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REVISED STRATIGRAPHY OF LATE TRIASSIC AGE STRATA OF THE DAN RIVER BASIN (VIRGINIA AND NORTH CAROLINA, USA) BASED ON DRILL CORE AND OUTCROP DATA

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ABSTRACT

The lithostratigraphy of the Triassic age strata (Dan River Group of the Newark Supergroup) in the Dan River Basin of Virginia and North Carolina is revised to consist of, in ascending order, the Pine Hall, Walnut Cove, Dry Fork, Cow Branch, and Stoneville formations. The basal Pine Hall Formation is largely fluvial and consists of red, gray, buff and relatively coarse, fluvial clastic rocks. The Walnut Cove Formation (new) consists of black and gray, largely lacustrine mudstone and minor coal. The Dry Fork Formation is comprised of gray, buff, and red lacustrine to fluvial strata. The Cow Branch Formation (restricted) is made up of mostly black and gray, predominately lacustrine mudstone and sandstone. The uppermost unit is the Stoneville Formation consisting mostly of red clastic rocks with abundant gray lacustrine, and gray and red fluvial components. All but the Pine Hall Formation show lithological cyclicity that we interpret to reflect lake level fluctuations paced by orbitally forced variations in solar insolation. Published and newly developed paleomagnetic polarity stratigraphy of the Dan River Basin provides a framework for precise temporal correlation with other Newark Supergroup basins. The extensive organic-rich, high-thermal maturity lacustrine rocks are a potential dry gas resource, given recent advances in recovery technology.

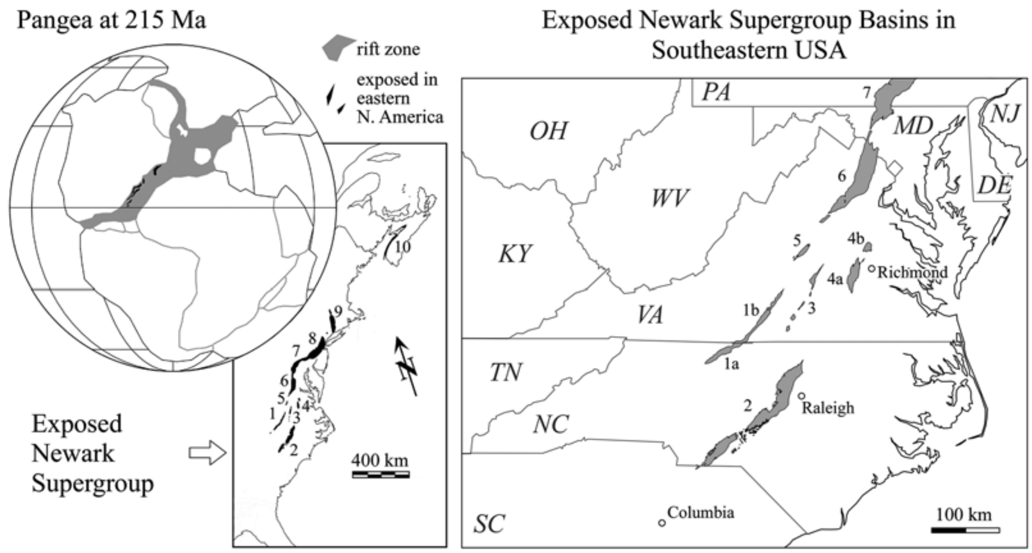

Figure 1. Newark Supergroup Basins in Pangea, Eastern North America and the southeastern United States showing the position of the Dan River Basin (1) and the Deep River Basin (2) of Virginia and North Carolina. Basins are: 1, Dan River (1a – Dan River Basin of older terminology, 1b, Dan River Basin of older terminology); 2, Deep River Basin; 3, Farmville and subsidiary basins to south; 4, Richmond Basin (4a) and Taylorsville Basin (4b); 5, Scottsville Basin; 6, Culpeper Basin; 7, Gettysburg Basin, 8, Newark Basin; 9, Hartford and Deerfield basins; 10, Fundy Basin.

INTRODUCTION

The Dan River Basin (Dan River-Danville Basin of Luttrell, 1989) of North Carolina and Virginia (Figure 1) contains Late Triassic age continental strata of demonstrated (light-weight aggregate) and potential (gas) economic value as well as important paleontological sites (Thayer and others, 1970; Reid and Milici, 2008; Milici and others, 2012; Olsen and others, 1978; Fraser and others, 1996; Fraser and Olsen, 1996; Blagoderov and others, 2007). The basins are remnants of formerly larger continental rift basins, a suite of which formed during Permian to Early Jurassic extension in central Pangea as the supercontinent began to fragment (Van Houten, 1977; Olsen, 1997). The Dan River Basin-complex is bound on the northwest by a largely normal border fault system and on the southeast mostly by onlap *via* a profound unconformity onto crystalline, hanging wall basement (Meyertons, 1963; Thayer, 1970). The purpose of this paper is to simplify and reconcile the stratigraphic nomenclature and to clarify the stratigraphic relationships, age, and depositional environments of the major lithostratigraphic units within the basins, their age, and depositional environments.

History of Stratigraphic Nomenclature

The Dan River and Danville basins are the names traditionally given to the southern and northern parts, respectively, of the same larger rift basin sharing lithostratigraphic units, but straddling the North Carolina-Virginia state line (Figures 2, 3) that Luttrell (1989), following the older literature, called the Dan River and Danville Basin. The lithostratigraphic nomenclatures developed separately in Virginia (Meyertons, 1963) and North Carolina (Thayer, 1970) are not fully consistent, and this dissonance has resulted in a confusing nomenclature that does not accurately portray the actual lithologic relationships. Progress from the analysis of huge quarry exposures, drill cores, and outcrops and exposures has now revealed a consis-

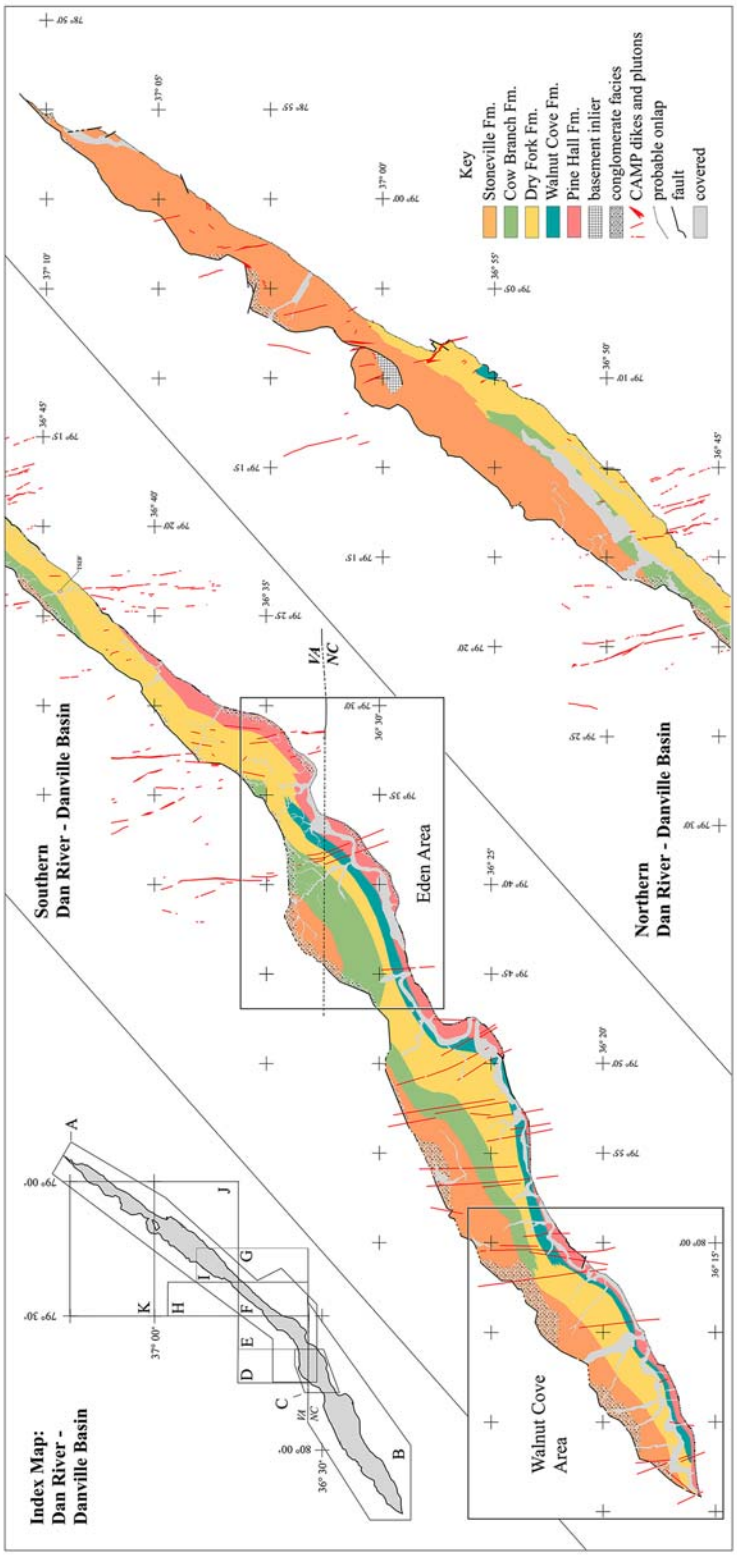

Figure 2. Dan River Basin showing distribution of formations and location of detailed maps in Figure 3 (Walnut Cove and Eden areas). Index map indicates sources of map data: A, Meyertons (1963); B, Thayer (1970); C, Kent and Olsen (1997); D, Price and others (1980a); E, Price and others (1980b); F, Henika and Thayer (1977); G, Henika and Thayer (1977); H, Marr (1984); I, Henika and Thayer (1983); J, Henika (2002); K, Henika (1997). TSDF, shows position of type section of Dry Fork Formation of Meyertons (1963).

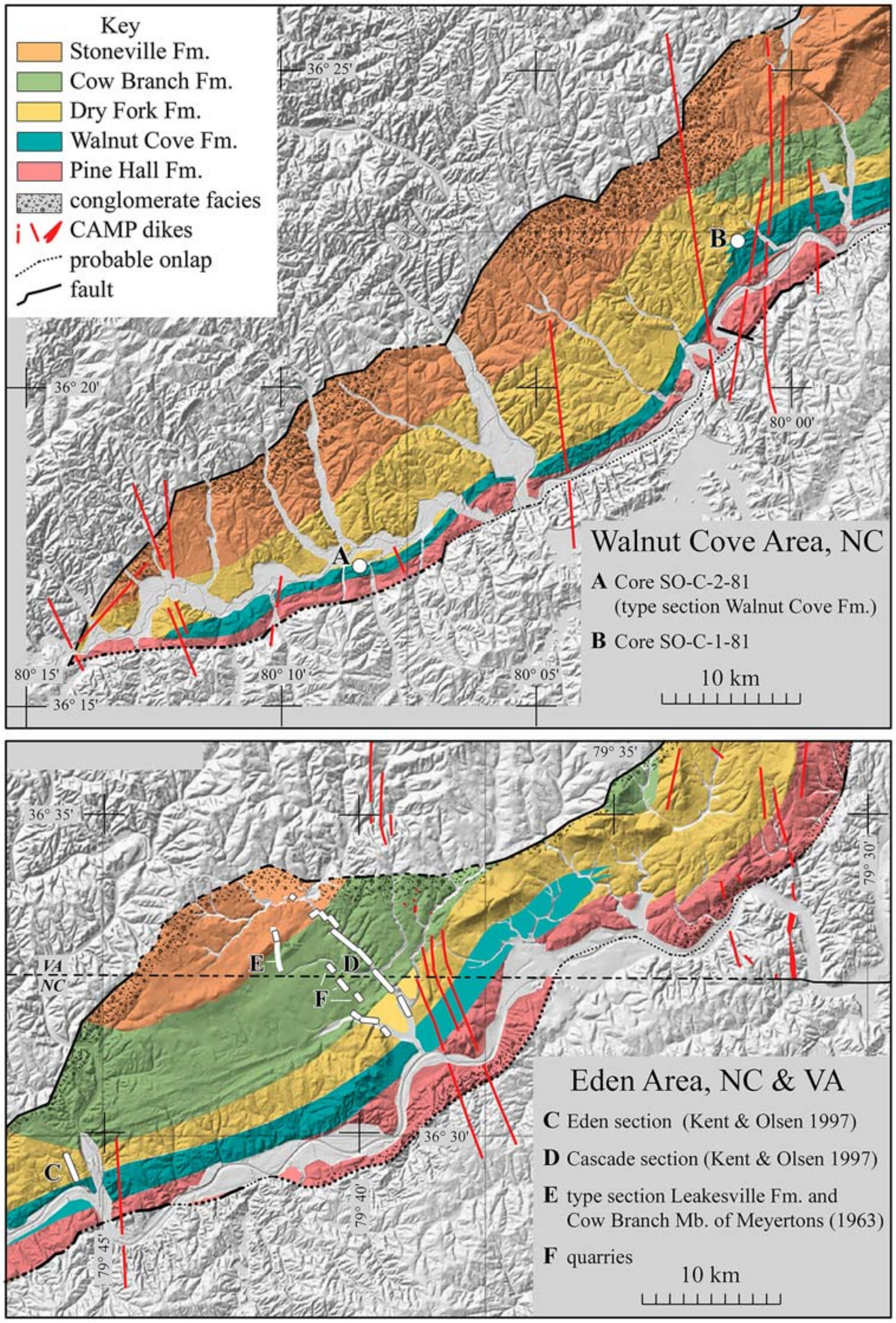

Figure 3. Detailed geologic maps of Walnut Cove, NC area and Eden Area (NC and VA) (See Figure 2 for location).

