite field. The matrix varies between sublithic and lithic arenite.

Zircons were especially abundant in some laminated sandstones, metasandstones, and quartzites, but less so in the matrix (text-fig. 5B). The dark mineral layers contain euhedral to rounded zircons and less common rounded tourmalines (text-figs. 5G and 5H)

Paleontology

Paleontology - previous studies

Although previous publications have documented the occurrence of fossil debris in the mudstones, shales, and sandstones of the Fincastle Conglomerate (e.g., Cullather 1988; 1992), no systematic studies of the clasts have been published. Gao and Ericksson (1991), cited macrofossil identification by B. Bennington, and listed the following species in the mudstone slump deposits; Bivalvia - *Praettucula* and *Tancrediopsis*; Gastropoda - Bellerophontacean, c.f. *Ectomaria*, c.f. *Liospira* and Archeogastropoda indet., filter feeders - Brachiopoda sowerbyellid, Bivalvia *Ambonychia*?, *Lichenia* [a chaetetid calcareous sponge], bryozoans, and crinoid columnals. Karpa (1974) reports *Sowerbyella cava* described by G. A. Cooper from the shale overlying the Fincastle Conglomerate. Tillman and Lowry (1973) discussed a conodont study of the carbonate clasts in an abstract, but neither species names nor a subsequent paper were published. The authors are not aware of any published paleontological study of the Fincastle Conglomerate carbonate clasts.

TABLE 6
Semi-quantitative X-ray diffraction data from carbonate clasts.

Data in volume %		ankerite/			
Sample	calcite	dolomite	silica	sulfides	feldspar
FC103	95	5			na
FC109	95	5			na
FC111	95		5		na
FC118	95		5		na
FC139	85		15		na
FC146	85		10	5	na
FC148	95		5		na
FC149	80		15		na
FC156	70		30		na
FC191	95		5		na
FC14	85		15		na
FC16	90		10		na
FC112**	15		85		na
FC114**	45		55		na
FC 2015 A1***	88	3	8		2
FC 2015 A2***	79	2	18		1
FC 2015 A3***	82	TR siderite*	15		3
FC 2015 B1***	95		4		1
FC 2015 B2***	93		6		1
FC 2015 B3***	89	TR siderite*	10		1

illite, chlorite, and kaolinite were not found in quantities > 5%
* siderite component ~ 0.5%
** cherty carbonate clast
*** brown limestone clast
TR = trace; na = not analyzed

Conodonts

Fourteen limestone clast/matrix samples were processed for microfossils, of which nine yielded conodonts, including proto-, para-, and euconodonts. A very common characteristic of the clasts must be recognized for the accurate interpretation of conodont paleontology. The limestone clasts, in fact all of the lithologies, tend to have a discontinuous matrix coating (e.g., text-figs. 5A & 5B). Although, this coating is usually thin, < 200 µm, we cannot preclude that conodonts were not in the adhering matrix. We analyzed one sample with thick (2 to 3 mm) matrix rinds (FC2015B) and one sample of mostly matrix with clasts (FC2015Am) (Table 9). The Fincastle Conglomerate matrix is a mixture of detrital material and authigenic clays. Included in the matrix are fragments from the mechanical disintegration of the limestone clasts during transport. Undoubtedly, conodonts from the clasts during transport could have become part of the matrix mixture. Therefore, it may be difficult to distinguish a conodont found in the matrix from (1) one formerly part of a fragmented clast OR (2) a conodont extant in the marine depositional environment, especially if the conodont taxa were long-ranging.

The most common of the protoconodonts, *Phakelodus elongatus* and *P. tenuis* (text-figs. 12F, 12P and 12Q), are found mostly in Cambrian strata but are fairly long ranging, from at least middle Cambrian (although having been reported even lower) into the Lower Ordovician (Tremadocian). Paraconodonts found include *Westergaardodina* sp. (text-fig. 12E), *Muellerodus oelandicus* (text-figs. 12G and 12H), *Furnishina furnishi* (text-figs. 12K and 12L), and *Prooneotodus gallatini* (text-fig. 12M). Paraconodonts are also long ranging, from the late/middle Cambrian to the Middle Ordovician. Euconodonts include several Lower Ordovician (Tremadocian)

TABLE 7
Representative EPMA analysis of carbonate clasts and intraclastic dolomite rhombs

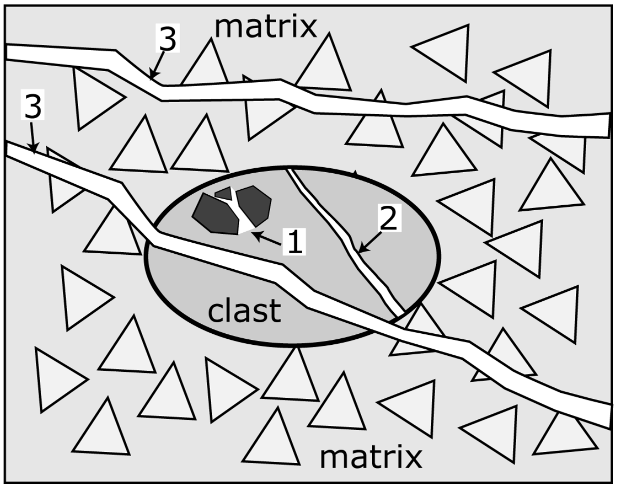
	carbonate clasts				dolomite rhombs			
Sample	FC107	FC145	FC77	FC16	FC145.4	FC145.3	FC157.7	FC157.18
n =	6	3	3	10	1	1	1	1
lithology	ls congl.	micrite	peloidal	peloidal				
CaO wt%	55.43	55.45	55.10	54.84	31.73	30.99	32.63	34.54
MgO	1.03	0.68	0.50	0.50	17.80	19.50	19.38	18.38
MnO	0.06	0.10	0.05	0.10	0.37	0.21	0.00	0.04
FeOT	0.04	0.02	0.06	0.05	3.94	2.02	0.64	0.13
SrO	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00
CO_2*	44.67	44.33	43.84	43.67	46.96	46.96	47.14	47.26
Total	101.22	100.62	99.56	99.16	100.80	99.68	99.78	100.35
cations on the basis of 6 oxygens								
Ca	1.947	1.963	1.972	1.970	1.060	1.035	1.086	1.147
Mg	0.050	0.033	0.025	0.025	0.827	0.906	0.898	0.849
Mn	0.002	0.003	0.001	0.003	0.010	0.005	0.000	0.001
Fe	0.001	0.000	0.002	0.001	0.103	0.053	0.017	0.003
Sr	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
C*	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
$CaCO_3$	97.4	98.1	98.6	98.5	53.0	51.8	54.3	57.3
$MgCO_3$	2.5	1.7	1.3	1.2	41.4	45.3	44.9	42.4
$MnCO_3$	0.1	0.1	0.1	0.1	0.5	0.3	0.0	0.1
$FeCO_3$	0.1	0.0	0.1	0.1	5.1	2.6	0.8	0.2
$SrCO_3$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

FeOT = total iron as FeO
CO_2*, C* determined by stoichiometry
n = number of analytical points averaged

