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Stratigraphic Influence on Deep Groundwater Flow in the Knox Group Copper Ridge Dolomite on the West Chestnut Ridge Site

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STRATIGRAPHIC INFLUENCE ON DEEP GROUNDWATER FLOW IN THE KNOX GROUP COPPER RIDGE DOLOMITE ON THE WEST CHESTNUT RIDGE SITE

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ABSTRACT

The Copper Ridge Dolomite of the Upper Cambrian Knox Group underlies a site at Oak Ridge, Tennessee under consideration by the Department of Energy (DOE) for a belowground waste disposal facility. The Copper Ridge was studied for DOE to understand the influence of lithology on deep groundwater flow. Three facies types are distinguished which comprise laterally continuous, 1 to 4-m-thick rock units interpreted to represent upward-shallowing depositional cycles having an apparently significant effect on groundwater flow at depth.

Rock core observations indicate one of the recurring facies types is characterized by thin to medium-bedded, fine-grained dolostone with planar cryptalgal laminae and thin shaley partings. Distinctive fracturing in this facies type, that may have resulted from regional structural deformation, is considered to be responsible for weathering at depth and the development of stratabound pathways of preferred groundwater flow. In addition, geophysical data suggest that one occurrence of this weathered facies type coincides with an apparent geochemical interface at depth. Geophysical data also indicate the presence of several fluid invasion horizons, traceable outside the study area, which coincide with the unweathered occurrence of this fine-grained facies type.

The subcropping of recurrent zones of preferred groundwater flow at the weathered/unweathered interface may define linear traces of enhanced aquifer recharge paralleling geologic strike. Vertical projection of these zones from the weathered/unweathered rock interface to the ground surface may describe areas of enhanced infiltration. Tests to determine the role of stratigraphic controls on groundwater flow are key components of future investigations on West Chestnut Ridge.

1. INTRODUCTION

The Department of Energy (DOE) is considering locations on the Oak Ridge Reservation (ORR) in Oak Ridge, Tennessee for the development and demonstration of new technologies for belowground waste disposal facilities. To assist DOE in its decision-making process to locate a suitable site, a rock coring and geophysical logging study was undertaken on West Chestnut Ridge on the ORR to develop increased understanding of saturated groundwater flow through weathered and unweathered bedrock beneath the proposed site.

Previous studies have determined that West Chestnut Ridge is potentially suitable for a belowground waste disposal site due to its comparatively thick residual soil and depth to the water table. This report describes the results of the rock coring and geophysical logging study and presents some geologic findings that provide qualitative insight into groundwater flow in the weathered and unweathered bedrock at the proposed West Chestnut Ridge site.

This report will describe the apparently controlling influence of stratigraphy on deep groundwater flow in the Copper Ridge. Specifically, it will describe detailed rock core characteristics used to define three facies types in the Copper Ridge which are interpreted to comprise laterally continuous, 1 to 4-m-thick, upward-shallowing cycles. Fracturing and weathering of one facies type in the cycles, and a distinctive lithologic characteristic within that facies type, coincides with geophysical data which will be shown to suggest the occurrence of thin stratabound pathways for preferred groundwater flow to depth. One of these pathways will also be shown to coincide with an apparent geochemical interface at depth. Finally, the relationship between stratabound flow pathways and both aquifer recharge and infiltration will be discussed.

2. TECHNICAL APPROACH AND DATA ACQUISITION

Core was obtained for this study to examine detailed lithologic features contributing to groundwater movement in the Copper Ridge. Coring was planned at five locations that together would provide a continuous stratigraphic section of the upper Maynardville Limestone and the Copper Ridge Dolomite from staggered positions normal to geologic strike at the proposed West Chestnut Ridge site (Fig. 1). Drilling locations and depths were estimated based on knowledge of geologic structure and stratigraphy from previous studies.

Coring utilized 3.7-in-OD carbide or diamond impregnated steel rotary drill bits, and 4-in steel drill surface casing was set at the first (shallowest) occurrence of competent, unweathered rock. NC gauge core was extracted in 10-ft intervals and loaded immediately into core boxes with drilling depths marked on each core box. Freshwater drilling fluid was obtained from a small impoundment in nearby Grassy Creek and pumped through 1-in-diameter PVC lines to the coring locations. Drilling continued for five months from May until September, 1986.