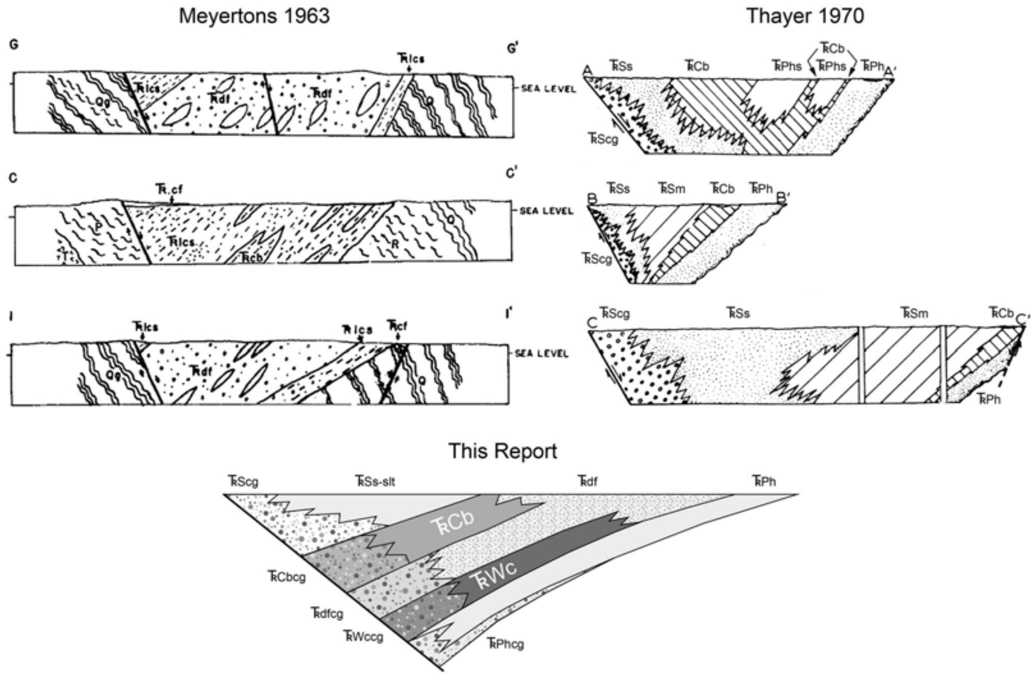

Figure 4. Schematic cross sections illustrating the relationship among lithological units based on Meyertons (1963), Thayer (1970), and our interpretations (this report). The cross sections of Meyertons and Thayer are schematic representations of specific locations in the Dan River Basin, and contain labels added by us. Abbreviations are: TRCb, Cow Branch Formation; TRCbcg, Cow Branch Formation, conglomerate facies; TRcf, Cedar Forest Formation; TRdf, Dry Fork Formation; TRlcs, Leaksville Formation, Cascade Station Member; TRlcb, Leaksville Formation, Cow Branch Member; TRdfcg, Dry Fork Formation conglomerate facies; TRPh, Pine Hall Formation; TRPhcg, Pine Hall Formation conglomerate facies; TRPh, Pine Hall Formation; TRSm, Stoneville Formation, mudstone-siltstone facies; TRSs, Stoneville Formation, sandstone facies; TRScg, Stoneville Formation, conglomerate facies; TRSs-slt, Stoneville Formation, sandstone-siltstone facies; TRWc, Walnut Cove Formation; TRWccg, Walnut Cove Formation, conglomerate facies; P, Qg, Q, R, T, various Paleozoic units from Meyertons (1963).

tency in stratigraphy across the entire larger basin.

Ninetieth and early to mid-twentieth century mapping and stratigraphic terminology (reviewed by Meyertons, 1963 and Thayer, 1970) for the Dan River Basin was generalized and superficial, and dependent upon very general comparisons being made with other basins (Rogers, 1838; Emmons, 1852; Stone, 1910; Roberts, 1928; Mundorff, 1948; Pickett, 1962). The first modern mapping and stratigraphic nomenclature was that of Meyertons (1963) and Thayer (1970) for the Virginia and North Carolina portions of the Dan River Basin, respectively. These pioneering works were done at a time when no conceptual model existed for how continental deposits might behave, save that they were supposed to coarsen toward source areas (Davis, 1898; Barrell, 1915), and be subject to abrupt lateral facies changes (Krumbein and Sloss, 1963).

Dan River Basin – Virginia

Meyertons (1963), based on his PhD thesis work of 1950, divided the Virginia part of the Dan River Basin (Danville Basin) section into three lithosomes, which he named as formations. In the 1950s and 1960s the concept of the

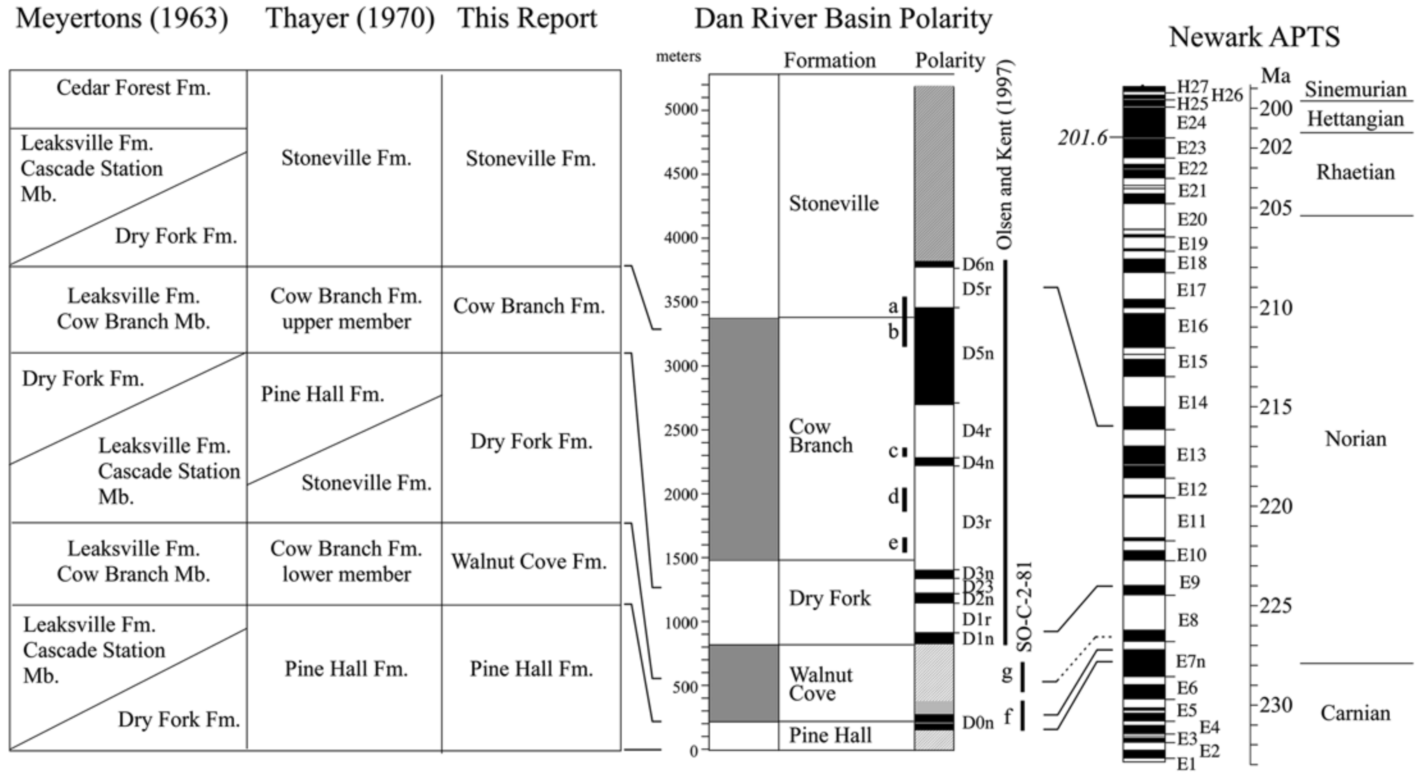

Figure 5. Dan River Basin nomenclatural systems and paleomagnetic polarity sequence with correlation to the Newark-APTS, Thayer (1970) for the Dan River subbasin, and this report for the Dan River Basin. Critical sampled sections are: a, type Leaksville Formation, Cascade Station Member of Meyertons (1963); b, type Leaksville Formation, Cow Branch Member of Meyertons (1963) and type section Cow Branch Formation of Thayer (1970); c, "upper" quarry at Cascade, VA; d, "middle" quarry at Leaksville (Eden), NC; e, "lower" quarry at Leaksville (Eden), f, preferred option of correlation of normal polarity interval D0n in SO-C-2-81 to a portion of Newark magnetozone E7n, g, second option with correlation of D0n to E8n (Whiteside and others, 2011). Hachured intervals indicate unsampled interval and gray represents indeterminate polarity (see Figure 7). The Newark APTS is from Kent and Olsen (1999) shown with the addition of the Hartford Basin polarity sequence from Kent and Olsen (2008).

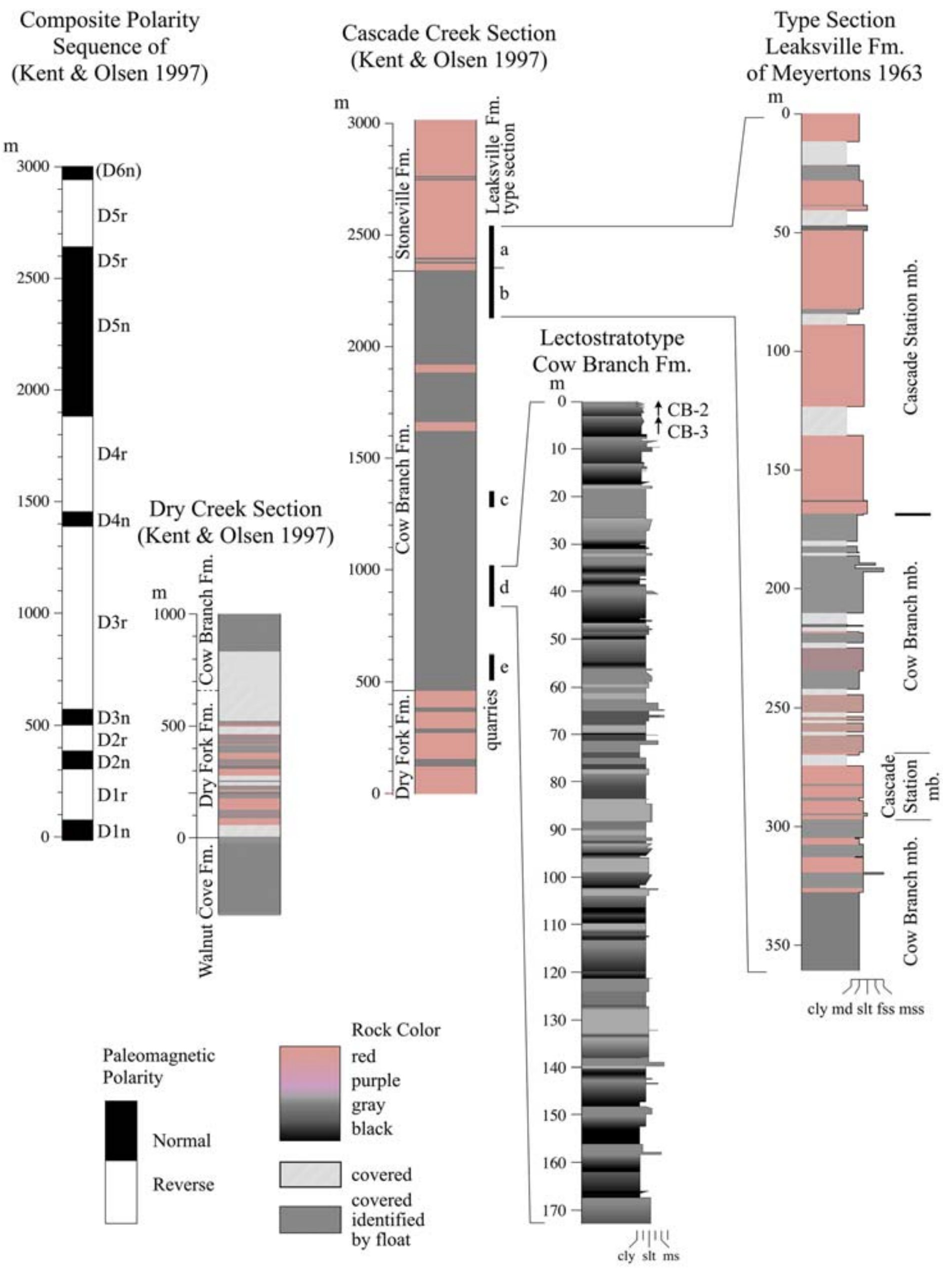

Figure 6. Details of the type section of Leaksville Formation of Meyertons (1966) sections examined by Kent and Olsen (1997) and lectostratotype of Cow Branch Formation: a, Leaksville Formation section now included in Stoneville Formation of Thayer (1970); b, type sections of Cow Branch Member of the Leaksville Formation of Meyertons (1963) and type section of Cow Branch Formation of Thayer (1970); c, upper quarry of Kent and Olsen (1997); d, main quarry of Kent and Olsen (1997) and lectostratotype of the Cow Branch Formation; d, lower quarry of Kent and Olsen (1997). Type section of Leaksville Formation graphically summarized from Meyertons (1963) with interpreted colors of unweathered rock; this section is now covered.

lithosome (Wheeler and Mallory, 1956; Krumbein and Sloss, 1963) was popular, with a lithesome being defined as, "…masses of rock of essentially uniform character and having intertonguing relationships with adjacent masses of different lithology…". In other words the formations consisted of lenses that could have any of a variety relationships with lenses of different lithology, with no particular order or specific relationship with one another except lithology. This concept was clearly illustrated by Meyertons (1963) in a series of conceptual cross sections of the basin accompanying the maps (Figure 4).