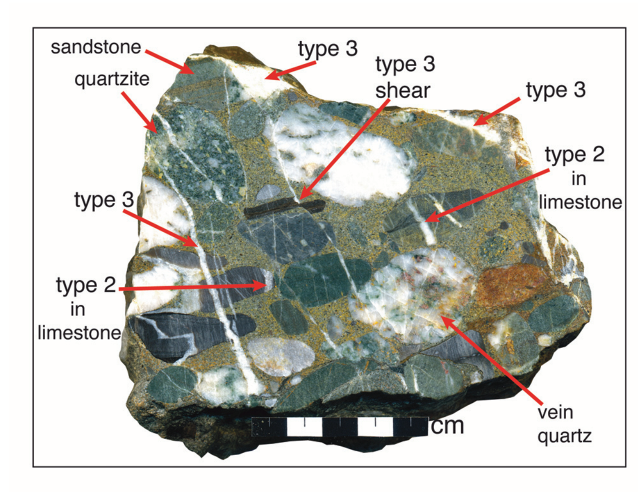
TABLE 8
Representative EPMA analysis of type 2 and 3 veins

	type 2 veins					type 3 veins			
Sample	FC142	FC186	FC77A	FC77B	FC74	FCV3A	FCV3E	FC122	FC186
n =	5	3	3	3	2	6	6	6	6
host	sandstone	sandstone	limestone	limestone	limestone	matrix	matrix	sandstone	matrix
CaO wt%	52.61	53.21	55.19	55.39	53.43	53.91	53.86	50.36	53.27
MgO	0.23	0.21	0.43	0.44	0.40	0.36	0.40	0.68	0.29
MnO	0.47	0.46	0.13	0.09	0.09	0.25	0.22	1.07	0.30
FeOT	0.95	0.92	0.18	0.21	0.24	1.18	1.21	1.62	1.08
SrO	0.14	0.06	0.00	0.00	0.06	0.11	0.11	0.00	0.13
CO_2*	41.85	42.23	43.32	43.48	41.97	43.60	43.62	41.91	43.01
Total	96.25	97.09	99.25	99.60	96.20	99.41	99.43	95.63	98.07
cations on the basis of 6 oxygens									
Ca	1.943	1.948	1.969	1.969	1.968	1.940	1.937	1.884	1.942
Mg	0.012	0.011	0.022	0.022	0.021	0.018	0.020	0.036	0.015
Mn	0.014	0.014	0.004	0.003	0.003	0.007	0.006	0.032	0.009
Fe	0.028	0.027	0.005	0.006	0.007	0.033	0.034	0.048	0.031
Sr	0.003	0.001	0.000	0.000	0.001	0.002	0.002	0.000	0.003
C*	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
$CaCO_3$	97.2	97.4	98.5	98.5	98.4	97.0	96.9	94.2	97.1
$MgCO_3$	0.6	0.5	1.1	1.1	1.0	0.9	1.0	1.8	0.8
$MnCO_3$	0.7	0.7	0.2	0.1	0.1	0.4	0.3	1.6	0.4
$FeCO_3$	1.4	1.3	0.3	0.3	0.4	1.7	1.7	2.4	1.6
$SrCO_3$	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.1

FeOT = total iron as FeO
CO_2*, C* determined by stoichiometry
n = number of analytical points averaged



TEXT-FIGURE 9
Schematic diagram that shows the various clast and matrix veining relationships: Type 1 - early vein in detrital grains comprising the clast, Type 2 - vein after clast lithification, but before erosion and clast formation, Type 3 - veins in matrix after conglomerate lithification, one cuts a clast and one does not.



TEXT-FIGURE 10
Image of cut slab from the Fincastle Conglomerate from the overturned limb along US 220 (text-fig. 2, locality 4). Note clasts - limestone, vein quartz, sandstone, and quartzite. This sample has been weathered and the entire matrix is brown-stained with hydrated iron oxides. Note type 2 veins in two limestone clasts. Some type 3 veins show right-lateral shear and have offset parts of clasts.

taxa that 'sourced' from clasts, including *Variabiloconus bassleri* (text-fig. 12B), *Rossodus manitouensis* (text-fig. 12C), *Parapanderodus* sp. (text-fig. 12D), and *Laurentoscandodus triangularis* (not figured). A few Middle or Upper Ordovician euconodonts were identified; these include *Panderodus* sp. (text-fig. 12I) and *Protopanderodus?* sp. (text-fig. 12J). A 4.9 kg sample of calcareous Martinsburg Shale from 101 m above the top of the Fincastle Conglomerate at the Dixon-Moore site (text-fig. 2) yielded seven broken euconodont elements, including the S element of *Phragmodus* sp. (text-fig. 12A; sample, USGS collection locality 10654-CO, collected by A. Schultz, USGS-retired). That conodont, along with one tentatively identified as *Baltoniodus aff. B. gerdae*, are consistent with an early Late Ordovician age for that level in the Martinsburg at that site.

Conodont Color Alteration Index

The conodont color alteration index (CAI) for the euconodonts was in the 3 to 3.5 range (Table 9), indicating that the host rocks were heated, post-deposition, to at least about 110 degrees C (Epstein et al. 1977). Proto- and paraconodonts have not been calibrated for CAI, and so only the euconodonts recovered in this study could be indexed. However, this range of CAI is consistent with the regional patterns for Ordovician rocks in this part of the Appalachian basin (Harris et al. 1978; Repetski et al. 2008).

DISCUSSION

Clast composition and diversity

Early reports of Fincastle clast lithology and host strata misidentified the lithology of some clasts and the structural setting (Stow and Bierer 1937 - diabase; Butts 1940 - grey quartzite; and Decker 1952 - an anticline). Subsequent detailed clast lithology counts by Kellberg and Grant (1956), Karpa (1974), and Cullather (1988; 1992) compared to the counts presented in this study (Table 2) show the variability that should be expected with small-scale, poorly sorted, discontinuous cobble and boulder conglomerate lenses. No carbonate clasts were recovered from the middle conglomerate (text-fig. 4, Table 2), and Cullather (1988; 1992) reported a similar result.

Sandstone petrography

Text-figure 13 shows the sandstone clast and matrix modal data (Tables 4 and 5) plotted on a Dickinson QFL plot (Dickinson et al. 1983; Dickinson 1985). Most of the clast composition is dominated by quartz with varying amounts of feldspar and minor lithics. Three-clast compositions plot along the Q-L side and these may represent a more mature depositional or recycled environment where the feldspar has not survived. The matrix modes comprise quartz with varying amounts of lithics and minor feldspar. Also shown on the diagram (text-fig. 13) are modal data from the Unicoi Formation (Simpson and Eriksson 1989) and the modal data for Appalachian foreland basin sandstones (Eriksson et al. 2004). These comparisons were done to assess, using the Dickinson QFL parameter, the composition of the Fincastle Conglomerate siliciclastic clasts with potential sources. The lithologic and petrographic similarity that the majority of siliciclastic clasts in the Fincastle Conglomerate share with the Unicoi Formation suggests that the Chilhowee Group sourced those clasts. Clasts composed of quartz, resistant lithics, but very minor feldspar were most likely sourced from the more mature Chilhowee strata such as the Erwin Formation and equivalents.

The absence of dolomite clasts

Karpa (1974) reported dolomite clasts in the Fincastle Conglomerate, although the author did not present details on the method of identification or about mineral or rock chemistry. Kellberg and Grant (1956), Cullather (1988, 1992) and this study did not identify any dolomite, although scattered dolomite rhombs do occur in some limestone clasts. The majority of the

Cambrian and Ordovician carbonate strata now exposed in central Virginia are dolomite or contain dolomite units (e.g., Butts 1940; Edmundson 1958), hence, if the Fincastle Conglomerate clast population were sourced from local strata, one would expect the majority of the carbonate clasts to be dolomite.