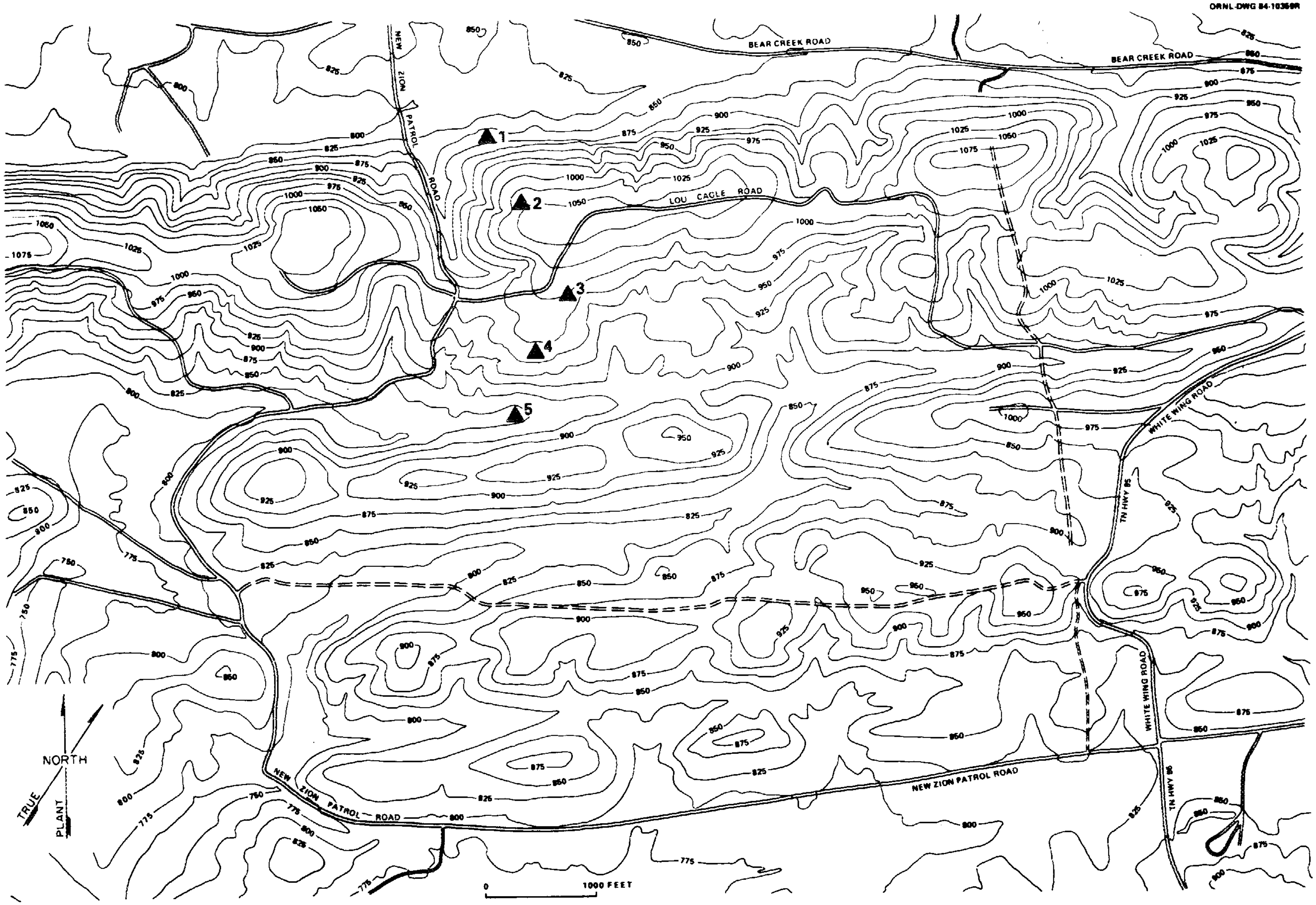

Fig. 1. West Chestnut Ridge site core hole locations.

Coring difficulties developed in the third core hole. Fractured and cavitose weathered rock was almost continuously encountered to a drilling depth of 210 ft. Drilling fluid circulation was also lost throughout the cored interval, presumably through the fractures and cavities. Core recovery was poor to nonexistent, consisting of large rock fragments and smaller cobble-sized rock. Measures to stabilize previously-drilled fractured rock by grouting the core hole prior to redrilling were unsuccessful. Fragmented rock dropped into the hole above the drill bit and created a potential for cutting the drill rods and losing the drill bit. For this reason, since insufficiently competent rock was available to emplace casing and since drilling fluid continued to be lost, the core hole was abandoned. Extracted core was heavily fractured, fragmented, and contained iron oxide staining on the fracture faces considered to represent weathering through the fracture and cavity network.

In core holes 4 and 5, 6-in air rotary drilling down to unweathered, competent rock was used in an attempt to minimize repetition of conditions encountered in core hole 3. This measure enabled 4-in. surface casing and grout to be emplaced down to competent rock for successful redrilling and core extraction.

3. PHYSIOGRAPHY AND REGIONAL GEOLOGY

The Oak Ridge Reservation (ORR) in eastern Tennessee is in the Valley and Ridge Physiographic Province of the Appalachian Highlands (Fig. 2). The Valley and Ridge is characterized by elongated alternating valleys and ridges formed subsequent to the Appalachian Orogeny. Chestnut Ridge is a northeast--to-southwest-oriented linear topographic high within the Valley and Ridge. On the ORR it consists of three discontinuous ridge lines with maximum elevations of from 280 to 320 m (920 to 920 ft) and ridge crest to valley floor relief from 30 to 68 m (100 to 225 ft). Valley drainage is from ephemeral streams within an overall weakly-developed trellis drainage system. Karst development contributes to surface drainage.

The ORR is underlain by Cambrian and Ordovician age clastic and carbonate rock units. A generalized stratigraphic column (Table 1) illustrates the mappable rock units comprising and immediately surrounding Chestnut Ridge. A geologic map of the ORR (Fig. 3) illustrates that regional geologic structure is characterized by imbricate thrust faults, trending N 45° to 65° E, with regional dip typically about 30° southeast varying locally from 20° to more than 45°. An idealized geologic cross section across the ORR (Fig. 4) shows the position of West Chestnut Ridge within the Whiteoak Mountain thrust sheet.

4. LITHOLOGIC DESCRIPTION

This section will present the detailed lithologic characteristics used to define three basic facies types that comprise cyclic rock units