Meyertons (1963) named: 1) the Leakesville Formation, for the predominately mudstone-dominated rocks of the basin, with the Cascade Station Member being comprised of largely red strata and the Cow Branch Member being made up of primarily gray and black strata; 2) the Dry Fork Formation for the primarily sand-dominated strata; and 3) the Cedar Forest Formation for the conglomerate-dominated strata, which he thought at the time were unconformable on the Dry Fork Formation (Figures 5, 6). These units had the advantage of simplicity, but were differentiated mostly by grain size.

Dan River Basin – North Carolina

Thayer (1970), also based on his PhD work (Thayer, 1967), divided the contiguous North Carolina part of the Dan River Basin section into three formations (Figure 5), but in a different way than Meyertons (1963). He named the Pine Hall Formation for the basal unit, resting unconformably on basement, consisting of primarily red and tan coarse clastics. He raised the rank of the overlying gray and black Cow Branch Member to formation, recommending abandonment of the Leakesville Formation because of the distinct mappability of the former. Finally, he named the Stoneville Formation for variable clastics overlying and intertonguing with the Cow Branch Formation (Figure 5). Thayer also argued that the Cedar Forest Formation of Meyertons (1963) did not unconformably overlie the Dry Fork Formation, but rather was a set conglomeritic lenses and beds within the latter. Finally, Thayer assigned all the formations of the North Carolina part of the Dan River Basin to the Dan River Group, without explicitly including the remaining Dry Fork formation of Meyertons in the Virginia part of the basin. Conceptually, however, the formations defined by Thayer were very similar to the lithosomes defined by Meyertons' as shown in the cross sections in Thayer's (1970) and Thayer and Robbins (1994) (Figure 4).

To some extent the dual nomenclature for the basin has survived to this day despite the inherent contradictions reviewed by Lutrell (1989). Most recent overviews (Thayer and Robbins, 1992, 1994; Fraser and Olsen, 1996) follow this pattern with the exception of Kent and Olsen (1997) who used Meyertons' (1963) Leakesville Formation in its original meaning subdivided into the Cow Branch and Cascade Station members, but also recognized the Pine Hall and Stoneville Formations of Thayer (1970) (Figure 5).

NOMENCLATURAL REVISION

Clarifying this confusing stratigraphic nomenclature is a principal goal of this paper, particularly in light of the recognition that the Cow Branch (formation or member) consists of two major distinct units with different lithological properties that can be mapped though most of the Dan River Basin. Based on new data from cores as well as previous available outcrop data, these distinctive units provide a framework that clarifies the entire stratigraphy with minimal disruption to existing usage (Figure 5). Below we describe the formations we recognize, which are in ascending order are: 1) the Pine Hall Formation; 2) the Walnut Cove Formation; 3) the Stoneville Formation; 4) the Cow Branch Formation; and 5) the Stoneville Formation.

We also abandon the term Dan River-Danville Basin and use the term Dan River Basin for the entire contiguous structural basin. The term Dan River Basin has priority, because it was used by Emmons (1852) and referred to as the Dan River area. The Danville Basin (area) is mentioned by Heinrich (1878), but he continued to use the term Dan River for the North Carolina area. Russell (1892, plate VI and p. 86) perpetuated the dual basin nomenclature by mistakenly mapping and mentioning a supposed interval of basement between the two, which does not exist. Perpetuating the dual basin name for the contiguous whole serves no purpose and does not conform to any actual structural entities, and therefore the term Dan River-Danville Basin should be abandoned, and this paper will use Dan River Basin in its place.

Strata of the Dan River Basin are assigned to the Newark Supergroup by Olsen (1978), Froelich and Olsen (1985), and (Luttrell, 1989), that consists of all of the exposed and some subsurface sedimentary strata and interbedded extrusive igneous rocks in the extensive Late Permian to Early Jurassic rift basins in eastern North America.

Dan River Group

Thayer (1970) named all of the sedimentary strata of the North Carolina part of the Dan River Basin the Dan River Group, while the strata of the Virginia part of the basin were not assigned to a group. We therefore redefine the Dan River Group to also include all of the formations in the Virginia portion of the Dan River Basin. Conversely, we do not apply the extension of Chatham Group as used by Weems and Olsen (1997) to the strata of the Dan River Basin, preferring instead to use the tectonostratigraphic sequence framework established by Olsen (1997), and the Newark Supergroup group-rank units as discussed by Olsen (1978) and Froelich and Olsen (1984).

Stratigraphic Revision

Thayer (1970) recognized that in the Dan River Basin, the predominately fine-grained, organic-rich, gray and black clastic strata of the Cow Branch Formation, consisted of two units, a lower more laterally traceable but thinner unit and an upper thicker lens. Olsen and others (1978), Olsen (1979), Olsen and others (1982) continued this distinction, recognizing that the overall facies, lithology, bedding character, and fish assemblages and taphonomy of the two units were substantially different and referred to them informally as the upper and lower members of the Cow Branch Formation. This practice was followed by Robbins (1982) and Thayer and Robbins (1992). However, Olsen and others (1989, 1991) followed Weems (1988) in suggesting that the two parts of the Cow Branch Formation could be the same unit repeated by normal faults (Figure 4).

Kent and Olsen (1997) used long outcrop sections along streams and large quarry exposures to delineate the paleomagnetic polarity stratigraphy of the Dan River Basin and in the process implicitly test and falsify the fault repetition hypothesis (Figure 4). They showed that there was a coherent polarity stratigraphy in two sets of approximately parallel sections stratigraphically above the mapped lower member of the Cow Branch allowing unambiguous correlation with the Newark Basin polarity stratigraphy. They attempted to use Meyertons' (1963) nomenclature for the Leaksville Formation, using the Cascade Station Member for the upper cyclical thick interval of red strata and informally dividing the Cow Branch Member into upper, middle, and lower Cow Branch members.

Whiteside and others (2011) briefly described the stratigraphy of core SO-C-2-81 (Figure 7). This and core SO-C-1-81 (Figure 7) contain the lower half of the lower member of the Cow Branch Formation (our Walnut Cove Formation) and upper Pine Hall Formation at Walnut Cove and near Pine Hall, respectively. Based on the paleomagnetic polarity stratigraphy, described below, a total of two major additional polarity zones are added to the Dan River Basin polarity stratigraphy (Figures 5, 7). The good correlation of the magnetostratigraphy to the Newark Basin section makes fault repetition of the sections unlikely and indeed, no evidence of faults exists in the appropriate places.

Thus, there are two separate major, mappable, gray and black mudstone units within the Cow Branch Formation of Thayer (1970). These two units are separated by cyclical tan, gray, and red sandstone and mudstone sequence that was formerly grouped with the Pine Hall or Stoneville formations (Thayer, 1970). They are however, physically connected to the Dry Fork

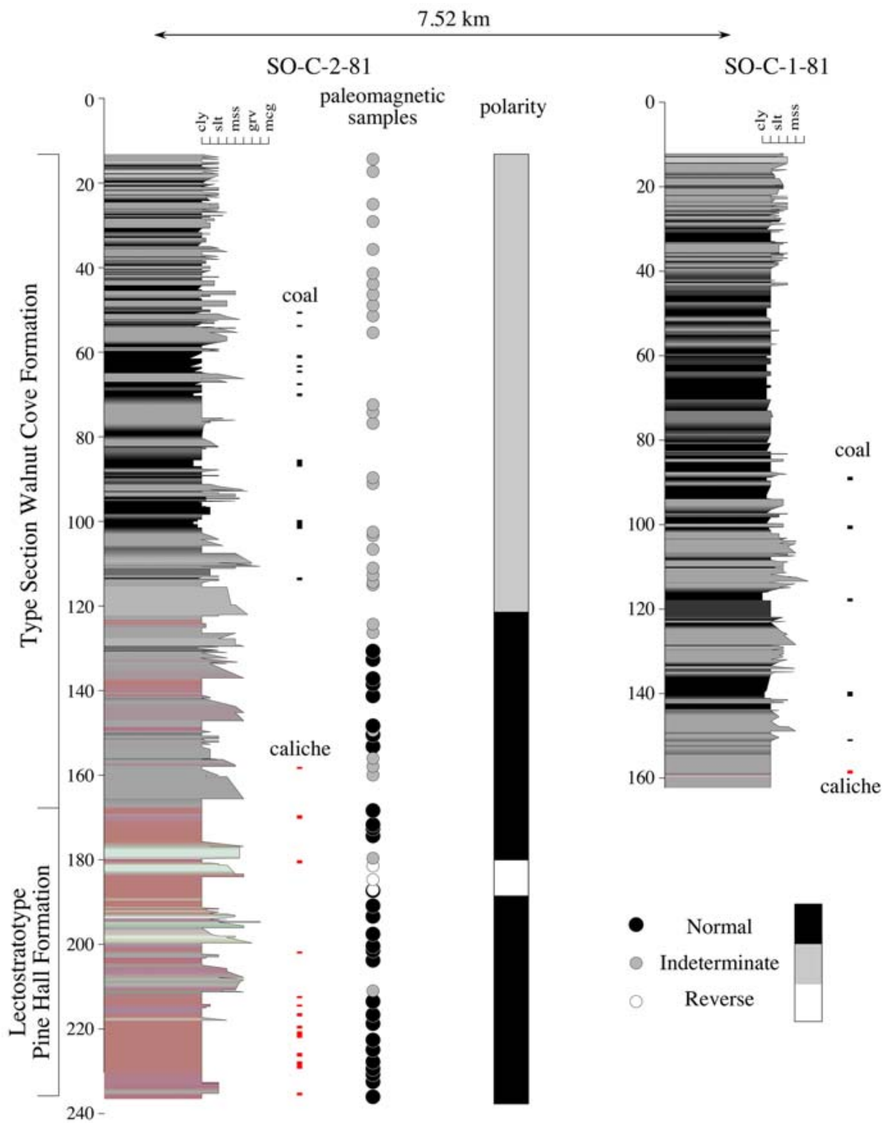

Figure 7. Dan River Basin core SO-C-2-81, including the type section of the Walnut Cove Formation, lectostratotype of the Pine Hall Formation and core SO-C-1-81 that is closer to the basin depocenter (see Figure 3 for locations), showing paleomagnetic polarity sequence.

Formation (map of Thayer, 1970), and we assert that these beds are more similar throughout their extent to the Dry Fork Formation than to either the Pine Hall or Stoneville formations. This scheme has the advantage of ease of mappability, relative simplicity, and predictability of content.

We propose that the "lower member" of the Cow Branch Formation be removed from that formation and be recognized as a formal new mappable unit of equal rank, the Walnut Cove Formation (see below). The "upper member", we argue, should retain the name of Cow Branch Formation (Figure 5, 6) as the latter's type section fully conforms to our restricted definition. Use of the Leakesville and Cedar Forest formations should be abandoned as suggested by (Luttrell, 1989). The Dan River Basin section thus consists of five formations, described as follows, from the base upwards.

Pine Hall Formation

The basal formation of the Dan River Basin is the Pine Hall Formation (Thayer, 1970) that consists largely of coarse clastic rocks and interbedded sandstones and red mudstones. We intend its use to be similar to that intended by Thayer (1970) and Thayer and others (1970). In most areas, there is a lower conglomeritic, largely tan portion and an upper mostly red sandstone and mudstone interval. Locally, silicified logs are present in the tan sandstone-dominated units (Emmons, 1856; Stone, 1910; Thayer, 1970; Thayer and Robbins, 1970) and reptile bones occur locally (P. Huber, pers. comm., 2014). The Pine Hall Formation is about 200 m thick in the area of its lectostratotype (below).