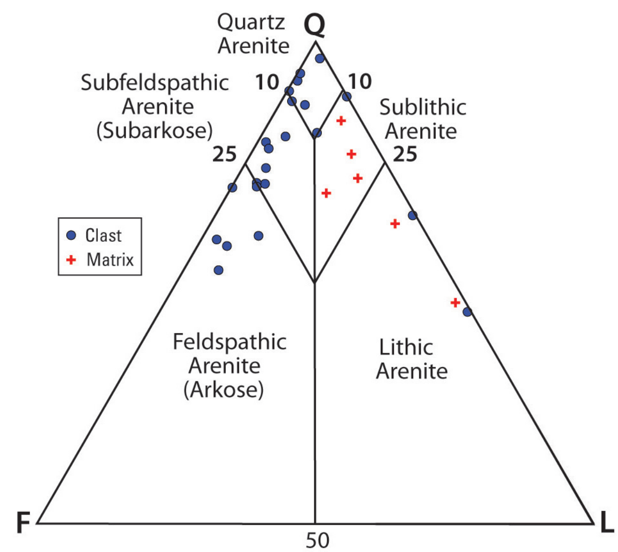
Kellberg and Grant (1956) recognized and discussed this problem. They found minor dolomite (dolomite = 1.5%, limestone = 77.7%) in only one of six studied conglomerates, at Cisco, GA, and suggested that most of the carbonate clasts were eroded from non-dolomitic portions of the Cambrian-Ordovician carbonate sequence from areas to the east of the conglomerates now overridden and hidden by thrusts related to the Blue Ridge tectonism. This lateral compositional variability is characteristic in many carbonate depositional environments where a transition from shallow to very shallow peritidal settings where dolomite was - or later became - abundant to deeper water ramp and margin settings where limestones were abundant (e.g., Pfeil and Read 1980). Gao and Eriksson (1991) measured unidirectional cross beds in sandstone above the Fincastle Conglomerate and found a directional mode to the southeast; however, it is uncertain what the original orientation would have been before thrust tectonism.

Igneous and high-grade metamorphic clasts

Composition and texture strongly suggest that most sandstone, metasandstone, and quartzite were derived from units of the Chilhowee Group or equivalents and may represent the lowest stratigraphic level of erosion seen in clasts of the Fincastle Conglomerate. Below the Chilhowee Group are Mt. Rogers Formation and correlatives, various Neoproterozoic granitoids of alkaline and peralkaline affinity, and basement rocks of Mesoproterozoic high-grade metamorphic and granitoid suites. This study and Cullather (1988, 1992) did not identify any igneous or high-grade metamorphic rock. Kellberg and Grant (1956) identified minor greenstone, and Karpa (1974) discussed one clast of augen gneiss (Karpa sample Fc 108). Karpa (1974) described the augen gneiss as a vein-quartz pebble conglomerate probably derived from the Marshall Metagranite. Kellberg and Grant (1956) and Karpa (1974) do not present any thin section petrography or mineral or whole rock chemistry to characterize these rocks. The Unicoi Formation, the lower portion of the Chilhowee Group, contains lavas, now greenstone (Butts 1940), making it possible that Kellberg and Grant (1956) may have sampled greenstone clasts, although no clast study subsequent to theirs has identified greenstone. In light of this, we conclude that the Chilhowee Group or stratigraphic equivalent probably is the lowest level of erosion during deposition of the Fincastle Conglomerate.

Erosional environment

The presence of both well-rounded siliceous and limestone clasts in the Fincastle Conglomerate suggests a high energy, and relatively rapid transport to the depocenter in order to preserve carbonates. During Ordovician time, pCO_2 is estimated to have been higher than today (e.g., Berner and Kothavala 2001; Munnecke et al. 2010) suggesting that in Ordovician humid tropical and temperate climates, limestone dissolution would have been at least as active as today, probably more so, although the chemical weathering process would have lacked significant humic or plant acids. Some paleogeographic climate reconstructions (e.g., Boucot et al. 2013, Map 4 Middle to Late Ordovician) suggest that the depocenter for the Fincastle Conglomerate was located in a global arid climate band. However, a recent study (Swanson-Hysell and Macdonald 2017) suggests that the paleomagnetic database on which the previous reconstruction was based is not robust. Swanson-Hysell and Macdonald (2017) suggest that the Appalachian margin moved within 10° of the equator by 465 Ma and was in a tropical, more humid, climate zone. Well-rounded siliceous, highly indurated clasts suggest that mechanical weathering was a major process during transport. The lack of dolomite clasts, more resistant to chemical weathering than limestone, suggests that the source regions supplied no dolomite, as dolomite clasts would have been less affected by chemical weathering than limestone and should have survived transport. Hickling and Belkin (1988) suggest that alluvial fans sourced from high relief environments were re-sedimented into the marine basin. Common sedimentary structures preserved in the Fincastle Conglomerate such as scour channels and fining upward from conglomerate to sandstone and associated units suggest a submarine fan complex type of deposit (Bartholomew et al. 1982; Rader and Gathright 1988; Cullather 1992).



TEXT-FIGURE 11
QFL ternary diagram (modified from Zaid 2012) that shows the classification of Fincastle Conglomerate sandstone and quartzite clasts (Table 4) and matrix (Table 5). Q = monocrystalline and polycrystalline (chert) quartz, F = all feldspars, L = all lithics.

Conodont paleontology

Our goal in processing the carbonate clasts and matrix for conodonts was to better constrain the provenance of the limestone clasts and the timing of Fincastle Conglomerate deposition. Conodont faunal zones are not generally used for biostratigraphic zonation below the upper part of the Cambrian stratigraphy in the Appalachians (text-fig. 14), where the euconodonts appear (Orndorff et al. 1988). Conodont faunal zonation is used, however, for stratigraphic correlation in the Ordovician (text-fig. 14). Unfortunately, most of the conodonts identified in our study are too long ranging to pinpoint clearly particular formations or provenance. In general, the conodont study confirms that the limestone clasts were sourced mainly from middle Cambrian to Lower/Middle Ordovician strata (text-fig. 14). Conodonts from a conglomerate matrix can be a mixture of fauna from clast source rock disaggregation plus fauna that were extant during conglomerate deposition. Two processed samples (HB-1B and HB-2A) yielded conodonts whose ages are Middle/Late Ordovician. These species have a range consistent with the overlying Martinsburg Formation. It is tempting to attribute these faunas to those existing in the foreland basin during deposition and were present in the adhering matrix, but that would be faulty for lack of confirming evidence. However, that speculation would be consistent with the Fincastle Conglomerate as a submarine fan-type deposit followed by the turbidite-bearing flysch Martinsburg Formation. Additionally, the conodonts identified from the limestone layer in the Martinsburg Formation are consistent with an early Late Ordovician age of that unit.

The conodont color alteration index (CAI) (Epstein et al. 1977) is an irreversible color change caused by the carbonization of organic material in the conodont structure and increases as a function of time and temperature. Only the Ordovician age euconodonts were indexed and had a range of 3 to 3.5. Therefore, we know that their limestone source lithologies were, at a maximum, in the range of 3 to 3.5 CAI. The carbonate clasts had pre-conglomerate veins and fractures similar in structure to those formed by post conglomerate deposition tectonism. Thus, it is not unreasonable to suggest that the carbonate source terrain had experienced a similar burial depth and degree of tectonism as the Ordovician rocks in this part of the Appalachian basin (Harris et al. 1978; Repetski et al. 2008).