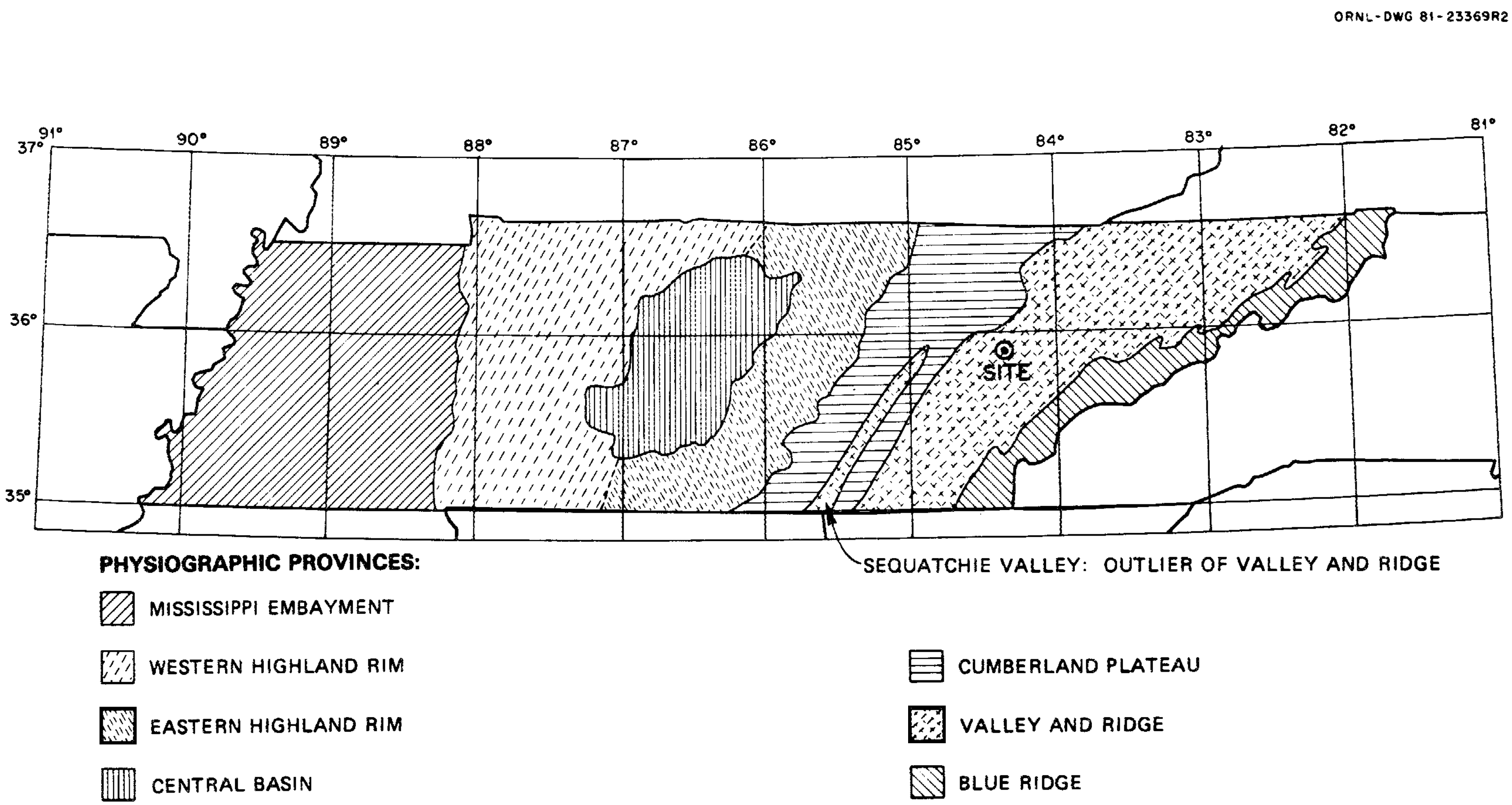

Fig. 2. Physiographic map of Tennessee.

Table 1. **Stratigraphic column of bedrock formations on the West Chestnut Ridge site**

System	Group	Formation	Estimated thickness	Description
Ordovician	Chickamauga	Undivided		Thin to medium-bedded, cherty carbonate lithologies. Maroon mudstone and argillaceous limestones.
	Knox	Newala	275 m (900 ft)	Medium-bedded dolostones and limestones with variable chert content, scattered chert matrix sandstones. Abundant maroon mottling in carbonates. Thin soil development.
		"Longview"	15 m (50 ft)	Dense massive chert, bedded chert, and dolomoldic chert observed in residuum.
		Chepultepec Dolomite	215 m (700 ft)	Fine to medium-grained, light to medium gray, crystalline dolostone, medium to thick-bedded where observed, sandy in part, particularly near base. Minor maroon mottling appears near top. Thin to thick soil development.
Cambrian		Copper Ridge Dolomite	300 to 400 m (1000 to 1300 ft)	Medium to thick-bedded, fine to coarse crystalline dolostone, medium to dark gray chert varies from massive porcellanous near base to blue-gray oolitic in upper 1/3 of the unit. Thin to thick soil development.
	Conasauga	Maynardville Limestone	60 to 90 m (200 to 300 ft)	Medium-bedded, light to dark gray, fine crystalline to oolitic limestone. Moderately thick soil development.