The contact with the overlying Walnut Cove Formation is marked by the presence of gray sandstone and mudstone with a much lower frequency of red mudstone. This transition can be seen in detail in both SO-C-1-81 and SO-C-2-81 cores. Where the Walnut Cove Formation is absent, Pine Hall clastic rocks can be differentiated from the overlying Dry Fork Formation by the presence of more abundant red strata in the Pine Hall. The Pine Hall Formation appears to pinch out against basement in the northern half of the Virginia segment of the Dan River Basin. (Figure 2).

Thayer (1970) did not designate a type section for the Pine Hall Formation due to lack of stratigraphically informative, continuous sections. Therefore, we designate a lectostratotype for the Pine Hall Formation from 174.7-245.7 m (573.0-806.2 ft.) core depth, corresponding to 167.8-236.2 m stratigraphic depth in the SO-C-2-81 core, where it consists primarily of red clastic rocks with abundant carbonate nodules and mottled strata of probable pedogenic origin (Figure 7; Appendix 1).

Walnut Cove Formation

The type section of the Walnut Cove Formation is from core SO-C-2-81 drilled at Walnut Cove, NC (Whiteside and others, 2011) at 36.286389 N, 80.1408330 W (Figure 7), 13.1-174.7 m (43.0-573.0 ft.) in core depth, corresponding to 13.1-167.8 (43.0-550.4 ft.) stratigraphic depth based on dips measured in the core (Figures 7; Supporting information in Whiteside and others, 2011). In its type section and elsewhere, the Walnut Cove Formation consists of cyclical black and gray mudstones and sandstones, and thin coal beds and minor, a sequence that was first observed by Emmons (1856) and investigated and mapped in some detail by Stone (1910). The black mudstones are massive, thin bedded to laminated, but never microlaminated and tend to have higher levels of total organic carbon than the dark gray to black mudstones of the Cow Branch Formation (Reid and Taylor, 2012, 2013: see below). The total thickness of the Walnut Cove Formation is minimally about 160 meters at its type section, but appears to thicken northeastward to about 600 m in Eden, NC (Kent and Olsen, 1997) (Figure 5).

Rocks of the Walnut Cove Formation have been mapped extensively in the North Carolina part of the Dan River Basin (Thayer, 1970; Kent and Olsen, 1997) as Cow Branch Formation. The former becomes indistinguishable from the Dry Fork Member north of Cascade Creek and into Virginia as the proportion of tan and gray sandstone becomes predominant at the expense of fine-grained strata, although the details are obscured by poor outcrop. There are places where Meyertons (1963) shows what are mapped as lenses of his Cow Branch Formation in the appropriate stratigraphic position to be outliers of Walnut Cove Formation, but the outcrops are presently so poor as to make their recognition uncertain. The Walnut Cove Formation also passes into coarse clastics at the southwestern terminus of the Dan River Basin near Germanton, NC. Outliers of the Walnut Cove Formation may be locally present in the Virginia portion of the basin particularly near Hermosa, VA (Meyertons, 1963).

A useful reference section is exposed in the abandoned Cranby Roberts (King and Hall) quarry in southwest Eden, NC (36° 28.38' N,

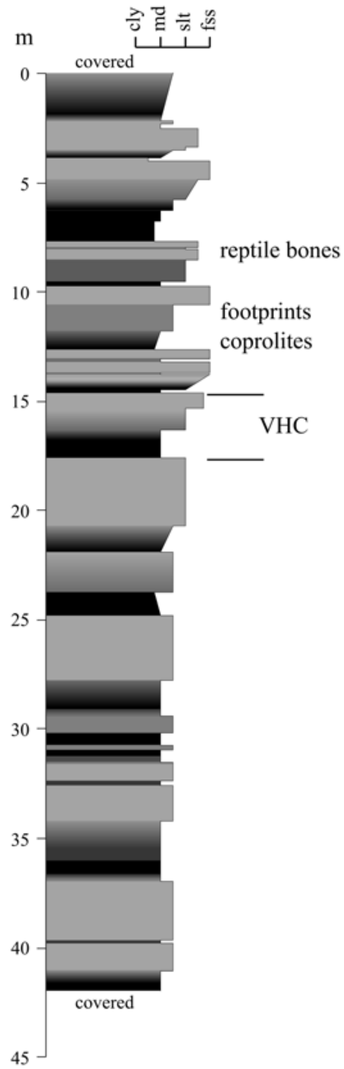

Figure 8. Section of the middle Walnut Cove Formation exposed in the Cranby Roberts (King and Hall) quarry measured 12/30/77. VHC stands for representative Van Houten cycle.

79° 47.15' W). The section exposes about 42 m of cyclical gray and black strata of the middle Walnut Cove Formation and has produced reptile bones and footprints (Figures 8, 9). Additional sections of comparable or greater thickness were described by Stone (1910) and Thayer (1970). We have been unable to locate any good outcrops of the transition from the Walnut Cove Formation into the overlying Dry Fork Formation, but can surmise that it is marked by the replacement of mostly gray mudstone and sandstone by red mudstone and tan and red sandstone.

Dry Fork Formation

The type section of the Dry Fork Formation consists of "Cuts along the Southern Railway on White Oak Mountain, 0.8 km south of the town of Dry Fork on State Road 718, 0.8 km west of U.S. Highway 29, Mount Hermon quadrangle, Pittsylvania County, Virginia (Meyertons, 1963)", (Luttrell, 1989) at about 36.747968°N, 79.396546°W (Figure 2). The Dry Fork Formation consists of tan to red sandstones with cyclically interbedded gray, purple, and red mudstones. In the Virginia portion of the Dan River Basin, this formation is typically coarser, more highly indurated, and has much less cyclical layering with a greater content of light-colored sandstone and conglomerate (Figure 6). The Dry Fork Formation also generally lacks the persistent black mudstone-bearing cycles typical of the Stoneville Formation that overlies the Cow Branch Formation, but does have gray and purplish shale cycles as seen along Dry Creek in Eden North Carolina and the tributary to Cascade Creek examined by Kent and Olsen (1997), and lenses of gray mudstone where it is the lateral equivalent of the Walnut Cove Formation, as noted above. The thickness of the Dry Fork is highly variable; it is about 700 m thick in Eden, NC where it is exposed along Dry Creek (Kent and Olsen, 1997) (Figure 5); but is much thicker where it replaces the Walnut Cove Formation in Virginia.

The long set of exposures of the type section along the Southern Railway cut in Pittsylvania County, VA (Meyertons, 1963) have an upper interval of largely gray coarse clastic rock with interbedded dark gray mudstones. We consider this interval to be a coarse facies of the Cow Branch Formation, whereas the rest of the exposures to the southeast are reddish to buff coarse clastics interbedded with finer largely reddish to purplish clastic rocks, which includes the Dry Fork type section of Meyerton (1963). The Dry Fork Formation is very indurated at its type section and remains so to the northeast and south-

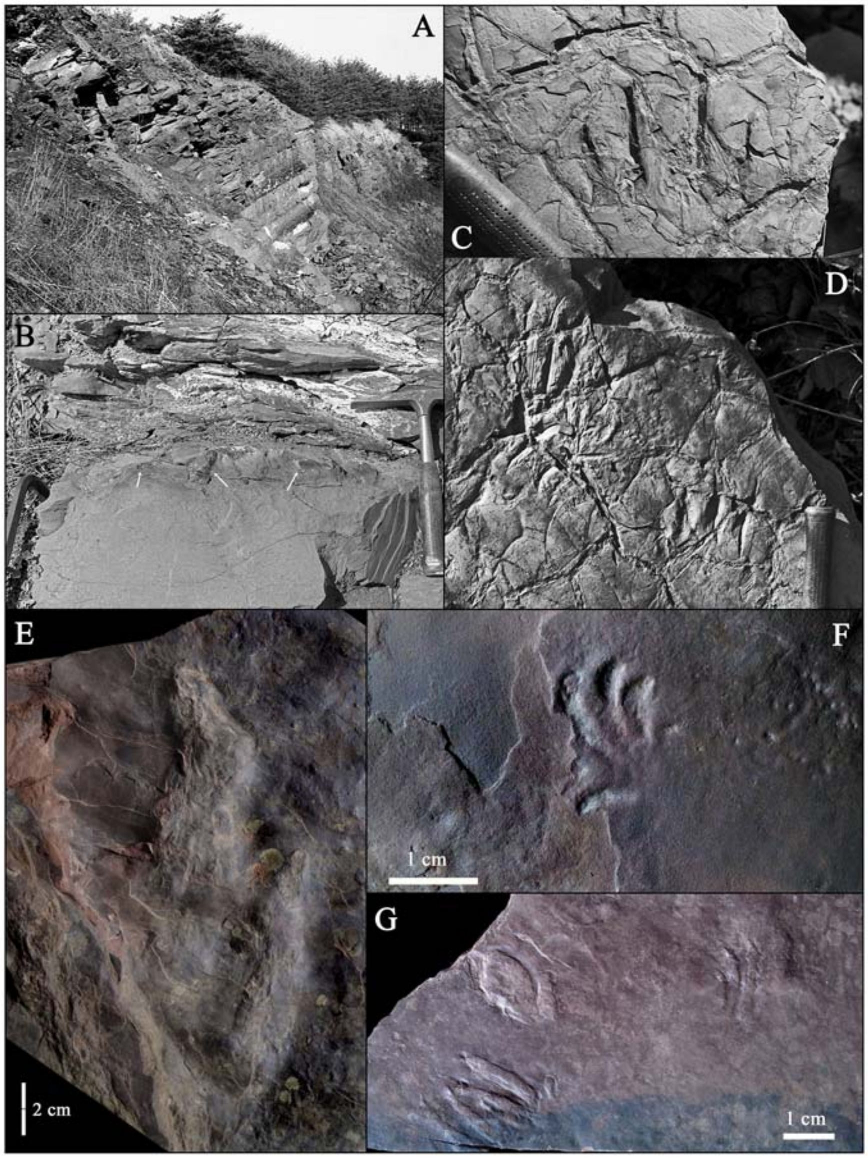

Figure 9. Exposures, tracks and bones from Cranby Roberts (King and Hall) quarry in middle Walnut Cove Formation and new locality in Stoneville Formation Dry Mountain Creek, Long Island, VA at 37° 3.965'N, 79° 5.140'W: A, section of exposed on the north wall of the Cranby Roberts (King and Hall) quarry in 1977 showing interval from 0 to 15 m in Figure 10; B, reptile bones (probable phytosaur, white arrows) *in situ* at about 8.1 m in the Cranby Roberts quarry section; C,?*Apatopus* (phytosaur) manus impression in mudcracked mudstone (from about 11.8 m) in Cranby Roberts quarry; D,?*Apatopus* (phytosaur) manus (on right) and pes (on left) impression in mudcracked mudstone (from about 11.8 m) in Cranby Roberts quarry; E, brontozoid (*Anchisauripus*) footprint at footprint locality on Dry Mountain Creek (Virginia Museum of Natural History VMNH 120179); F, *Rhynchosauroides brunswickii* manus impression (VMNH 120117b) from footprint locality on Dry Mountain Creek; G, natural casts of *Rhynchosauroides brunswickii* manus and pes impressions (VMNH 120178) from footprint locality on Dry Mountain Creek.

west forming a very prominent linear ridge, including White Oak Mountain. The prominent ridge can be traced with breaks to Boyd Mountain where it strikes into the less indurated strata that separate the Walnut Cove from the Cow Branch formations near the Virginia-North Carolina state line. The change in induration may be associated with an increase in the proportion of red mudstone at the expense of gray and buff coarse clastics, with conglomerates becoming rare. Southwest of Eden, the formation becomes yet finer grained and proportionally more red.

The upward transition between the Dry Fork and the Cow Branch formations is marked by an increase in the frequency of gray strata with distinctly darker gray to black laminated mudstones than typical for the former. These dark mudstones contain abundant conchostracans, ostracodes, and fish fragments. One temporary exposure adjacent to the southeast quadrant of the intersection of US Highway 220/311 and NC Highway 135 / US 311 (approximately at 36.413242° N, 79.937311°W consisted of at least three dark and medium gray mudstone sequences interlayered between fine red siltstone, mudstones and fine grained sandstones, with laminated to finely laminated red claystones and fine to very finely laminated gray mudstones containing conchostracans (P. Hubert 2014 based on observations made in 1998). An additional large exposure was the pit of the Webster Brick Company in Eden, North Carolina (36.532233°N, 79.665197°W), briefly described in Olsen and others (1989). Fossils from the black shale include the fish *Turseodus*, *Synorichthys*, and *Diplurus*, as well as possible phytosaur teeth, coprolites, conchostracans, and extremely abundant darwinulid ostracodes. Large inclined sandstone and siltstone beds were exposed above the black shale. The exposure is presently overgrown.