TEXT-FIGURE 12

Conodonts from limestone clasts and adhering matrix from Fincastle Conglomerate.
Specimens carbon-coated and imaged on scanning electron microscope (SEM). Secondary electron images, all scale bars = 100 µm. Illustrated specimens catalogued with USGS Cambrian-Ordovician locality numbers (xxxxx-CO) and reposited at the Paleobiology Department conodont type collections, at U.S. National Museum of Natural History, Washington, DC, with their catalogue numbers (USNM-644723 through 644738).

A *Phragmodus* sp indet. Sc element fragment; upper Middle or Upper Ordovician; sample 10654-C0, from silty limestone in Martinsburg Formation, from 101 meters above top of conglomerate (Table 1), USNM-644723.

B *Variabiloconus bassleri* (Furnish). Lateral view of broken specimen. Lower Ordovician (Tremadocian). From limestone clast FC-145. USGS 12117-CO; USNM-644724.

C *Rossodus manitouensis* Repetski & Ethington. Posterolateral view of coniform element. Lower Ordovician (Tremadocian); from limestone clast FC-145. USGS 12117-CO; USNM-644725.

D *Parapanderodus* sp. Posterolateral view. Lower Ordovician, from sample of clasts and matrix, FC-2015A. USGS 12118-CO; USNM-644726.

E *Westergaardodina* sp. indet. Posterior view. Most likely Cambrian; from sample of clasts and matrix, FC-2015A. USGS 12118-CO; USNM-644727.

F *Phakelodus elongatus* (An). Lateral view of individual element; from sample of clasts and matrix, FC-2015A. USGS 12118-CO; USNM-644728.

G,H *Muellerodus? oelandicus* (Müller and Hinz). Upper and upper lateral-oblique views of same specimen; from sample of matrix with clasts, FC2015Am. USGS 12119-CO; USNM-644729.

I *Panderodus* sp. Inner lateral view; Middle or Upper Ordovician euconodont from matrix adhering to Cambrian clast HB-2A. USGS 10947-CO; USNM-644730.

J *Protopanderodus*? sp. Inner lateral view; fragmental Middle to Upper Ordovician euconodont from matrix adhering to Cambrian clast HB-1B. USGS 10946-CO; USNM-644731.

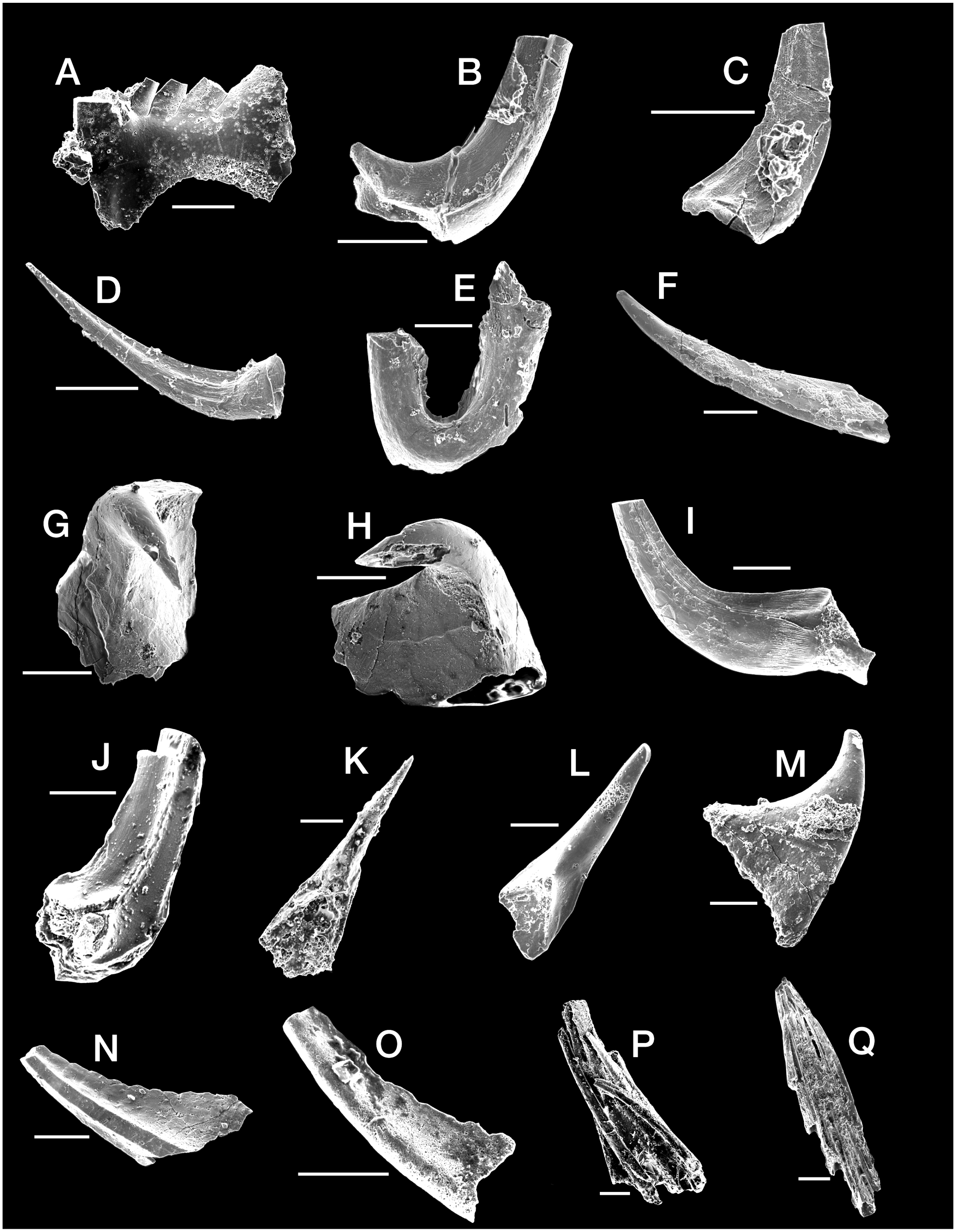
K,L *Furnishina furnishi* Müller, posterior views of elements from clast HB-1B (K) and clast HB-1A (L); late Middle Cambrian to earliest Ordovician. USGS 10946-CO and 10945-CO; USNM-644732 and 644733, respectively.

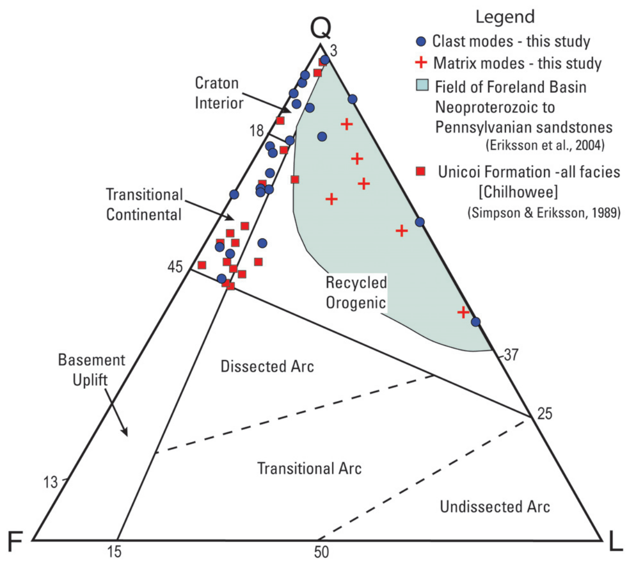
M *Prooneotodus gallatini* (Müller); outer lateral view of paraconodont with adhering phosphatic grains; from sample HB-2A, clast with matrix. USGS 10947-CO; USNM-644734.