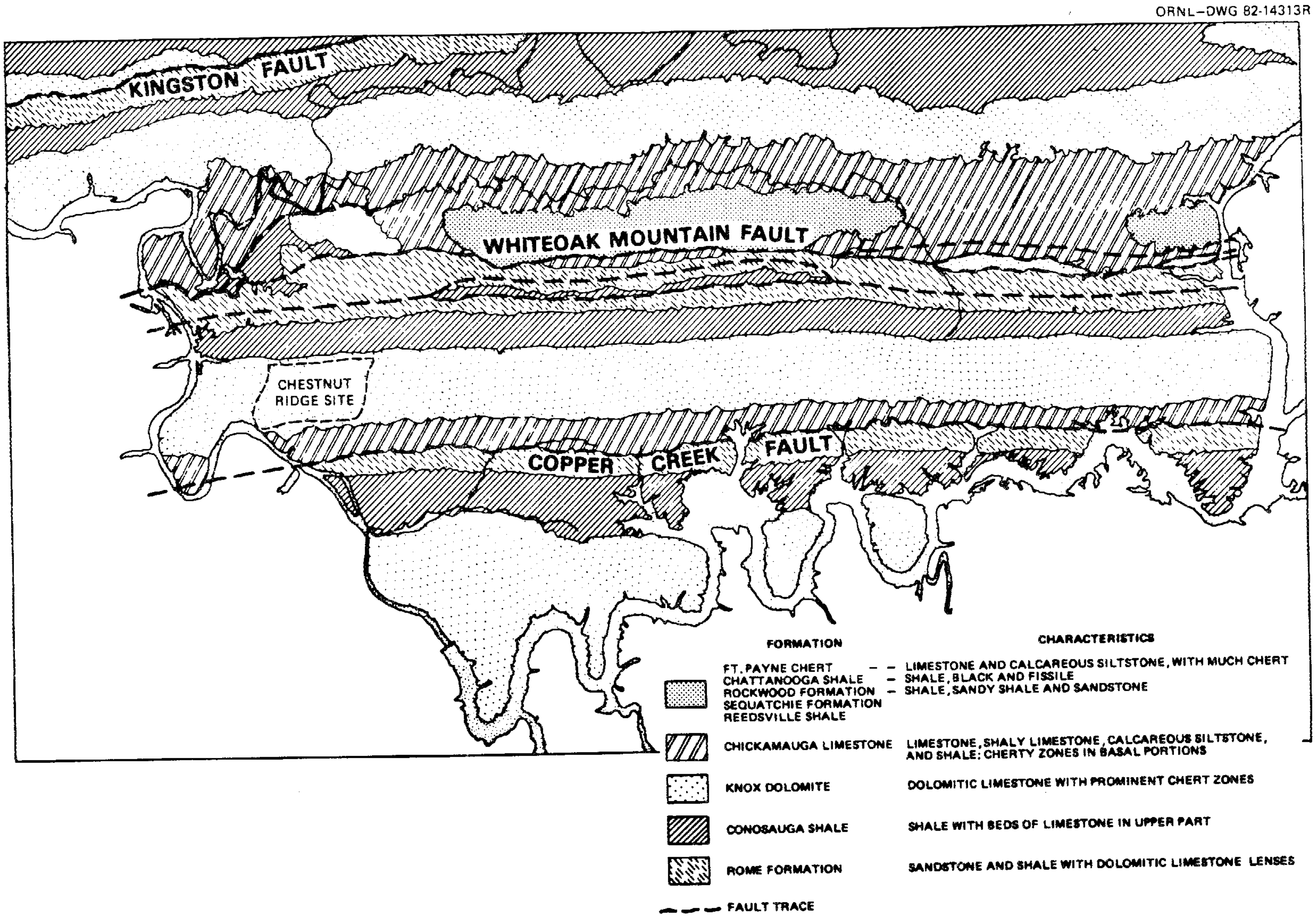

Fig. 3. Geologic map of the Oak Ridge Reservation.

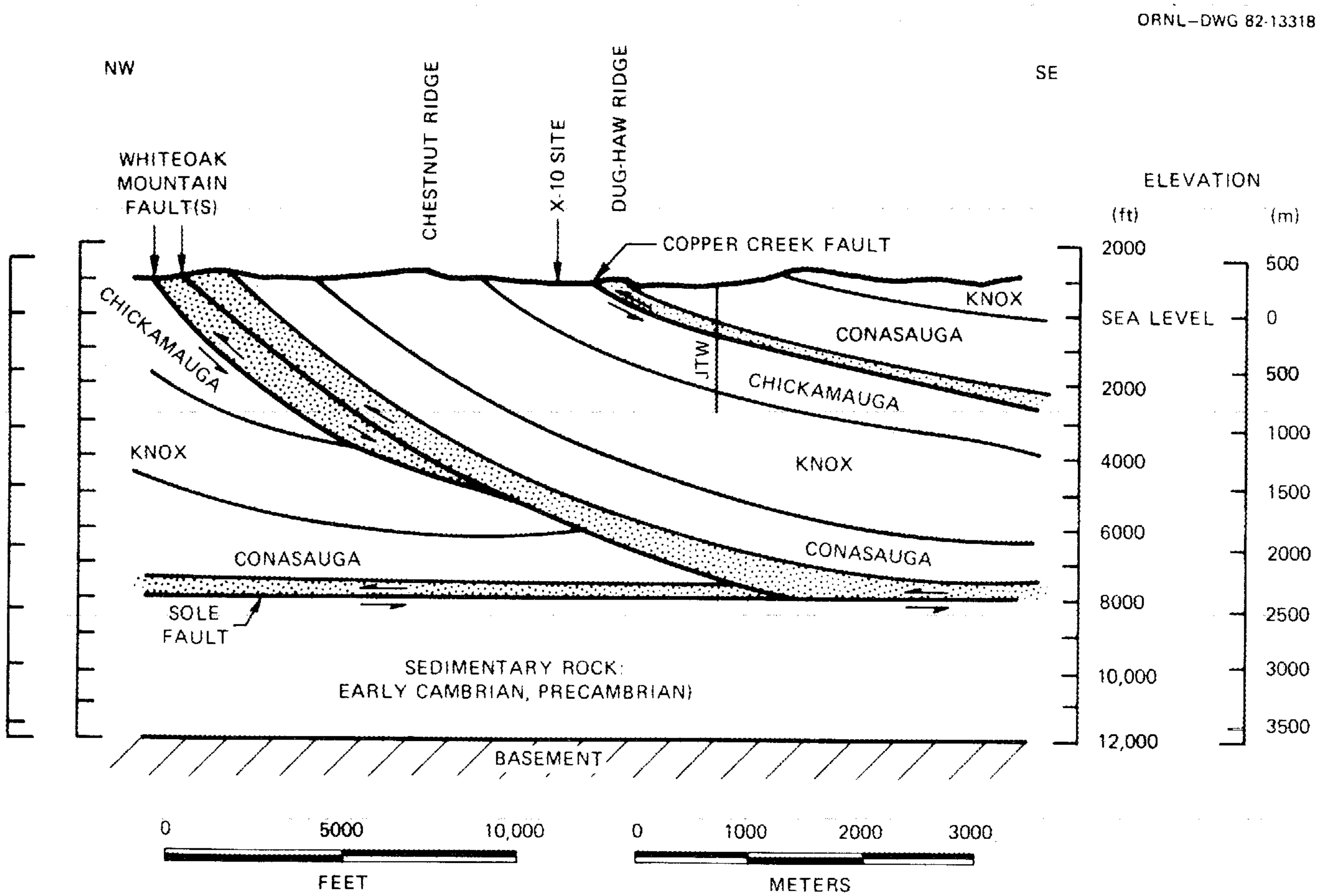

Fig. 4. Geologic cross section of the Oak Ridge Reservation.

in the Copper Ridge. Both the overall cyclic nature of the Copper Ridge and the frequency of occurrence of each facies type within the cycles are important to the understanding of groundwater flow. Primary and secondary lithologic features of one facies type (facies type 1) will be shown in subsequent sections of this report to be directly related to groundwater flow to depth.