Cow Branch Formation

The type section of the Cow Branch Formation of Thayer (1970) comprised the stratigraphically lower half of the Leaksville Formation of Meyertons (1963) as exposed along Virginia State Road 856, between 0.32 km (0.2 mi) south of State Road 622 and 0.32 km (0.2 mi) north of the VA State line, Pittsylvania Co., VA. Based on Meyertons' section, translated to geography, the top of the Cow Branch should be at about 0.72 km south of State Road 622, and the center of the section should be at about 36.546804°N, 79.692766°W. Unfortunately, almost all of the exposures along this road have been covered since at least 1975, with the exception of red strata at near the top of the section in what we regard as Stoneville Formation.

Therefore, strata exposed in the "main quarry" section of Olsen and others (1978) in the Ararat Rock Products Co. quarry (formerly the Solite and then Cemex quarry), beginning at about 36.539691°N, 79.672671°W are designated a lectostratotype for the Cow Branch Formation. As seen here, the formation consists of cyclical gray and black mudstone and minor sandstone with abundant highly-fossiliferous microlaminated mudstones. The Cow Branch Formation also contains laterally equivalent gray sandstones and conglomerates with cyclically occurring black and dark gray mudstone intervals. Unfortunately, the adjacent Cascade Creek outcrops, while extensive do not make a suitable lectostratotype because the outcrops are nearly all at water level and comprised almost entirely of the massive portions of cycles, with virtually no outcrops of laminated strata. The maximum thickness of the Cow Branch Formation appears to be in the area of the Virginia-North Carolina State line where it reaches about 1900 m.

The Cow Branch Formation locally grades laterally into coarse gray clastic rocks. In such cases, the Cow Branch Formation can be difficult to distinguish from the Dry Fork Formation. However, a rarity or absence of fine-grained, gray and purple beds leads us to map such rocks as Dry Fork Formation, whereas the presence of black and dark mudstone beds leads us to map such rocks as Cow Branch Formation.

The Cow Branch Formation becomes much coarser both southwest and northeast of its type area, but retains its dominant gray color and persistent, if less abundant, black mudstones. In areas where the coarse clastics dominate, Thayer (1970) mapped them as Stoneville Formation, particularly to the southwest of the type area. For example, at Eden, NC, spectacular outcrops are present for about 1.2 km (geographic distance) on the southeast bank of the Smith River, north of the bridge for State Route 700 (old State Highway 770); these strata were mapped by Thayer as Stoneville Formation.

However, these outcrops contain abundant periodically spaced laminated black mudstones that are clearly a continuation of the pattern seen in the exposed, underlying, fine grained Cow Branch Formation and are along strike from its type section. We therefore consider these exposures to more properly belong to the Cow Branch Formation. At least as far southwest as Mayodan and Madison, NC (e.g., along the roads and adjacent areas from 36° 25.5' N, 79° 54.4' W to 36° 25.8' N, 79° 54.9'W; railroad embankment exposures at 36° 24.3' N, 79° 58.0' W to outcrops in and along the Mayo River at 36° 24.9' N, 79° 57.7' W), there persists a mappable and homotaxial unit comprised of a lower cyclical interval dominated by finer clastics grading into an upper cyclical interval dominated by coarser clastics, all with periodic black and gray mudstones. We also assign these rocks to the Cow Branch Formation, whereas the overlying largely red clastic rocks, also often coarse, are assigned to the Stoneville Formation. We have not yet been able to confirm the presence of the Cow Branch Formation southwest of Mayodan and Madison because of poor outcrop.

In the Virginia part of the Dan River Basin there are areas where fine-grained facies of the Cow Branch Formation are present, particularly in the area from near Motley Mills to Stinking River, VA. This area shows the relationship between the Cow Branch and underlying Dry Fork formations exceptionally well, and the homotaxial relationships with the northern North Carolina part of the Dan River Basin. In that area, a lower strikingly cyclical gray laminated mudstone and gray mudstone and sandstone sequence (e.g. at between 36° 49.59' N, 79° 19.13' W and 36° 49.21' N, 79° 18.83' W) are directly comparable to the Cow Branch Formation in the Eden area, and are succeeded by cyclical, largely red and gray strata (e.g. at 36° 53.65'N, 79° 13.73'W. The latter, includes the type locality of the dinosauromorph ichnotaxon *Banisterobates boisseau* (Fraser and Olsen, 1996).

The transition between the Cow Branch Formation and overlying Stoneville Formation is marked by a cyclically increasing frequency of red strata upward, at the expense of gray mudstone and sandstone. This transition was described by Meyertons (1963) in his type section of his Leaksville Formation (Figure 6), discussed above.

Stoneville Formation

Overlying the Cow Branch Formation is the Stoneville Formation, which is differentiated by a very strong preponderance of red instead of gray and black clastic rocks. However, the Stoneville continues the cyclicity seen in the Cow Branch Formation and periodically spaced, purple, gray, and black mudstone beds remain, including where the formation is dominated by coarse clastic rocks. We have yet to find sections that demonstrate that gray and black Cow Branch lithologies pass laterally into red-dominated Stoneville lithologies, which is one of our reasons for not differentiating between these two formations solely on the basis of grain size. Although the maximum thickness of the Stoneville Formation has not been ascertained, is at least 1800 m in the area of the Virginia-North Carolina State line, and nearly twice that is preserved adjacent to the Staunton River in Virginia.

The type section of the Stoneville Formation is described by Thayer (1970, 1978) and Thayer and Robbins (1992) and is the road cut on west side of US Route 220 Bypass, 0.4 km (0.25 mi) north of Rockingham County road 2164 (Frye Road), Mayodan (36.435815°N, 79.930237°W). It is dominated by coarse red clastics, largely sandstone, fine gray mudstone and sandstone are present near the middle of the section. The reference section provided by Thayer (1970, 1978) and Thayer and Robbins (1992) along the cut on the west side of the Norfolk and Western railroad tracks, 0.32 km (0.2 mi) northeast of Mayodan city limits at about 36.425485°N, 79.962263°W, is finer grained and is clearly cyclical with several thin gray and dark gray mudstones in the section. The Stoneville Formation is represented in the region near Motleys Mills by fine grained largely red but cyclical facies, such as seen in the area to the north west of the Banister River to the northwest edge of the basin. Cores drilled for the Marline Uranium Company show the rhythmic alternation of red and gray and black strata (Christopher, 2007) typical of the Stoneville Formation.

In the portion of the Dan River Basin northeast of the Staunton River, we have not yet found the Cow Branch Formation. The thinning of the mapped extent of the Dry Fork Formation from the south towards the Staunton River and its restriction to the eastern edge of the basin in that area suggests that only part of the Cow Branch Formation may be present. Our preliminary investigations in the region north of the Staunton River suggests that only lithofacies characteristic of the Stoneville Formation are present and the tongues of the "Cow Branch Member" as mapped by Meyertons (1963) are gray and black units within Stoneville marking out its characteristic cyclicity.

PALEOMAGNETIC POLARITY STRATIGRAPHY OF THE DAN RIVER BASIN

Kent and Olsen (1997) produced a composite paleomagnetic polarity stratigraphy for most of the Dan River Basin in and adjacent to Eden, NC (Figure 5) based on long quarry and stream outcrop sections. The composite section includes what we now term the Dry Fork and Cow Branch formations and the lower part of the Stoneville Formation. The ~3000 meter-thick composite magnetostratigraphy was based on 113 sampling sites and comprised of 11 normal and reverse polarity zones designated D1n to D6n and varying in thickness from ~100 to 800 m, that form a pattern that correlates remarkably well to chrons E9n to E14n of the Newark APTS. This interval thus spans ~7.5 Myr from 224 Ma to 216.5 Ma (APTS adjusted for base of E24n, virtually coincident with base of CAMP volcanics, at 201.6 Ma rather than 202 Ma used in Kent and Olsen, 1999).

Here we extend the Dan River Basin magnetostratigraphy downward by adding data from continuous core for the Walnut Cove Formation and the uppermost Pine Hall Formation (preliminary results reported by Whiteside and others, 2011) (Appendix 1) (Figures 5, 7). The 233.6 m (corrected from marked driller depth) of the SO-C-2-81 core (232.3 m core depth; 222.8 m stratigraphic depth) taken at Walnut Cove, NC (36.286389N, 80.1408330W) spans the uppermost Pine Hall Formation and the Walnut Cove Formation, including the latter's type section as described above. Core SO-C-2-81 was selected for sampling for paleomagnetic polarity stratigraphy because it has a relatively high percentage of red strata, a lithology that usually has a more easily interpretable demagnetization behavior compared to gray strata in this basin (Kent and Olsen, 1997). For all cores, the core section was measured in contiguous intervals, and bedding dip magnitude was recorded where judged reliable. A dip model was constructed using linear regression (and for other cores, except SO-C-2-81) by interpolation at increments of 0.1 ft. and then dip corrected by the linear regression at 3.048 cm (0.1 ft., in original driller units), with all increments being summed to corrected stratigraphic depths as depicted in Figure 7. Note however that the observed bedding dips in the core, typically 15°, are ~30° shallower than reported from nearby outcrop (~45° or more to the north; Thayer, 1970). The simplest explanation is that the core drilling deviated from vertical toward the south into (perpendicular to) bedding. A second core, SO-C-1-81 taken near Madison, NC (36.371944°N, 80.018333W), spans nearly the same section, but was taken in a more basinward position in finer grained rock with a higher proportion of gray strata, and is shown here to demonstrate the continuity of cyclostratigraphy in the formation (Figure 7). In this core an exponential regression was a much better fit to the dip data, unlike SO-C-2-81, because the core captures the high outcrop dips initially before deviating into (perpendicular to) the bedding capturing lower apparent dips.

For paleomagnetic analysis, 62 sample plugs 2.5 cm in diameter were taken in SO-C-2-81 from the most intact segments of the cores, for which the up direction was judged reliable and taken parallel to the azimuth of bedding, where visible. Remanence measurements were made on a 2G Model 760 3-axis DC-SQUID cryogenic rock magnetometer in a magnetically shielded room in the Paleomagnetics Lab at LDEO. Samples were subjected to progressive thermal demagnetization in a dozen or more temperature steps to 575°C for the gray lithologies, which almost invariably are dominated by magnetite and sulfide remanence carriers, and to 675°C for the hematite-bearing red lithologies. Very few of the gray lithologies produced reliable polarity data, typically because of interference by large magnetic alteration during laboratory heating (monitored by repeat measurements of magnetic susceptibility) just when a diagnostic albeit weak paleomagnetic polarity signal might have become apparent. The red lithologies provided much more consistent and reliable polarity results, especially in samples that had articulated demagnetization trajectories like the example illustrated for an outcrop sample (Figure 3j in Kent and Olsen, 1997); this demagnetization pattern likely reflects a partial normal polarity overprint of an original or characteristic magnetization (ChRM) with reverse polarity. Samples with a normal polarity ChRM are more difficult to diagnose because an often pervasive normal polarity overprint (e.g., component Bh in Kent and Olsen (1997)) tends to be subparallel to the normal polarity ChRM, whose designation thus often relies on having the higher unblocking temperature (e.g., Figure 3e in Kent and Olsen, 1997). Combined with evaluating added variables of dipping beds in drill holes that may have deviated substantially from vertical, our estimation of ChRM polarity from the sample data should be regarded as qualitative.We are most confident of data from red bed samples indicating reverse polarity ChRM, which are indicated by open circles in the stratigraphic plots. Samples of red bed lithology with good quality data pointing to normal polarity ChRM (with due caveats) are indicated by filled circles. Samples with indeterminate ChRM polarity are indicated by gray circles and almost invariably come from futile sampling efforts to obtain polarity information in gray beds in the absence of systematic absolute orientation. Preliminary results from SOC-2-81 were presented by Whiteside and others (2011).

ChRM polarity could not be assigned to any of the samples from the gray-dominated Walnut Cove Formation in the upper ~123 m of core section (samples from 14.6 to 137.7 m stratigraphic depth; 48 to 467.8 ft., drillers depth) (Figure 8). However, paleomagnetic data from samples from the lower part of the Walnut Cove Formation that showed hints of red (and high unblocking temperature magnetizations), as well as the red-dominated Pine Hall Formation, provide meaningful results that indicate mostly normal polarity ChRM for the lower ~334 m of the core stratigraphy (samples from 138.5 to 236.7 m stratigraphic depth; 471.5 to 805.5 ft. driller's depth). The exception is a thin zone from which 3 samples from 180.9 to 187.6 m stratigraphic depth (615.8 to 638.6 ft. driller's depth) show more articulated demagnetization trajectories consistent with reverse polarity ChRM.