N Indeterminate paraconodont or basal filling of indeterminate euconodont; lateral view; from sample HB-2A, clast with matrix. USGS 10947-CO; USNM-644735.

O Indeterminate paraconodont or basal filling of indeterminate euconodont; lateral view; from sample HB-2A, clast with matrix. USGS 10947-CO; USNM-644736.

P,Q *Phakelodus elongatus* (An); fused clusters. Posterolateral (P) and posterior (Q) views of two nearly complete half-apparatuses from sample HB-2A, clast with matrix. USGS 10947-CO; USNM-644737 and 644738, respectively.


A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q



TEXT-FIGURE 13
QFL ternary diagram from Dickinson et al. (1983) showing the fields of sandstones related to tectonic setting. Plotted are the compositions of Fincastle Conglomerate sandstone clasts (Table 4) and matrix (Table 5), the field of foreland basin sandstones (Eriksson et al. 2004) and compositions from all facies of the Unicoi Formation (Simpson and Eriksson 1989). Q = monocrystalline and polycrystalline (chert) quartz, F = all feldspars, L = all lithics.

Clast provenance

Various authors have correlated Fincastle Conglomerate clasts to known exposed formations in the area especially to the southeast. For example, Karpa (1974) correlated the following: sandstone/quartz/pebble conglomerate – Unicoi Formation, limestone/limestone conglomerate – Conochocheague Limestone, Copper Ridge Dolomite, or Elbrook Limestone, clean quartz sandstone/quartzite – Erwin or Unicoi Formations, sandy siltstone – Hampton, Unicoi, or Erwin Formations, black chert – Elbrook Limestone, Knox Group, Middle Ordovician limestones, white chert – Knox Group, partially dolomitized limestone - Copper Ridge Dolomite or Conococheague Limestone, and calcite-cemented sandstone – Liberty Hall Formation. Karpa (1974) also identified rare augen gneiss that he correlated to the Marshall Metagranite. Cullather (1992) suggested the following correlations: quartzite, metaarkose, metaconglomerate sandstone, and shale – Chilhowee Group, phyllite, slate – Chilhowee Group or Rome Formation, calcareous gray and red shale – Rome, Liberty Hall or Bays Formation, and limestone and chert – Elbrook Limestone, Knox Group, New Market Limestone, Lincolnshire Limestone, and the Botetourt Limestone of Cooper and Cooper (1946).

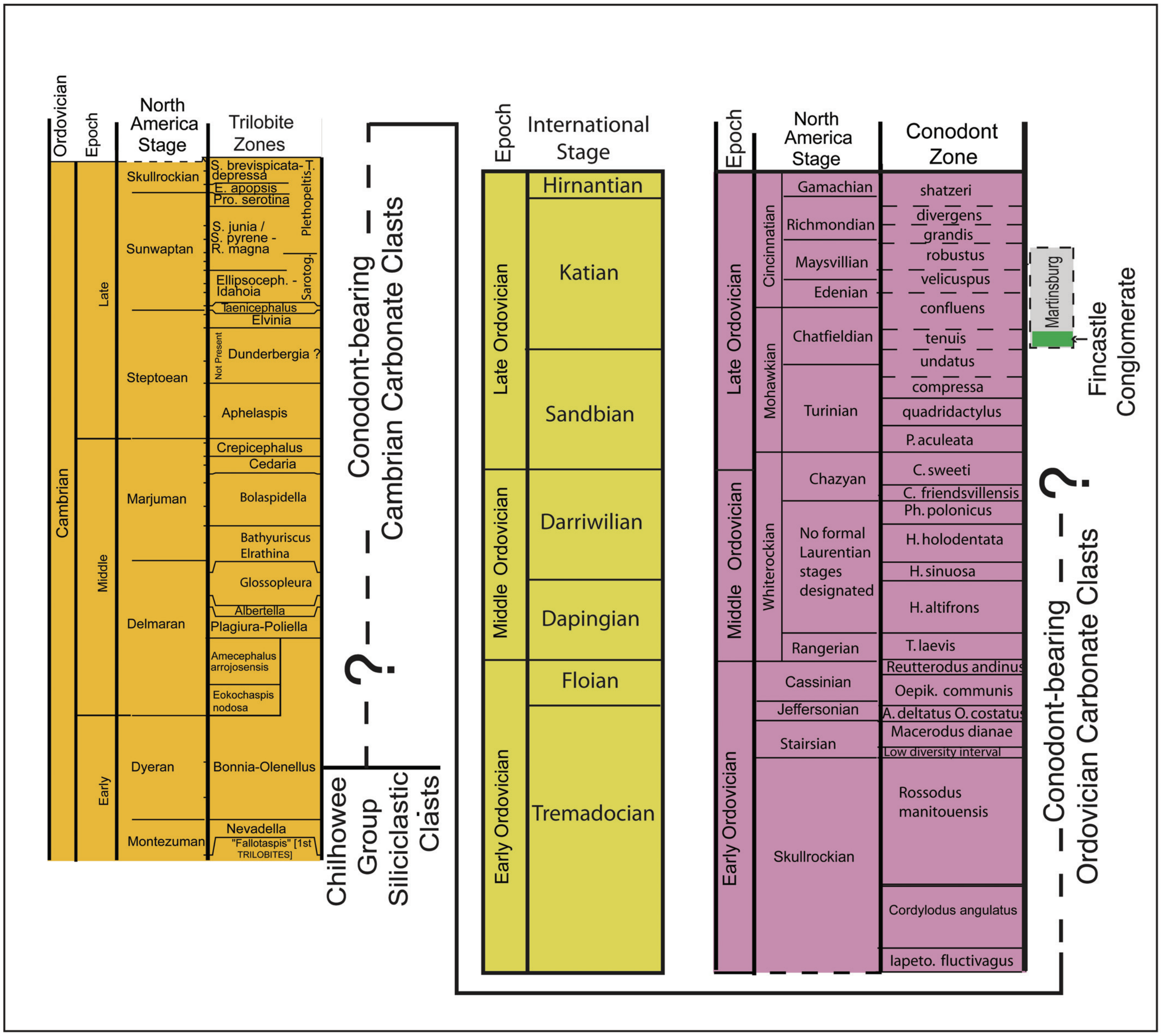
Karpa (1974) suggested that the vein quartz may represent erosion of the Blue Ridge Mesoproterozoic basement, but Cullather (1992) points out that if the vein quartz represents eroded Blue Ridge basement, there should be conspicuous gneiss and granitoid clasts in the Fincastle Conglomerate and there are not.

We have not correlated the limestone clasts to any nearby or distant formation for two reasons: (1) No lithologic, mineralogic, or paleontologic parameter was unique in such a way as to definitely relate a clast to a known exposed formation. The exceptions are clast samples FC74, FC145, and FC2015B, all of which contained euconodonts indicative of a limestone equivalent of the Chelpultepec Formation, however more data would be needed for confirmation. The lack of dolomite clasts in the Fincastle Conglomerate now surrounded by many dolomitic formations (e.g., Butts 1940) suggests that these local surrounding units did not contribute to the conglomerate, and/or (2) all surrounding formations, especially those that comprise thrust sheet units may not have been exposed in the particular drainage supplying the clasts during its accumulation. But more likely is that since the Ordovician, significant erosion probably has removed the units directly supplying the conglomerate and/or the late Paleozoic thrust imbrication in the Appalachian orogen has covered potential provenance candidates. The Fincastle siliciclastic clasts contain Grenville-age zircons (Eriksson et al. 2004; Park et al. 2010; Thomas et al. 2014) and are reasonably correlated to the Chilhowee Group or stratigraphic equivalents. Although the current "highlands" containing the siliceous clast provenance candidate, the Chilhowee Group, lie to the southeast due to late Paleozoic tectonism and subsequent exhumation, we do not know the topography, i.e., Taconic highlands, extant during conglomerate formation.