Units for stratigraphic position and core thickness are reported in downhole feet. This convention allows more ready comparison of stratigraphic position both between cores and between core and geophysical logs.

4.1 CORE DESCRIPTION

The results of drilling provided a nearly complete, spatially discontinuous stratigraphic section of the upper Cambrian Knox Group Copper Ridge Dolomite. Bedding dip ranges between 32° and 40° decreasing down the core. The Copper Ridge is a thick, megascopically monotonous accumulation of generally fine to medium-grained, buff, light gray, and dark gray dolostone. With the exception of stratiform and columnar stromatolites, to be discussed later, it is uniformly devoid of fauna. Primary sedimentary structures are limited to occasional faint, low-angle cross laminae. Black, blue, and gray to buff chert occurs commonly throughout the formation. Large (>1 mm) oolites occur in roughly the upper and lower thirds of the section, often in conjunction with replacement chert.

The differentiation of the Copper Ridge into locally mappable upper and lower members (see Rodgers, 1953 and Bridge, 1956) is generally supported by this study. Although exceptions occur and will be discussed more fully later, the thick lower portion is generally darker gray and more massively bedded than the thin, lighter gray and more thinly bedded upper portion. The reported asphaltic nature of the lower portion is not striking but can be recognized when water on core beads up around isolated asphaltic points.

For several hundred feet near the top of core 2, repetitious 5 to 10-cm-thick, buff colored, jagged-edged features occur in otherwise dark gray, medium-grained dolostone giving the core a mottled appearance. The features are unconfined by, and appear to be unrelated to, detailed facies boundaries and possess no features readily attributed to drilling. Their buff color suggests weathering, but their jagged, discontinuous edges sharply crossing detailed facies boundaries argues against such an explanation. However, because the occurrence of these features is limited to the shallow portion of the core and for lack of a more satisfying explanation, they are suspected to represent an initial phase of weathering.

Detailed core examination reveals substantial internal facies variation within the generally monotonous Copper Ridge. Three basic facies types are recognized that form repetitive, asymmetric, upward-shallowing cycles on a 1 to 4-m scale. Cycles are internally gradational and commonly contain only two of the three facies types. Transgression is recognized as a bedding plane of nondeposition or erosion separating aggradational cyclic deposition. Similar cyclicity has received extensive treatment in the literature (i.e. Aitken, 1966; Wilson, 1967; Mossop, 1973; Read, 1973; James, 1979; Goodwin and Anderson, 1985; and Grotzinger, 1987).

In the Copper Ridge core, cycles are most easily recognized when composed of distinct facies types and in core from near the weathered/unweathered interface where weathering enhances facies distinctions. When facies type distinctions are minor, and in deeper portions of the core unaffected by near surface weathering, cycles are more cryptic.

Cycles containing similar combinations of facies types recur throughout the section, each cycle possessing a nearly unique signature that distinguishes it from others. In addition, the typical occurrence of incomplete cycles complicates cycle interpretation and illustration. Therefore, an idealized cycle is presented in Fig. 5 which includes paleoenvironmental interpretations for each facies type within the overall shallow marine, peritidal Copper Ridge depositional setting. In Fig. 5 the bottom of the overlying cycle and the top of the underlying cycle are included to illustrate the diversity of characteristics that define each facies type. Portions of the overlying and underlying cycles are included in Fig. 5 to illustrate that criteria used to define one cycle may not necessarily apply to those adjacent to it. Table 2 summarizes the lithologic characteristics comprising each facies type and their respective paleoenvironmental interpretations. Illustrations of representative cycles will be provided as examples in a subsequent section of this report.

Facies type 1 forms the cycle tops in several distinct portions of the section principally in the upper Copper Ridge. It is a medium-bedded, fine-grained to aphanitic, light gray dolostone weathering buff. Cryptalgal laminites and fenestral fabric occur commonly, particularly in the upper portion of the section. Obscure vertical burrows or dewatering features may occur. Shale occurs almost exclusively in this facies type as discrete thin beds, densely arrayed partings, or distinct thin irregular partings. Flat-pebble breccia, consisting of small angular or elliptical intraclasts, occurs when the facies is well-represented in the section. Thin oolitic zones are common, but unlike those in facies type 3, they are seldom associated with chert occurrence. Chert is most often light gray, buff when the facies type is weathered buff, or blue and occurs in thin (roughly 2 to 5-cm-thick) zones. This facies type is interpreted to represent upper intertidal to supratidal deposits that may include tidal pond deposits.