CORRELATION WITH THE NEWARK BASIN APTS

The extended polarity stratigraphy can now be placed in the framework of the lithostratigraphy and polarity stratigraphy of Kent and Olsen (1997), based on the outcrops and exposures in and around Eden, NC (Figure 5) and the projected map position of the boundary between the Pine Hall and Walnut Cove formations and the original stratigraphic thicknesses from SOC-2-81. The Walnut Cove Formation thickens from the southwest into the Eden area by an increase in the proportion of gray and black strata with no discernable change in dip (Figure 3 and Kent and Olsen, 1997). Based on the map-based thickness estimate, it is clear that the two cores sampling the Walnut Cove Formation span only its lower third (Figures 5, 10). Superposition however, is clear and the relationship with the polarity stratigraphy given in Kent and Olsen (1997) for the overlying Dry Fork, Cow Branch, and Stoneville Formations is unambig-

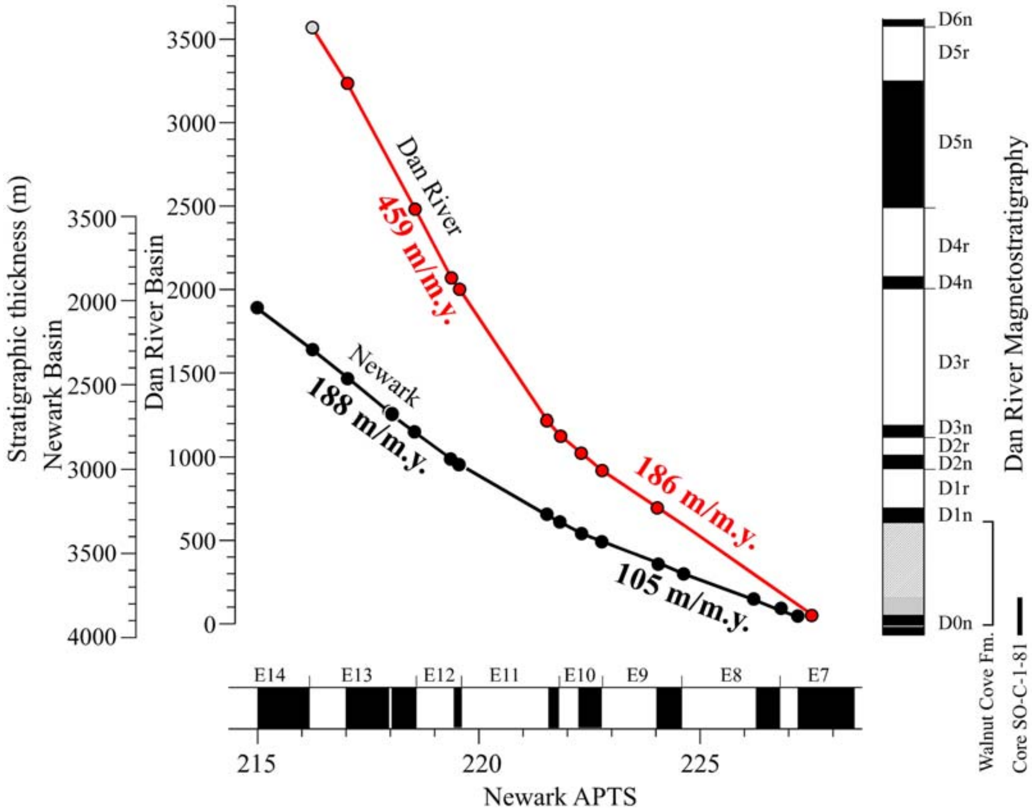

Figure 10. Cross correlation of composite Dan River Basin section, Newark Basin section and Newark APTS (from Kent and Olsen, 1999) that was revised from Kent and others (1995) with the addition of cyclostratigraphic control for chrons E8-E10. The slopes of the lines are average sediment accumulation rates for those segment. Note that the sedimentation rate for base of Dan River magnetozone D1n through all of D0 is extrapolated from the correlation line of the top of D1n through the base of D2n. Hachured gray intervals represent unsampled section and gray represents indeterminate polarity.

uous (Figure 5). Because of the unsampled (uncored and poorly exposed) interval of the upper Walnut Cove and Dry Fork Formations, the downward extension of the Dan River polarity section can only be tentatively correlated with the Newark Basin APTS (Figure 10). The correlation between D1n though D6n as presented in Kent and Olsen (1997) to the Newark APTS chrons E9n to E14n is unambiguous. The floating normal polarity magnetozone D0n in the bottom part of the Walnut Cove Formation in SO-C-2-81 could represent E8n or E7n (f and g, respectively in Figure 5). Assuming that sediment accumulation rates based on the magnetostratigraphy (~190 m/Myr) stayed more or less uniform in the older part of the sequence (or at least were not punctuated by drastic increases or unconformities for which there is no evidence), we believe that D0n is most compatible with a correlation to E7n (Figure 10); this assignment is supported by new results from the Deep River Basin (Olsen and others, in preparation). An equivalent to the very thin reverse polarity zone in D0n of the Dan River Basin cores is not seen in the Princeton no. 1 core, from which the relative polarity zones for this part of the Newark APTS was derived. There are several possible explanations for this mismatch, amongst which is the lack of comparable resolution (lower sediment accumulation rate and

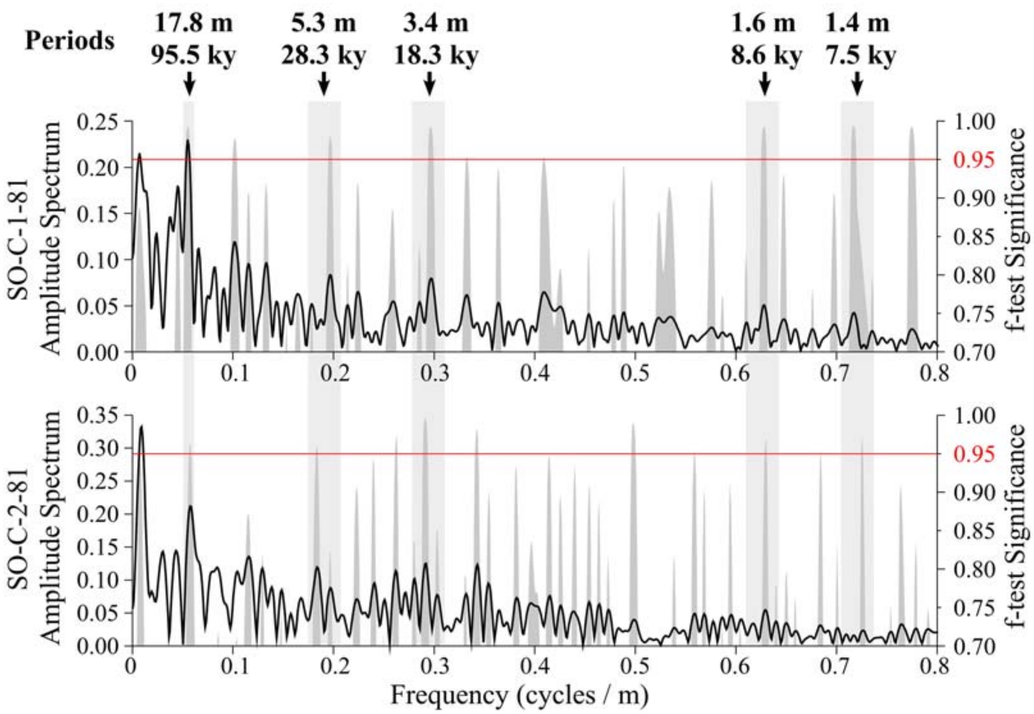

Figure 11. Amplitude spectra and f-test significance of color in the SO-C-2-81 and SO-C-2-81 cores. The highlighted spectral peaks are these that occur in both core sections and which rise above the 0.95 significance level. Periods in time use the accumulation rate derived from correlation of the Dan River Basin section and Newark APTS in Figure 10.

lower sampling density) in the Princeton no. 1 core, which is largely fluvial or marginal lacustrine sandstone (e.g., Turner-Peterson, 1980), whereas, the core from the Dan River Basin is largely lacustrine mudstones and thus it is likely the thin reverse interval is simply below the level of sampling resolution in that part of the Newark Basin sequence.

CYCLICITY OF THE WALNUT COVE FORMATION

The visually conspicuous cyclicity in the SO-C-1-81 and SO-C-2-81 cores and outcrops suggests a prominent thickness periodicity of from 3 to 6 m (Figures 7, 8) corresponding to the Van Houten cycle seen in the Cow Branch Formation and other lacustrine Newark Supergroup basins (Olsen, 1986; Whiteside and others, 2011). This is supported by the multitaper method spectra (MTM) for SO-C-2-81 and SO-C-2-81, the significant peaks (t test >0.95) of which display periods around 3.4 and 5.3 m (the Van Houten cycle) as well as a period around 17.8 m, suggesting the short modulating cycle (Figure 11). Using the accumulation rate of 186 m/m.y. derived from correlation between D1n though D2n and the Newark APTS E9n through E10n, (using APTS, of Kent and Olsen, 1999) shows these thickness periodicities to be consistent with the Milankovitch climatic precession cycles of ~20 ky, hemiprecession of ~10 ky and short eccentricity cycle of ~100 ky.

CORRELATION WITH OTHER NEWARK SUPERGROUP BASINS

The expanded paleomagnetic polarity sequence of the Dan River Basin allows detailed comparison and correlation with other Newark Supergroup basins (Figure 12). This is especially interesting given the apparent climatic con-

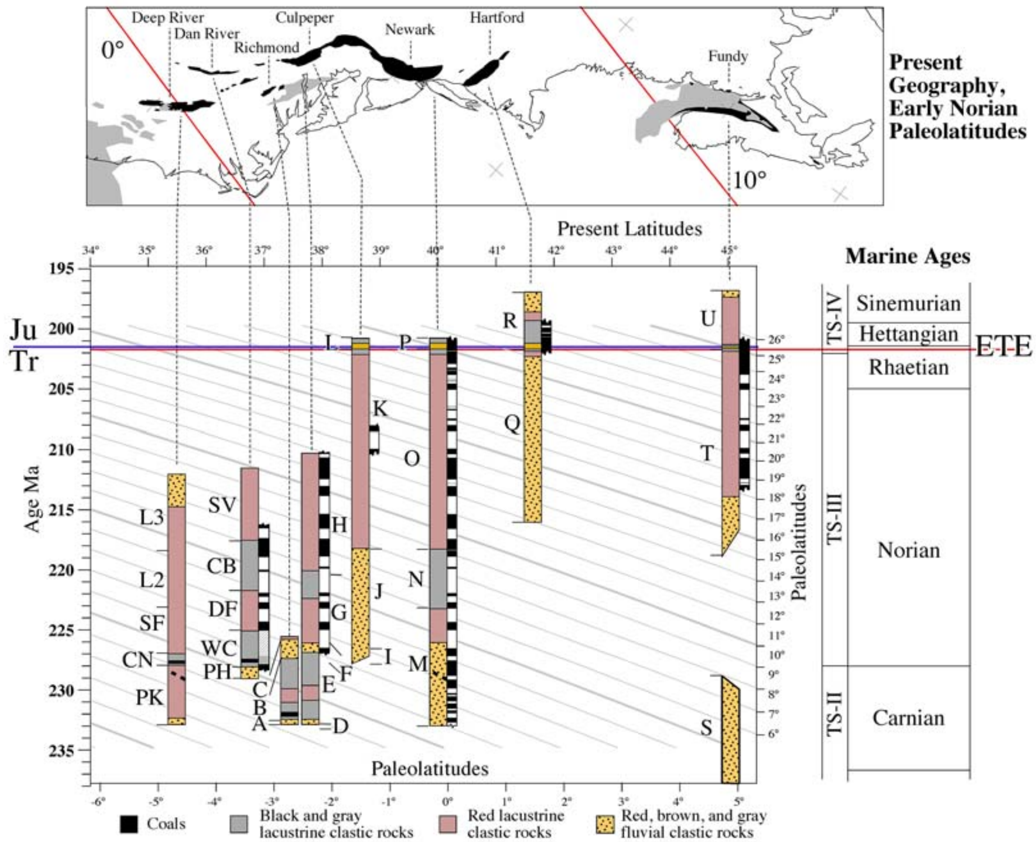

Figure 12. Latitude – age nomogram of the Dan River Basin and other exposed basins in eastern North America showing numerical age derived from the Newark APTS, tectonostratigraphic sequences (TS-II – TS-IV) and marine-based standard ages. Abbreviation of formations are: CB, Cow Branch; CN, Cumnock; DF, Dry Fork; PH, Pine Hall; PK, Pekin; SF, Sanford; SV, Stoneville; WC, Walnut Cove; L2, Lithofacies Association II; L3, Lithofacies Association III; A, lower barren beds; B, Vinita; C, Otterdale; D, Stag Creek; E, Falling Creek; F, Newfound; G, Port Royal; H, Leedsville; I, Reston; J, Manassas; K, Balls Bluff; L, extrusive zone (Mt. Zion Church Basalt, Midland, Fm., Hickory Grove Basalt; Turkey Run Formation; Sander Basalt; Waterfall Fm.); M, Stockton; N, Lockatong; O, Passaic; P, extrusive zone and overlying unit (Orange Mountain Basalt, Feltville Fm., Preakness Basalt, Towaco Fm., Hook Mt. Basalt, Boonton Fm.); Q, New Haven; R, extrusive zone and overlying unit (Talcott Basalt, Shuttle Meadow Fm., Holyoke Basalt, East Berlin Fm., Hampden Basalt, Portland Formation); S, Wolfville; T, Blomidon; U, extrusive zone and overlying unit (North Mountain Basalt, McCoy Brook Fm.).

trol of the lacustrine facies and modes of orbitally forced cyclicity expressed in the basins that vary with latitude (Olsen, 1990; Whiteside and others, 2011).