Fincastle Conglomerate stratigraphic position and nomenclature

Kellberg and Grant (1956) provide detailed stratigraphic and lithologic descriptions of the six studied Ordovician conglomerates that crop out from the Fincastle locality south to the Cisco Area, GA. The conglomerates have similar lithologic characteristics as described above, but also have similar stratigraphic relationships. The Fincastle and South Holston localities conformably overlie an anoxic, graptolitic deep-water black shale; the Paperville Shale for the Fincastle and the Athens Shale for the South Holston conglomerates. Conformably overlying the conglomerates at both localities is a flysch, turbidite-bearing shale with minor sandstone and carbonate; the Martinsburg Formation at Fincastle and the Tellico Formation at South Holston. At the four other localities, the conglomerate is located in the Tellico Formation, which overlies the Athens Shale. From the outcrop descriptions given by Kellberg and Grant (1956), it appears that the conglomerate occurs higher in the Tellico Formation section the further south you go, but Kellberg and Grant (1956) note the poor nature of some outcrops and the possibility of tectonic complications. Beginning in middle Ordovician, the Blountian orogeny, the early southern phase of the Taconic orogeny, centered on the southern Appalachians, introduced major siliciclastic sedimentation into the developing foreland basin (Shanmugam and Walker 1980 and references therein). All six conglomerates are either just below or occur in the foreland basin flysch sedimentation. Kellberg and Grant (1956) suggest that the conglomerate locations may represent positions of major drainages emptying into the foreland basin. Perhaps the occurrence of boulder conglomerates marks a major seismic and climatic event that caused flushing of very coarse debris into the basin.

The U.S. Geological Survey considers the Fincastle Conglomerate a formation, but also indicates that State Geological surveys consider it a member of various formations. The U.S. Geological Survey subscribes to the nomenclature guidelines



TEXT-FIGURE 14
A diagram showing Cambrian and Ordovician biostratigraphy modified from Read and Repetski (2012; biostratigraphy from Taylor et al. 2012). Note that this diagram shows the old tripartite Cambrian division and not the most recent four-part division (Cohen et al. 2013; version 2017/02). An additional column from Cohen et al. (2013; version 2017/02) shows the International Stages in comparison to the North America-Laurentian Stages. Note that numerical ages are not shown as these are subject to revision and do not define units in the Phanerozoic, only Global Boundary Stratotype Section and Points do. Shown are the age ranges that are potential sources of the conodont-bearing carbonate clasts for the Fincastle Conglomerate. The Precambrian-Cambrian Chilhowee Group is shown as the probable source of the siliciclastic clasts. The general stratigraphic position of the Fincastle Conglomerate shown.

outlined by the North American Commission on Stratigraphic Nomenclature (USGS 2017). Considering the similarity of stratigraphic relationships and probable common origin of the other conglomerates, we favor the decision made by Rader and Gathright (1986) who called the Fincastle Conglomerate a member of the Martinsburg Formation above the Paperville Shale.

CONCLUSIONS AND COMMENTS

Clast lithology identification confirms previous studies that the Fincastle Conglomerate is polymictic dominated by siliciclastic (2/3) and limestone (1/3) lithologies in contrast to five other conglomerates that are carbonate dominated and crop out south of the Fincastle locality. Field study, electron beam, or X-ray instrumentation did not identify dolomite, igneous, or high-grade metamorphic lithologies. Outcrop erosion and the inherent variability and relatively small-scale, discontinuous coarse conglomerate lenses indicating lateral migration of the depositional channels

TABLE 9
Conodont summary table of clast and matrix analysis. All samples analyzed for conodonts came from the upper or third conglomerate unit, unit D in this study, except for FC74 from unit E (text-fig. 4).

Sample	rock mass processed	conodonts found	CAI
FC74	155 g	*Laurentoscandodus triangularis* - 2	3 - 3.5
		indeterminate coniform euconodonts - 2	
FC103	166 g	no conodonts	
FC122	155 g	no conodonts	
FC145	143 g	*Variabiloconus bassleri* - 2	~ 3.5
		Rossodus manitouensis - 1 coniform element	
FC152	175 g	no conodonts	
FC153	165 g	no conodonts	
FC2015A	5.0 kg (clasts w/matrix)	*Gapparodus* sp. indet., fragment - 1	
		Parapanderodus sp. - 1	
		Phakelodus elongatus (An)	
		14 single elements	
		3 [partial] fused clusters	
		Phakelodus tenuis (Müller) - 3 single elements	
		Prooneotodus ? sp. indet. - 1	
		Westergaardodina sp. - 1	
FC2015Am	1.4 kg (matrix w/clasts)	*Muellerodus oelandicus* Müller & Hinz - 1	
		Phakelodus elongatus (An) - 1	
FC2015B	2.5 kg (clasts w/matrix)	*Cordylodus intermedius* Furnish -1 S element	3 - 3.5
		Phakelodus sp. - 1 fragment	
		Teridontus nakamurai (Nogami) - 1	
		Utahconus cf. *U. utahensis* (Miller) - 1 coniform el.	
		indet. drepanodontiform elements - 2	
HB-1A	500 g (single clast)	*Furnishina furnishi* Müller - 1	
		Phakelodus tenuis (Müller) - 1 element	
HB-1B	800 g (single clast)	*Furnishina furnishi* Müller - 1	
		Furnishina ? sp. - 2	
		Protopanderodus? sp. - 1	
		paraconodont, indet.genus & species - 1	
		Protopanderodus ? - 1	
HB-2A	4.3 kg (single clast)	*Drepanoistodus* sp.; 1 drepanodontiform element	~ 3
		Panderodus sp.; 1 element	
		Diaphanodus ? sp. - 2 elements	
		Phakelodus tenuis (Müller)	
		41 single elements	
		9 fused clusters; 2 to 10 elements each	
		Prooneotodus gallatini Müller) - 1	
HB-2B	1.1 kg	no conodonts	
HB-2C	1.3 kg	*Phakelodus tenuis* (Müller)	
		2 partial fused clusters; 3 elements each	
		indeterminate coniform euconodont - 1 fragment	~ 3

suggest subsequent lithologic studies will likely derive somewhat different lithology proportions. However, we would encourage future lithologic and especially paleontologic research in order to more clearly define provenance and age of the Fincastle Conglomerate and the other five carbonate-clast dominated conglomerates . Our study suggests that the erosional level during clast deposition progressed down only to within the Chilhowee Group and did not erode the Grenville basement.

The Fincastle Conglomerate is the most northern yet found of similar cobble to boulder Ordovician-age conglomerates that may represent rarely preserved deposits from local high-energy erosional regimes in the headwaters of major drainages emptying into the developing foreland basin.

ACKNOWLEDGMENTS

This paper is dedicated to the late Nelson L. Hickling who started this study in the 1980's before retirement from the U.S. Geological Survey. We thank the Dixon Construction Co. (1987) and Mr. Chris Moore (2015) for access to the outcrops on their property. We thank David J. Weary and Randall C. Orndorff (both U.S. Geological Survey), and Stephen A. Leslie and John T. Haynes (both James Madison University) for their very insightful and constructive reviews. We also gratefully acknowledge support from the Butts Institute for Appalachian Geology. Trade, product, or firm names used in this report are for the purpose of full disclosure of analytical methods; no endorsement of any commercial product by the U.S. Government is implied.