Facies type 2 occupies the middle position in the idealized cycle but in different portions of the section may also form the bottom or top facies in the cycle. It is fine to coarse-grained. When coarse-grained and overlying facies type 3 deposits at cycle tops, it is dark gray; when fine-grained and underlying facies type 1 deposits at cycle bottoms, it is typically lighter gray. The facies type is quite uniform internally, current-winnowed, and possesses few internal features beyond an occasional hint of small-scale, low-angle, cross lamination. Discrete chert lenses or beds are lacking. Environmentally shallower than facies type 3, subject to the effects of current

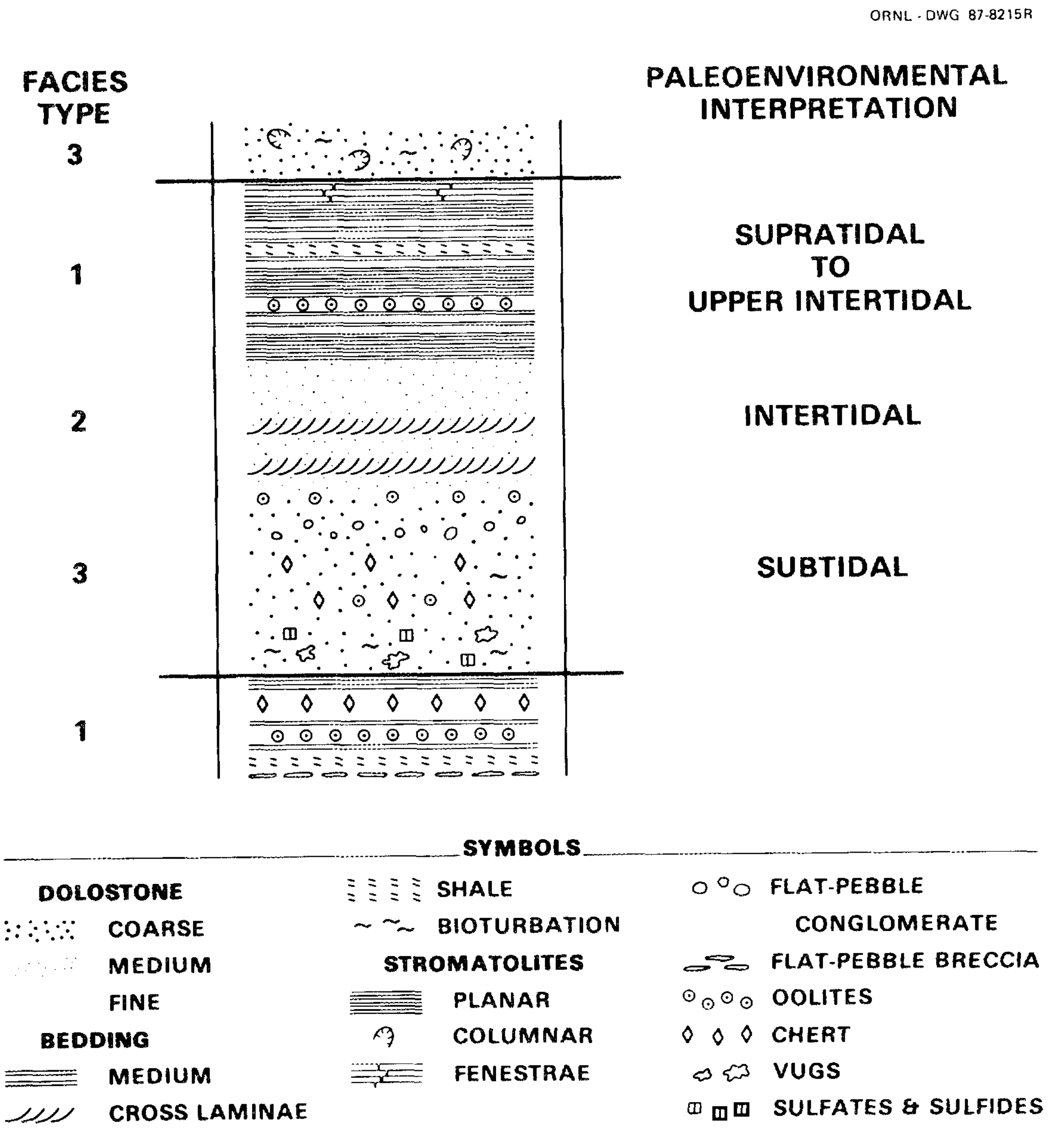

Fig. 5. Idealized Copper Ridge Dolomite upward-shallowing cycle.

Table 2. Lithologic features of Copper Ridge Dolomite facies types

Facies type	Lithologic features	Paleoenvironmental interpretation
1	Medium-bedded, fine-grained to aphanitic, light gray to buff dolostone. Thin shale lenses and beds. Thin light gray, blue, and buff chert lenses. Small flat-pebble breccia. Oolites. Fenestral fabric and cryptalgal laminites.	Lower supratidal to Upper intertidal
2	Massive, coarse- to medium-grained, dark to medium gray dolostone. Current laminae. Well sorted.	Lower intertidal to Upper subtidal
3	Massive, coarse-grained, dark gray dolostone. Bioturbated or crudely laminated. Columnar stromatolites, occasionally detached. Black chert beds and nodules, large oolites, vugs, sulfate and sulfide minerals. Large flat-pebble	Subtidal

action, this facies type is considered to represent upper subtidal to lower intertidal deposits.

Facies type 3 occurs most frequently in the lowermost portion of the Copper Ridge. It is generally coarser grained than facies types 1 and 2, dark gray, massive, and bioturbated or crudely laminated when containing large (>1 mm) pellets or oolites. In one distinctive portion of the section, the facies type is characterized by relatively thick accumulations of columnar stromatolites similar to those described in the upper Knox Mascot Dolomite (Harris, 1969). Large flat-pebble conglomerate may occur throughout the facies type. Chert is typically porcellanous, black, and occurs as distinct 5 to 10-cm-thick zones often replacing oolites or as roughly 10-cm- diameter nodules. Sulfate and sulfide minerals occur infrequently in a limited portion of the section. Large (>1 cm) vugs often containing well-developed replacement dolomite rhombohedra are common. This facies type is considered to represent restricted subtidal deposits below and near the lower reaches of wave base.