As noted by Whiteside and others (2011), the Walnut Cove Formation and the Cumnock Formation of the Deep River Basin are remarkably similar, not only in gross aspects of lithology, but also in respect to their detailed cyclostratigraphy and biostratigraphy (Whiteside and others, 2011; Olsen and others, 1982). This implies extremely tight climatic control over facies, or a direct hydrologic connection between the two basins. Correlation between the Walnut Cove and Cumnock formations implies correlation of the Dry Fork Formation with the lower Sanford

Formation, and the possible correlation of the Cow Branch Formation with at least part of the upper Sanford Formation.

Based on the polarity stratigraphy and correlation to the Newark Basin section, the Walnut Cove Formation correlates with the Cutaloosa Member of the Stockton Formation and the Dry Fork Formation correlates with the Raven Rock member, whereas the Cow Branch Formation correlates with the Lockatong and lowest Passaic Formations as previously published (Kent and Olsen, 1997). For similar reasons, the Stoneville Formation correlates generally with the Passaic Formation that it very strongly resembles lithologically, except for the apparent absence of an equivalent of the upper Passaic Formation in the Dan River Basin (Figure 12).

FOSSILS AND DEPOSITIONAL ENVIRONMENTS

The Dan River Basin has produced classic fossil material for 160 years (Emmons, 1852; 1857) and now is renowned for some of the richest fossil assemblages of the global Late Triassic, including a world-class Konservat-Lagerstätten from the Cow Branch Formation (Olsen and others, 1978; Grimaldi and others, 1996; Blagoderov and others, 2007). Here we will briefly review highlights of the fossil assemblages by formation.

Pine Hall Formation

Sandstones and conglomerates of the Pine Hall Formation have produced silicified wood, apparently locally very abundant as isolated fragments and logs (Emmons, 1852; Stone, 1910), and bone fragments at Walnut Cove, but overall, the unit is poorly explored. Emmons (1852; 1856, 1857) described and figured semi-articulated tetrapod elements from the upper Pine Hall Formation near Germanton, at the southern end of the basin. Thayer (1970) and Thayer and others (1970) interpreted the Pine Hall Formation as a fluvial sequence with the coarser units being parts of alluvial fans originating along an eastern fault system, although given the curving geometry of the eastern margin, it is hard to see how there can be a major eastern border fault. Thayer and Robbins (1992) interpreted part of the formation as a braided stream deposit. The uppermost Pine Hall Formation as seen in the SO-C-1-81 and SO-C-2-81 cores consists of red mudstones with apparently pedogenic carbonate nodules and gray-green mottling associated with rhizomorphs (root traces). These primarily red beds are consistent with distal flood plain or marginal, very shallow water lacustrine environments. Pending detailed analysis, it is simplest to interpret the formation as a whole as fluvial in origin.

Walnut Cove Formation

The Walnut Cove Formation has produced a diverse but largely unstudied faunal assemblage. Bivalve mollusks have been found (by PEO) at one locality (36° 19.67' N, 80° 2.35' W) (uncataloged YPM invertebrate paleontology collection), and the unit has long been known for its conchostracans and ostracodes (Emmons, 1952), with *Anyuanestheria* (Kozur and Weems, 2007) and *Darwinula* being very common, respectively. A large suite of insect elements, largely wings and beetle elytra summarized by Huber and Fraser (1998) have been collected from the lower part of the formation (at approximately 36° 23.23' N, 79° 56.46' W) and reside as yet undescribed in the collections of the Virginia Museum of Science in Martinsville, VA. Generally isolated fish remains are common, and these are closely comparable to those from the Cumnock Formation of the Deep River Basin (Olsen and others, 1983), including the redfieldiid *Synorichthys* sp., and scraps of undetermined coelacanths as well as their presumed coprolites (Huber and Fraser, 1998). Phytosaur bones (uncataloged YPM collection) and teeth are not uncommon. Reptile footprints, tentatively assigned to *Apatopus* (Figure 9) and *Brachychirotherium* (P. Huber, pers. comm., 2014) have been found as well. Floral remains are largely undescribed, but include conifers, and pollen and spores (Robbins and Traverse, 1980; Robbins, 1985;

Robbins et al., 1988; Litwin and Ash, 1993), although preservation is poor. There is very little doubt that careful prospecting will yield much additional material.

The overall environmental context of the Walnut Cove and Cow Branch formations has long been recognized as lacustrine, and additionally that the lacustrine environment fluctuated from relatively deep to shallow and subaerially exposed (Emmons, 1852; Meyertons, 1963; Thayer, 1969, 1970; Thayer and others, 1970; Olsen and others, 1978, 1989, 1991; Thayer and Robbins, 1992, 1994; Fraser and others, 1996; Whiteside and others, 2011). Salient evidence for a primarily lacustrine, as opposed to marine or fluvial, environment for the Walnut Cove Formation includes the general evidence of largely suspension-dominated deposition (fine grain size and great lateral continuity of beds, see Fig. 7), coupled with the total absence of marine-restricted invertebrates and the presence of conchostracans and darwinulid ostracodes, which are characteristic nonmarine arthropods. The lacustrine facies alternate vertically between black to dark gray deeper water mudstone facies with high total organic carbon content (TOC up to 8%) that generally lack indications of subaerial exposure such as desiccation cracks, and lighter gray low TOC mudstones with abundant desiccation cracks, sometimes with tetrapod tracks (Fig. 9). A very distinctive facies, absent from the Cow Branch Formation, is a rooted dark gray or black mudstone, sometimes associated with thin overlying coal beds. These facies are present only in the lower Walnut Cove Formation and clearly represent swamp deposits. Another distinctive aspect of this formation is the previously mentioned lack of microlaminated mudstones and the correlated lack of articulated (as opposed to fragmentary) fish and insects.

Correspondingly, the lakes that deposited the Walnut Cove Formation never became deep enough, relative to their area, to perennially, chemically stratify, and sufficient oxygen and current activity reached the bottom, probably on a seasonal basis to prevent preservation of delicate, laterally-persistent laminae and articulated animals. The lower TOC mudstones, often with desiccation cracks, were deposited in even shallower water environments subject to at least occasional exposure to air. Sandstones present are usually associated with the shallower water mudstones and appear to be parts of very low relief sheet-deltas (e.g., Smoot, 1991). Paleomagnetic data indicate an equatorial position for the Dan River Basin during the early part of its depositional history (Kent and Tauxe, 2005), including the Walnut Cove Formation. As previously noted, the deeper water and shallower water facies alternate in a cyclical pattern, with thickness periodicities indicative of control by orbitally forced changes in insolation (Whiteside and others, 2011), with climatic precession being dominant.

Dry Fork Formation

To our knowledge, the Dry Fork Formation has produced no fossils except for the invertebrate trace fossil *Scoyenia*, undetermined coalified (Olsen and others, 1989) and silicified wood (Meyertons, 1963), and rhizomorphs (root traces: pers. obs.). Many outcrops in the northern Dan River Basin exhibit fining-upward cycles that often consist of gravel lenses with low-angle cross beds to large trough cross beds (J.P. Smoot, cited in Olsen and others, 1986), fining upward into dark gray, massive-appearing or trough cross-bedded, very coarse-grained sandstone, commonly containing scattered pebbles and cobbles (Thayer and others, 1970). These in turn grade upward into red or gray fine-grained sandstone, capped by red, massive, very fine-grained sandstone or siltstone (Thayer and others, 1970). The presence of fining-upward cycles, possible channel lag conglomerates, and dune-scale cross bedding suggests fluvial deposition (Thayer and others, 1970). The cycles are interpreted to be the result or channel filling and migration in a braided stream environment because of the high ratio of coarse to fine-grained rock, the wide range of grain sizes, and the presence of fining-upward sequences (Thayer *and others,* 1970).

One locality where the geometry of the strata can be seen is a 300 m along-strike exposure at the Chatham Quarry of the Vulcan Materials

Corporation (36.744221° N, 79.388819° W), superficially described in Olsen and others (1989). In general, bedding appears irregular and difficult to trace laterally due to large-scale channeling and small-scale faulting. Large-scale tilted surfaces and large channel-form lenses in pale gray to nearly white or light purple clastic rocks are observed in the quarry walls. Small-scale sedimentary structures seem mostly obliterated by intense bioturbation or diagenetic overprints, although locally abundant coalified wood and plant fragments are present. The geometry of the tilted surfaces suggests the possibility of delta foresets and the channel-form lenses, suggest downcutting streams. Overall, the exposures suggest fluvial to marginal lacustrine environments.

Less detail is known about the more southern areas of the Dry Fork Formation. However, temporary exposures in the vicinity of Eden exhibit sedimentary cycles consisting of gray thin-bedded mudstones grading upward into bioturbated red mudstones and sandstones (with *Scoyenia* and/or rhizomorphs). These suggest muted and shallow water lacustrine cycles that might be lateral to the deltaic and fluvial facies to the northeast, and like the sedimentary cycles of the Walnut Cove and Cow Branch formations, these were probably paced by orbital climate forcing.

COW BRANCH FORMATION

The Cow Branch Formation produced one of the earliest vertebrates from the basin, a partial skeleton of a phytosaur referred to *Rutiodon carolinensis* (Emmons, 1852), found in Eden, NC, near the bridge for Old State Highway 770 (probably at 36.504052° N, 79.757476° W). More recently it has produced a suite of remarkable invertebrate and vertebrate remains comprising a major North American Konservat-Lagerstätten (Olsen, 1988; Olsen and others, 1978; Olsen and Johansson, 1994; Fraser and others, 1996; Sues and Fraser, 2010; Fraser and Sues, 2011), diverse in both faunal and floral elements. The faunal assemblage comprises darwinulid ostracodes, the conchostracans *Euestheria ovata* and *Euestheria princetonensis* (Kozur and Weems, 2007), an unidentified shrimplike crustacean (Olsen and others, 1978), a remarkably diverse assemblage of insects (Olsen and others, 1978; Fraser and others, 1996; Grimaldi, and others, 2004; Blagoderov, and others, 2007; Kearns and Orr, 2009), several genera of fish (Olsen and others, 1978; Olsen and others, 1982), and abundant articulated tanystropheid reptiles (*Tanytrachelos*: Olsen, 1979; Casey at al., 2007), a very unusual gliding reptile, *Mecistotrachelos* (Fraser, and others, 2007), indeterminate phytosaur elements, and the reptilian ichnotaxa *Gynnedichnium*, *Apatopus*, possible *Atreipus*, and other dinosauromorphs (Olsen and Baird, 1986; Olsen and others, 1989). The faunal assemblage is especially notable for its diverse flies, extraordinary abundant water bugs, and soft tissue preservation including the skin of reptiles. The floral assemblage is notable for the abundance of large foliage remains and reproductive structures (Olsen and others, 1978; Cornet, 1993; Axsmith and others, 1997, 2013). The taxa include lycopods, scouring rushes, ferns, ginkgos, conifers, cycadeoids, cycads, and some undetermined forms. Pollen and spores have been recovered although like those from the Walnut Cove Formation, the preservation is poor (Robbins and Traverse, 1980; Robbins, 1985; Robbins et al., 1988; Litwin and Ash, 1993).

Beds of microlaminated (<1 mm thick laterally continuous laminae) mudstone and less well-laminated dark mudstone alternate with massive mudcracked mudstones form asymmetrical lithological cycles averaging about 9 m in thickness. The latter are very similar to those seen in the age-equivalent Lockatong Formation of the Newark Basin and which have been described in terms of a modal sedimentary sequence called a Van Houten cycle (Olsen, 1986) and ascribed to climatic precession-forced climate. Time series analysis of the Cow Branch Formation sequences (Whiteside and others, 2011) showed also that the Cow Branch Formation also exhibits a thickness periodicity corresponding to about one half a Van Houten cycle paced by hemiprecession, which should be expected from local insolation changes close to the equator. This "double cyclicity' is, however, much more strongly expressed than in the Cow Branch Formation than in the underlying Walnut Cove Formation.

A predominately lacustrine origin for the Cow Branch Formation is evident on the basis of the same criteria applied to the Walnut Cove Formation, especially the paleontological data. There is no evidence of marine influence, whereas a lacustrine deltaic and fluvial component is certainly present, especially near the base of the formation and where it is conglomeritic in proximity to the northwestern border fault system. The basic lithological pattern of the Cow Branch Formation is similar to that of the Walnut Cove Formation, varying between thin-bedded black organic-rich mudstones and mudcracked massive mudstones, except that microlaminated mudstones are a relatively abundant part of the dark mudstone end member. These microlaminated mudstones, as is typical for this kind of facies, produce a wealth of articulated vertebrates and continental arthropods, especially insects (Olsen and others, 1978; Fraser and others, 1976). Olsen and others (1978, 1986) argued that the microlaminated mudstones of the Cow Branch Formation were deposited by perennially chemically stratified lakes that were deep relative to their area, restricting the efficacy of wave mixing to the bottom (Olsen, 1991). The microlaminated mudstones were deposited in depths devoid of oxygen below the chemocline and where both bioturbation and physical disturbance were minimal. The characteristic preservation of complete, articulated vertebrates and arthropods is a feature many beds of this facies that have been examined in the largest significant exposures of this formation in the quarries of the Ararat Rock Products Co. (formerly Solite) in Eden, NC.