REFERENCES

AMATO, R. V., 1974. Geology of the Salem quadrangle, Virginia. *Virginia Division of Mineral Resources Report of Investigations* 37, 40 pp.

ANDREWS, L. E., 1952. "Structure of the area north of Roanoke, Virginia." Unpublished Ph.D. dissertation, Johns Hopkins University, Baltimore, Md.,126 pp.

ARMSTRONG, J. T., 1995. CITZAF: A package of correction programs for the quantitative electron microbeam X-ray analysis of thick polished materials, thin films, and particles. *Microbeam Analysis,* 4: 177–200.

BARTHOLOMEW, M. J., 1987. Structural evolution of the Pulaski thrust system, southwestern Virginia. *Geological Society of America Bulletin*, 99: 491–510.

BARTHOLOMEW, M. J., SCHULTZ, A. P., HENIKA, W. S. and GATHRIGHT, T. M., II, 1982. Geology of the Blue Ridge and the Valley and Ridge at the junction of the central and southern Appalachians. In: Lyttle, P. T., Ed., *Central Appalachian Geology*, 121–170. Combined Northeastern-Southeastern Section, Geological Society of America Field Trip Guidebooks.

BENN, D. I. and BALLANTYNE, C. K., 1993. The description and representation of particle shape. *Earth Surface Processes and Landforms*, 18: 665–672.

BERNER, R. A. and KOTHAVALA, Z., 2001. GEOCARB III: a revised model of atmospheric CO2 over Phanerozoic time. *American Journal of Science*, 301:182–204.

BISCAYE, P. E., 1964. Distinction between kaolinite and chlorite in recent sediments by X-ray diffraction. *American Mineralogist*, 49: 1281–1289.

BOUCOT, A. J., XU, C. and SCOTESE, C. R., 2013. *Phanerozoic paleoclimate: an atlas of lithologic indicators of climate*. Society of Economic Paleontologists and Mineralogists, Concepts in Sedimentology and Paleontology No. 11 Map Folio.

BUTTS, C., 1940. Geology of the Appalachian valley in Virginia, pt. I; Geologic text and illustrations. *Virginia Geological Survey Bulletin* 52, 568 pp.

COHEN, K. M., FINNEY, S. C., GIBBARD, P. L. and FAN, J.-X., 2013. The ICS International Chronostratigraphic Chart. *Episodes* 36: 199-204.
URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2017-02.pdf

COLLINSON, C., 1963. Collection and preparation of conodonts through mass production techniques. *Illinois State Geological Survey, Circular* 343: 16 pp.

COOPER, B. N., 1960. The Geology of the Region Between Roanoke and Winchester in the Appalachian Valley of Western Virginia. *Johns Hopkins University Studies in Geology* No. 18, Guidebook 2, 84 pp.

COOPER, B. N., 1969. *Geology field trip, October 5, 1969, Southeastern Section, Seismological Society of America.* Blacksburg: Virginia Polytechnic Institute and State University, Department of Geologic Sciences, Guidebook no. 4, 11 pp.

COOPER, B. N., ARKLE Jr., T. and LATIMER Jr., I. S., 1961. *Grand Appalachian Excursion, Guidebook no. l*. Blacksburg: Virginia Polytechnic Institute and State University, 114 pp.

CULLATHER, C. M., 1988. The depositional environment of the Fincastle Conglomerate near Roanoke, Virginia. Washington, D.C.: George Washington University, unpublished M.Sci. Thesis, 110 pp.

CULLATHER, C. M., 1992. Depositional Environment of the Fincastle Conglomerate near Roanoke, Virginia. *U.S. Geological Survey Bulletin* 1839-H, 28 pp.

DALY, R. A., 1917. Low-temperature formation of alkaline feldspars in limestones. *Proceedings of the National Academy of Sciences*, 3:659–665.

DECKER, C. E., 1952, Stratigraphic significance of graptolites of Athens Shale. *American Association of Petroleum Geologists Bulletin*, 36:11–145.

DICKINSON, W. R., 1985. Interpreting provenance relations from detrital modes of sandstones. In: Zuffa, G.G., Ed., *Provenance of Arenites*, 333-361. Boston: D. Reidel Publishing Company, NATO ASI Series, Series C: Mathematical and Physical Sciences 148.

DICKINSON, W. R., BEARD, S. L., BRAKENRIDGE, G. R., ERJAVEC, J. L., FERGUSON, R. C., INMAN, K. F., KNEPP, R. A., LINDBERG, F. A. and RYBERG, P. T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin,* 94:222–235.

EDMUNDSON, R. S., 1958. Industrial limestones and dolomites in Virginia; James River district west of the Blue Ridge. *Virginia Division of Mineral Resources Bulletin* 73: 137 pp.

EPSTEIN, A. G., EPSTEIN, J. B. and HARRIS, L. D., 1977. Conodont color alteration—an index to organic metamorphism. *U.S. Geological Survey Professional Paper* 995: 27 pp.

ERIKSSON, K. A., SIMPSON, E. L., KROGSTAD, E. J., MCLENNAN, S. M. and NORMAN, M., 1994. Provenance characterization of Appalachian clastic wedges from sandstone petrography and clast compositions. *Geological Society of America Abstracts with Programs*, 26(4): 1–12.

ERIKSSON, K. A., CAMPBELL, I. H., PALIN, J. M., ALLEN, C. M. and BOCK, B., 2004. Evidence for multiple recycling in Neoproterozoic through Pennsylvanian sedimentary rocks of the central Appalachian Basin. *Journal of Geology*, 112:261–276.

GAO, Z. and. ERIKSSON, K. A., 1991. Internal-tide deposits in an Ordovician submarine channel: Previously unrecognized facies? *Geology,* 19:734–737.

HARRIS, A. G., HARRIS, L. D. and EPSTEIN, J. B., 1978. Oil and gas data from Paleozoic rocks in the Appalachian basin; Maps for assessing hydrocarbon potential and thermal maturity (conodont coloral alteration isograds and overburden isopachs). *U.S. Geological Survey Miscellaneous Investigations Series* Map I-917-E, 4 sheets, scale 1:2,500,000.

HAYNES, J. T. and GOGGIN, K. E., 1994. K-bentonites, conglomerates, and unconformities in the Ordovician of southwestern Virginia, 65–93. *Field guides to southern Appalachian structure, stratigraphy, and engineering geology*. Blacksburg: Virginia Tech Department of Geological Sciences Guidebook 10.

HICKLING, N. L. and BELKIN, H. E., 1988. Provenance and depositional history of the Fincastle conglomerate of southwestern Virginia. In: Schultz, A., Ed. *Appalachian Basin Symposium: Program and Extended Abstracts*, 46-49. U.S. Geological Survey Open-File report 88-585 [reprinted in U.S. Geological Survey Circular 1028, p. 13-14, 1989].

HOSTERMAN, J. W. and DULONG, F. T., 1989. A computer program for semiquantitative mineral analysis by X-ray powder diffraction. In: Pevear, D.R. and Mumpton, F.A., Eds., *CMS Workshop Lectures, Vol. 1, Quantitative Mineral Analysis of Clays*, 37–50. Evergreen: The Clay Minerals Society.

KARPA III, J. B., 1974. The Middle Ordovician Fincastle Conglomerate north of Roanoke, Virginia, and its implications for Blue Ridge tectonism. Blacksburg: Virginia Polytechnic Institute and State University, unpublished M.Sci. Thesis, 164 pp.