4.2 OUTCROP DESCRIPTION

Reconnaissance-level observations were made of the Copper Ridge from two nearby outcrops, one along geologic strike roughly 19 km (12 miles) to the northeast along the Clinch River, and the second from an outcrop in the next thrust sheet to the northwest, the Kingston thrust sheet. Outcrops were visited to determine the extent to which weathering might enhance lithologic features less evident in freshly drilled and unweathered core.

Outcrop mapping exceeded study limitations but the locations were visited to investigate the cyclic nature of the Copper Ridge. This reconnaissance-level investigation indicates that cycle identification is enhanced by weathering to the extent that many cycles, difficult to define in core, are more readily identified in outcrop.

Facies types 2 and 3, protruding from the plane of the outcrop, are massively bedded to blocky and appear to be relatively resistant to weathering. The fine-grained facies type 1 is distinguished by thin to medium-bedding, weathering enhancement of cryptalgal laminites and shaley partings, and nearly ubiquitous fractures normal to bedding. In general, the fine-grained facies appears to be more weathered and is eroded behind the plane of the outcrop.

5. STRATIGRAPHY

This study applies an episodic stratigraphic model to accomplish physical stratigraphic correlation. The interpreted peritidal deposits of the Copper Ridge are conducive to the application of the model in that relatively small changes in base level in the paleodepositional setting are seen commensurately as distinct vertical facies changes in the stratigraphic record. The model (Goodwin and Anderson, 1985) assumes that cycles represent gradual, upward-shallowing deposition (aggradation) during periods of slightly lowering or static base level and are separated by nondepositional or erosional discontinuities representing relatively rapid base level rise (transgression). For purposes of stratigraphic correlation, these discontinuities represent geologically instantaneous events that enable precise physical correlation to the bedding plane level. Similar cycles in the overlying Chepultepec Formation in Virginia are considered to be relatively synchronous over large areas (Bova, 1982).

Stratigraphic overlap was achieved between core holes 4 and 5 for a coring interval of 162 ft and between core holes 3 and 4 over the 210 ft interval of hole 3. Since core recovery in core hole 3 was poor to nonexistent, extracted core is extremely weathered and fractured, and geophysical logging tools could not be lowered into the core hole, detailed stratigraphic correlations cannot be reliably conducted over this interval. In holes 4 and 5, acquisition and detailed observation of rock core allowed for excellent correlation to be achieved beyond that available from geophysical logs alone.

The contact between the Copper Ridge and the overlying Chepultepec Dolomite has not been definitively located from the core; however, circumstantial evidence suggests it is near the top of core hole 5 at about 300 ft below ground surface. This is of some note because scaled, cross-sectional drawings of stratigraphic thickness taken from core indicate the Copper Ridge to be roughly 1425 ft thick on West Chestnut Ridge, in contrast to the maximum reported regional thickness of 1100 ft (Rodgers, 1953) and the thickness of 907 ft (Bridge, 1956) at the classic Thorn Hill section northeast of the ORR. No evidence of thickening as a result of structural deformation was found to explain the unusually thick section in the study area.

Rodgers (1953) places the formational contact below a thick (> 1 m) sandstone bed but above oolitic chert beds. Walker (1985) also describes arenaceous dolostone, oolites, and oolitic chert at the top of the Copper Ridge which are absent in the lower Chepultepec. Outcrop examination on the same thrust belt 19 km (12 miles) to the northeast, where the sand bed is covered, and from the Kingston thrust sheet, where the sand is well exposed, supports these descriptions. Thin sand lenses first appear roughly 30 m (100 ft) below the contact, and oolitic chert, common in the upper Copper Ridge, is not recognized above the formational contact.

In core, the prominent sand bed described by Rodgers (1953) was not recovered. The uppermost oolitic zone occurs roughly 30 m (100 ft) below the top of core, a thin sand lense occurs roughly at the same horizon, and a massive blue chert occurs roughly 15 m (50 ft) below top of core. Above the chert is coarse, granular, bleached, and weathered dolostone; granular uncemented chert grains; and unrecovered cavities. Oolites are absent. This evidence suggests that the stratigraphically lowest position for the selection of the formational contact is within the granular, weathered material.

6. RELATIONSHIP BETWEEN GROUNDWATER MOVEMENT AND STRATIGRAPHY

This chapter will present evidence from rock core observations and geophysical log analysis that relates groundwater movement in the Copper Ridge to the recurrence of stratigraphically correlative facies type 1 deposits. Specifically, fracturing and weathering at depth occur solely in facies type 1 deposits. Similar fracturing and weathering in facies types 2 and 3 deposits are limited to occurrences near the weathered/unweathered interface and when bounded by weathering of facies type 1. The frequency of geophysical evidence of fluid invasion is significantly higher in facies type 1 deposits than in facies types 2 and 3 combined. Fluid invasion of facies type 1 deposits is also stratigraphically continuous; whereas, fluid invasion of facies types 2 and 3 appears to be stratigraphically localized.

6.1 PREVIOUS GROUNDWATER STUDIES ON WEST CHESTNUT RIDGE

Ketelle and Huff (1984) and Pin et al. (1984) report representative hydraulic conductivity in unweathered rock on West Chestnut Ridge to be 1 x 10E-4 cm/s, which is similar to the measured hydraulic conductivity in the overlying weathered rock. The unweathered rock permeability is attributed to flow in fractures and/or open bedding planes.

6.2 CORE HOLE GEOPHYSICAL LOGS

Selected geophysical logs were obtained from holes 1, 2, 4, and 5. Because fractured and fragmented rock in the core holes jeopardized retrieval of geophysical logging tools, geophysical logging was limited to those logs that might be of most use in understanding groundwater movement and to logging tools that would not become stuck in the holes. Gamma ray, spontaneous potential, fluid resistivity, and long/short normal resistivity logs were obtained.