One particular microlaminated mudstone bed in the former Solite quarry has produced the famous Konservat Lagerstätte described by Olsen and others (1978) and Fraser and others (1996). The basal, roughly 3 cm of this bed is especially finely microlaminated and produces the bulk of insects and reptiles with soft tissue preservation (Olsen, 1979; Olsen and others, 1978). Liutkus and others (2010) interpret this interval as deposited by a shallow saline and alkaline lake during the initial stages of transgression over lake margin sediments affected by groundwater seeps, an interpretation significantly different from the stratified lake model for the same interval (e.g., Olsen and others, 1978). Although a detailed treatment of this interpretation is beyond the scope of this paper, we argue that such a special interpretation of this facies is unnecessary and not supported by available evidence or any modern analog environment. It is much more simply interpreted as a deposit produced just after transgression of the chemocline over normal shallower lake mudstones, when that particular geographic location was closest to shore and where preservation of articulated organisms and residues of soft tissue was possible (c.f., Olsen, 1978). Intervals bearing insects are present in other basal microlaminated beds within the former Solite quarry and the particular interval in question is not unique in what it preserves, but is unusual in often splitting along bedding on which the organic remains are preserved, allowing the soft tissue preservation to be seen. Very similar examples include numerous lacustrine Konservat Lagerstätte, such as the Eocene Green River Formation of the Western, USA (Bradley, 1948; Ferbera and Wells, 1995) and the Early Cretaceous Yixian of northeast China (e.g., Zhang and Sha, 2012).

Stoneville Formation

Despite covering much of the basin, the Stoneville Formation has hardly been prospected for fossils. Nonetheless, the burrow *Scoyenia* is abundant, conchostracans occur in some of the dark gray mudstones, and reptile tracks have been found (Fraser and Olsen, 1996: reported as Dry Fork Formation) and may be very widespread and diverse (e.g., Figure 9). Pollen and spores have been recovered (Litwin and Ash, 1993) and are better preserved than those described to date from the Cow Branch Formation. Thayer and others (1970) and Thayer and Robbins (1994) stressed that the presence of rhythmic sandstone-siltstone alternations comprising fining-upwards cycles in the largely red

Stoneville argued for fluvial deposition in high-gradient, low-sinuosity streams. The cyclical pattern of alternations of thin-bedded black to gray mudstones (that we interpret as deeper-water lacustrine deposits using the same criteria as for the similar Walnut cove and Cow Branch mudstones) with shallow-water deposits is prevalent in the Stoneville Formation as well, with the fluvial deposits stressed by Thayer and others (1970) and Thayer and Robbins (1994) occurring in the shallow water intervals of the cycles. Thus the pattern of cyclicity seen in the Cow Branch Formation continues up section into the Stoneville formation with an upward increase in the frequency of red shallow water and fluvial deposits, much like the transition between the Lockatong and overlying Passaic formations of the Newark Basin (Olsen and others, 1996).

Igneous Rocks

Numerous diabase (dolerite) dikes cross the basin and the strata are intruded by a small pluton or sheet near Renan, Virginia. All of these bodies belong to the Central Atlantic Magmatic Province (Marzoli and others, 1999). These intrusives have been discussed in general by Ragland and Puffer (1994), but to our knowledge there is no detailed study specifically on those intruded into the basin. Cummins (1987) and Gottfried and others (1991) provide geochemical data on diabase bodies in the Virginia part of the basin; nine of the ten sampled dikes are high iron, quartz normative (HFQ) tholeiites, the other being an olivine normative dike. The Renan pluton also has an HFQ tholeiitic composition. Given the minute volume of the basin occupied by these intrusive rocks their direct contact metamorphism is very limited, although their hydrothermal effect may have been more substantial.

AGE

Because of the stratigraphically extensive magnetostratigraphy available for the Dan River Basin, correlation to the other Newark Supergroup basins is secure (Figure 12). Based on correlation to the Newark Basin APTS, the numerical ages of the lithostratigraphic units are also well defined (Figure 12). However, the relative ages in terms of the marine, i.e., Tethyan, standard ages remain contentious (e.g., Muttoni and others, 2004; Olsen and others, 2010; Lucas and others, 2012; Ogg, 2012) and a resolution is well outside the scope of this work. However, three marine hosted U-Pb dates of middle to early Norian age (mostly based on conodonts) are 223.8±0.74 and 224.47±0.29 from British Columbia (Diakow and others, 2012), and 225±3 Ma from Alaska (Gehrels and others, 1987), ruling out a Carnian-Norian boundary age younger than 225 Ma. Taken together with a late Carnian (late Tuvalian, based on conodonts) U-Pb age of 230.91±0.33 from marine strata in Italy (Furin and others, 2006), the Carnian-Norian boundary must be between 225 and 231 Ma. Of the two options for the length of the Norian (Ogg and others, 2012), the so-called “short” and “long Norian”, these data are only compatible with the long Norian option. Correlation of the U-Pb dated Italian section to the Newark Basin APTS suggests the Carnian-Norian boundary should be between Newark Chrons E5r and E7n (Furin and others, 2006). An independent Panthalassan (Japan) astrochronology correlated to the Tethyan section by conodonts suggests the Carnian-Norian boundary should correlate to Newark Chron E8r at 225 Ma (Ikeda and Tada, 2014), which also is consistent with the long Norian option. In any case, either the base of the Walnut Cove Formation is at the Carnian-Norian boundary age, or well within the early Norian (whether D01 correlates to E8n or E7n). Therefore, virtually the entire stratigraphy of the Dan River Basin is early to middle Norian in age (Pine Hall to lower Stoneville formations), and may possibly into the Rhaetian age (upper Stoneville Formation), with Carnian age strata are absent or virtually absent. This also means that the famous “Solite” biotic assemblages are of Norian and, not Carnian as is usually stated (e.g., Olsen and others, 1978, 1989; Fraser et al., 2007).

The CAMP intrusive rocks of the Dan River Basin have not been directly dated, although if they are like other North American CAMP rocks, they were emplaced within a 1 million year period at around 201 Ma (Olsen and others, 2003b), straddling the latest Triassic-Jurassic boundary (Olsen and others, 2003b; Blackburn and others, 2013). A few of the dikes cross the basin border fault without apparent displacement (Figures 2, 3), which if mapped correctly may indicate emplacement after subsidence and inversion ceased (e.g., Withjack and others, 2012a, b) ceased.

ECONOMIC GEOLOGY

Potential and realized economic resources of the Dan River Basin include crushed stone, light weight aggregate (expanded shale), clay (from weathered mudstone), uranium (actually from the footwall rock on the border fault system) coal, and shale gas. The former four resources have been reviewed by Thayer (1970), Thayer and others (1970, 1994), and Stone (1910) and will not be dealt with here. The potentially very important Coles Hill Uranium Prospect is located in the foot wall of the Chatham Fault on the northwest side of the Virginia segment of the Dan River Basin, with the primary host rock being gneissic-porphyritic to schistose metamorphic rocks of the Smith River Allochthon. While strictly not within the rift basin proper, its direct contact with the sedimentary rocks of the basin suggests a potential genetic relationship. Yet, despite its potential economic importance and its discovery more than 35 years ago (Dribus, 1978), this deposit has not been the subject to a comprehensive scholarly analysis, although it has been discussed in several short presentations, reports, and masters theses, as well as a National Academy of Sciences study that dealt primarily with socio-economic and environmental issues (e.g., Wales, no date; Christopher, 2007; Wyatt, 2009: and Committee on Uranium Mining in Virginia; Committee on Earth Resources; National Research Council, 2011). We note that minor enrichments of uranium occur along the unconformable basin contact with the pre-Triassic, along hornfelsed contacts between sediments and diabase dikes, and within cyclical stratigraphic intervals of interbedded black mudstones and red sandstones in the Stoneville Formation (Dribus, 1978). Because the present paper deals with the sedimentary geology of the basin, in particular the shale-rich Walnut Cove and Cow Branch formations, additional discussion of the hydrocarbon potential of the basin is in order.

Oil and gas potential

The economic hydrocarbon potential of the Dan River Basin was assessed by the U.S. Geological Survey (Milici and others, 2012) as part of a review of potential oil and gas resources of the East Coast Mesozoic basins of the Piedmont, Blue Ridge thrust belt, Atlantic Coastal Plain, and New England provinces. The source rock rocks with the potential to have yielded oil and gas in this and other eastern U.S. Mesozoic basins include the gray and black mudstones and coal beds. Most of the high TOC mudstones accumulated in deeper lacustrine environments, with the obvious exception of the carbonaceous mudstones and coal beds that accumulated in swamps and shallow lakes. Kerogen (non-soluble organic matter) in the mudstones originated from vascular plants and microbes that had the potential to form both oil and gas. Thayer and others (1982) suggested that any petroleum and gas that was generated in the rift basin was later destroyed by high heat flow supported by sparse published TOC (Thayer and Robbins, 1992) and thermal maturity data (Maliconico, 2002). The average total organic content (TOC) of the Walnut Cove Formation is 3.55% (n=122) from outcrop and three diamond drill holes. Its %Ro is 1.85 (n=23). The TOC for the Cow Branch Formation is 1.38% (n=42) from a continuous quarry section. Its %Ro is 2.08 (n=25) (Reid and Taylor, 2013). These data indicate the Triassic strata are within the dry gas window. Bitumen found in a number of samples during organic petrographic analysis indicates a thermal evolution path that passed through the oil window and ended in the preserved dry gas window.

Potential reservoir rocks in the Dan River Basin could include diverse lithologies such as boulder conglomerates, very coarse sandstone, mudstone, and coal. Mudstone units that are interbedded with coarse-grained strata could be seals. The organic-rich mudstone units themselves could be reservoirs accessible via hydraulic fracturing. The 2011 U.S. Geological Survey numerical resource assessment of the Dan River-Danville "Continuous Gas Assessment Unit" indicated a mean of 49 BCFG (billion cubic feet gas) and no natural gas liquids (NGL) (Milici and others, 2012). Milici and others (2012) supply a range of values estimated for BCFG and NGL. However, this assessment made use of data available in 2011 and did not include more recent N.C. Geological Survey organic geochemical data.

IMPLICATIONS

A particularly interesting aspect of the Dan River Basin is the combination of sedimentary units resembling both more northern basins (i.e., Lockatong and Passaic formations of the Newark Basin) and more southern basins (Cumnock Formation of the Deep River Basin). Especially for the temporally overlapping Newark Basin section, there is well developed magnetostratigraphy (Kent and Olsen, 1997; Figures 5, 7, 10), allowing a qualitative understanding of the tectonostratigraphic development of the Dan River Basin as well a quantitative comparative assessment of the changes in accumulation rate in the basin.

Tectonostratigraphic Evolution of the Dan River Basin

Olsen (1997), modified by Olsen and others (2003a; 2008) and Medina and others (2011), recognized 4 major tectonostratigraphic sequences (TS-I – TS-IV) within the basins of the conjugate central Atlantic margin (CAM). These tectonostratigraphic sequences consist of at least partially unconformity-bound sequences (Olsen, 1997) that may pass into correlative conformities towards the basin depocenters. Although deducible on the basis of either lithological pattern or biostratigraphy, the correlation of the magnetostratigraphy to the Newark APTS clearly shows that the entire sampled stratigraphy of the Dan River Basin belongs to TS-III (Figure 12). This sequence, where completely preserved, spans the early Norian to the late Rhaetian and is the most widespread of the four tectonostratigraphic sequences in eastern North America and Morocco. That said, it is clearly possible that, lacking data from the lower tow-thirds of the Pine Hall Formation, part of the latter could belong to the next lower tectonostratigraphic sequence, TS-II.

The Dan River Basin sequence thus resembles the Culpeper and Gettysburg basin sequences that lie along strike, that do preserve a very small part of TS-II, contrasting with the Newark Basin and most of the other larger CAM basins that have a thick TS-II sequence (Olsen, 1997; Sues and Olsen, 2014). This plausibly indicates that the strands of faults marking the southern segment of the western boundary of the Triassic-Jurassic rift basin complex were not particularly active until well into the rifting history of the CAM complex.

Unlike the other major basins to the northeast along strike, the Dan River Basin does not preserve any of TS-IV, including the lava flows of the Central Atlantic magmatic province. On the other hand, much of the sequence exhibits high thermal maturity as indicated by both pollen and spore preservation (Robbins and Traverse, 1980; Litwin and Ash, 1993) and vitrinite reflection (Maliconico, 2002). Because large intrusive bodies that could have supplied the heat are not preserved, a much greater thickness of strata may have originally been present but subsequently eroded away. If true, the Dan River Basin may be but a narrow erosional remnant of what was an originally much larger basin.

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