KELLBERG, J. M. and GRANT, L. F., 1956. Coarse conglomerates of the Middle Ordovician in the Southern Appalachian valley. *Geological Society of America Bulletin*, 67:697-716.

LESLIE, S. A. and BERGSTRÖM, S. M., 1995. Revision of the North American late Middle Ordovician standard stage classification and timing of the Trenton transgression based on K-bentonite bed correlation. In: Cooper, J.D., Droser, M.L and Finney, S.C., Eds., *Ordovician odyssey: Short papers of the 7th International symposium on the Ordovician System.* Pacific Section SEPM Publication 77: 49–54.

LOWRY, W. D., MCDOWELL, R. C. and TILLMAN, C. G., 1972. The Diamond Hill and Fincastle conglomerates Evidence of great structural relief between the Blue Ridge anticlinorium and Salem synclinorium in Middle Ordovician time. *Geological Society of America Abstracts with Programs*, 2(4):88.

MCGUIRE, O. S., 1970. Geology of the Eagle Rock, Oriskany, and Salisbury quadrangles, Virginia. *Virginia Division of Mineral Resources Report on Investigations* 24, 39 pp.

MUNNECKE, A., CALNER, M., HARPER, D. A. and SERVAIS, T., 2010. Ordovician and Silurian sea–water chemistry, sea level, and climate: a synopsis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 296:389–413.

NICHOL, R. F., 1959. "Geology and mineral resources of the Tinker Mountain-Fincastle, Virginia area." Unpublished M.Sci. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, 86 pp.

ORNDORFF, R. C., TAYLOR, J. F. and TRAUT, R. W., 1988. Uppermost Cambrian and lowest Ordovician conodont and trilobite biostratigraphy in northwestern Virginia. *Virginia Minerals*, 34:13–20.

PARK, H., BARBEAU Jr., D. L., RICKENBAKER, A., BACHMANN-KRUG, D. and GEHRELS, G., 2010. Application of Foreland Basin Detrital Zircon Geochronology to the Reconstruction of the Southern and Central Appalachian Orogen. *Journal of Geology*, 118:23–44.

PFIEL, R. W. and READ, J. F., 1980. Cambrian Carbonate Platform Margin Facies, Shady Dolomite, Southwestern Virginia, U.S.A. *Journal of Sedimentary Petrology*, 50:91–116.

POHN, H.A., 2000. Lateral Ramps in the Folded Appalachians and in Overthrust Belts Worldwide—A Fundamental Element of Thrust-Belt Architecture. *U.S. Geological Survey Bulletin* 2163, 63 pp.

PROTHERO, D. K. and SCHWAB, F. L., 2013. *Sedimentary Geology, Third edition.* New York: W.H. Freeman, 500 pp.

RADER, E. K. and GATHRIGHT II, T. M., 1986. Stratigraphic and structural features of Fincastle Valley and Eagle Rock Gorge, Botetourt County, Virginia. In: Neathery, T.L., Ed., *DNAG Centennial Field Guide - 6 Southeastern Section,* 105–108. Boulder, CO.

RAIS, P., LOUIS-SCHMID, B., BERNASCONI, S. M., REUSSER, E. and WEISSERT, H., 2008. Distribution of authigenic albites in a limestone succession of the Helvetic Domain, eastern Switzerland. *Swiss Journal of Geosciences*, 101:99-106.

READ, J. F. and REPETSKI, J. E., 2012. Cambrian–lower Middle Ordovician passive carbonate margin, southern Appalachians. In: Derby, J.R., Fritz, R.D., Longacre, S.A., Morgan, W.A. and Sternbach, C.A., Eds., *The great American carbonate bank: The geology and economic resources of the Cambrian – Ordovician Sauk megasequence of Laurentia*, 357–382. American Association of Petroleum Geologists Memoir 98.

REPETSKI, J. E., RYDER, R. T., WEARY, D. J., HARRIS, A. G. and TRIPPI, M. H., 2008, Appalachian basin thermal maturity patterns (CAI and %Ro) in Upper Ordovician and Lower-Middle Devonian rocks: A major revision of USGS Map I-917-E using new subsurface collections. *U.S. Geological Survey Scientific Investigations Map* 3006: 131 ms p. + 11 figs. CD.

SHANMUGAM, G. and WALKER, K. R., 1980. Sedimentation, subsidence, and evolution of a foredeep basin in the Middle Ordovician, southern Appalachians. *American Journal of Science*, 280: 479–496.

SIMPSON, E. L. and ERIKSSON, K. A., 1989. Sedimentology of the Unicoi Formation in southern and central Virginia: Evidence for late Proterozoic to Early Cambrian rift-to-passive margin transition. *Geological Society of America Bulletin*, 101: 42–54.

SPÖTL, C., LONGSTAFFE, F. J., RAMSEYER, K. and RÜDINGER, B., 1999. Authigenic albite in carbonate rocks–a tracer for deep-burial brine migration? *Sedimentology*, 46: 649–666.

STOW, M. H. and BIERER, J. C., 1937. Some significance of an Athens conglomerate near Fincastle, Virginia. *Virginia Academy of Science Proceedings* 1936-1937: 71.

SWANSON-HYSELL, N. L. and MACDONALD, F. A., 2017. Tropical weathering of the Taconic orogeny as a driver for Ordovician cooling. *Geology*, 45: 719–722.

TAYLOR, J. F., REPETSKI, J. E., LOCH, J. D. and LESLIE, S. A., 2012. Biostratigraphy and chronostratigraphy of the Cambrian – Ordovician great American carbonate bank. In: Derby, J. R., Fritz, R. D., Longacre, S. A., Morgan, W. A. and Sternbach, C. A., Eds., *The great American carbonate bank: The geology and economic resources of the Cambrian – Ordovician Sauk megasequence of Laurentia*, 15–35. American Association of Petroleum Geologists Memoir 98.

THOMAS, W. A., MUELLER, P. A. and GEHRELS, G. E., 2014. Detrital-zircon record of provenance of Ordovician–Devonian sandstones in the Appalachian foreland. *2014 Geological Society of America Annual Meeting in Vancouver, British Columbia (19-22 October 2104)*. Paper No. 327–328.

TILLMAN, C. G. and LOWRY, W. D., 1971. The Salem Synclinorium: A treasury of Appalachian tectonic history. In: Lowry, W. D., Tillman, C. G., Fara, M. and Kettren, L. P., Jr., Eds., *Guidebook to contrast in style of deformation of the southern and central Appalachians of Virginia*, 23-68. Blacksburg Virginia Polytechnic Institute Department of Geologic Sciences Guidebook 6.

TILLMAN, C. G. and LOWRY, W. D., 1973. Conodonts from the Fincastle conglomerate, Virginia. *Geological Society of America Abstracts with Programs*, 5(4): 359.

U.S. GEOLOGICAL SURVEY (USGS), 2017. National Geologic map Database, Geolex Search "Fincastle Conglomerate" https://ngmdb.usgs.gov/Geolex/search (Accessed 22 September 2017).

WOODWARD, H. P., 1936. Geology and Mineral resources of the Natural Bridge Region, Virginia. *Virginia Division of Mineral Resources Open File Report 12*: 350 pp.

ZAID, S. M., 2012. Provenance, diagenesis, tectonic setting and geochemistry of Rudies sandstone (Lower Miocene), Warda Field, Gulf of Suez, Egypt. *Journal of African Earth Sciences*, 66–67:56–71.