6.2.1 Long/Short Normal Resistivity Logs

Long/short normal resistivity geophysical logs provide information regarding the hydraulic conductivity of rock units. Separation between the long and short normal resistivity log traces indicates fluid invasion of the logged interval (Asquith, 1982). In the Copper Ridge long/short normal resistivity trace deflections occur in areas representing both primary and secondary lithologic features.

Provided below are examples of the dominantly recurring secondary lithologic features exhibiting significant long/short normal resistivity deflections and their associated primary lithologic features. Each example is accompanied by a figure illustrating the long/short normal resistivity anomaly, its correlative gamma ray log trace, and a lithologic drawing of a representative cycle within the illustrated interval.

Figure 6 shows a major long/short normal resistivity anomaly in core hole 2 between 690 and 640 ft. The interval is dominated by cycles with thick accumulations of facies type 3 containing extensive unremineralized, cm-scale vugs overlain by thin, medium-grained facies type 2 deposits. The lack of character of the gamma ray trace illustrates the overall facies uniformity in this portion of the Copper Ridge. The long/short normal resistivity anomaly is presumed to be identifying fluid invasion within the vugs. By contrast, the two cycles above the 640 ft depth that are lithologically similar to those between 640 and 690 ft lack well-developed vugs and possess no corresponding long/short normal resistivity anomalies.

Higher in core hole 2, Fig. 7 shows most of a distinctive lithologic sequence that occurs in the Copper Ridge between 340 and 280 ft. The sequence is comprised of cycles with bioturbated columnar stromatolites (facies type 3) underlying light gray, fine-grained facies (facies type 1) with cryptalgal laminites, fenestral fabric, and shaley partings. The long/short normal resistivity deflections correspond to the shaley partings in the fine-grained facies, seen as deflections on the gamma ray trace, as well as bedding-normal fractures.

Examination of four cores, reportedly recovered from similar stratigraphic intervals as core 2 (Haase, et al., 1987), suggests this

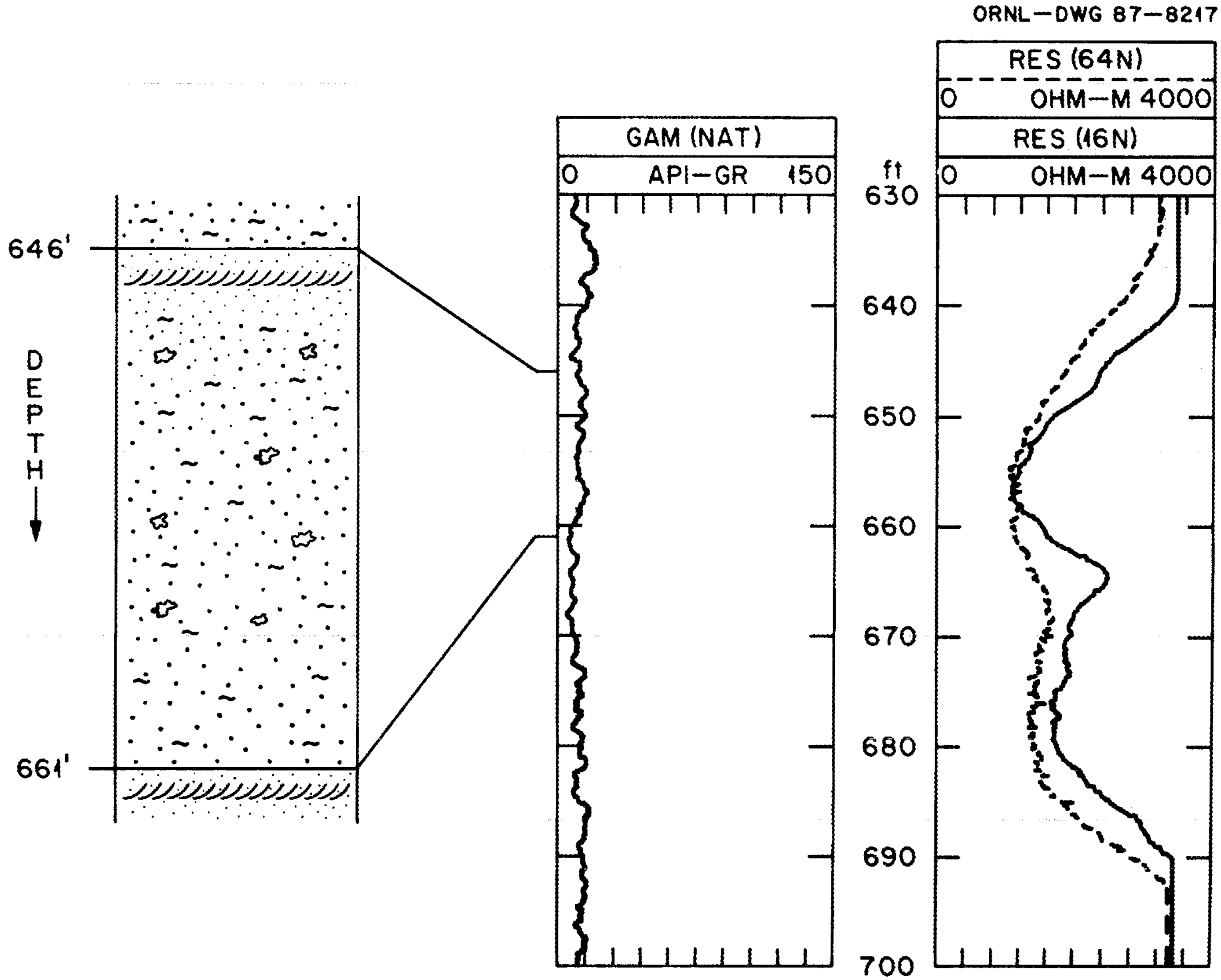

Fig. 6. Long/short normal resistivity anomaly; 690-640 ft in core hole 2.

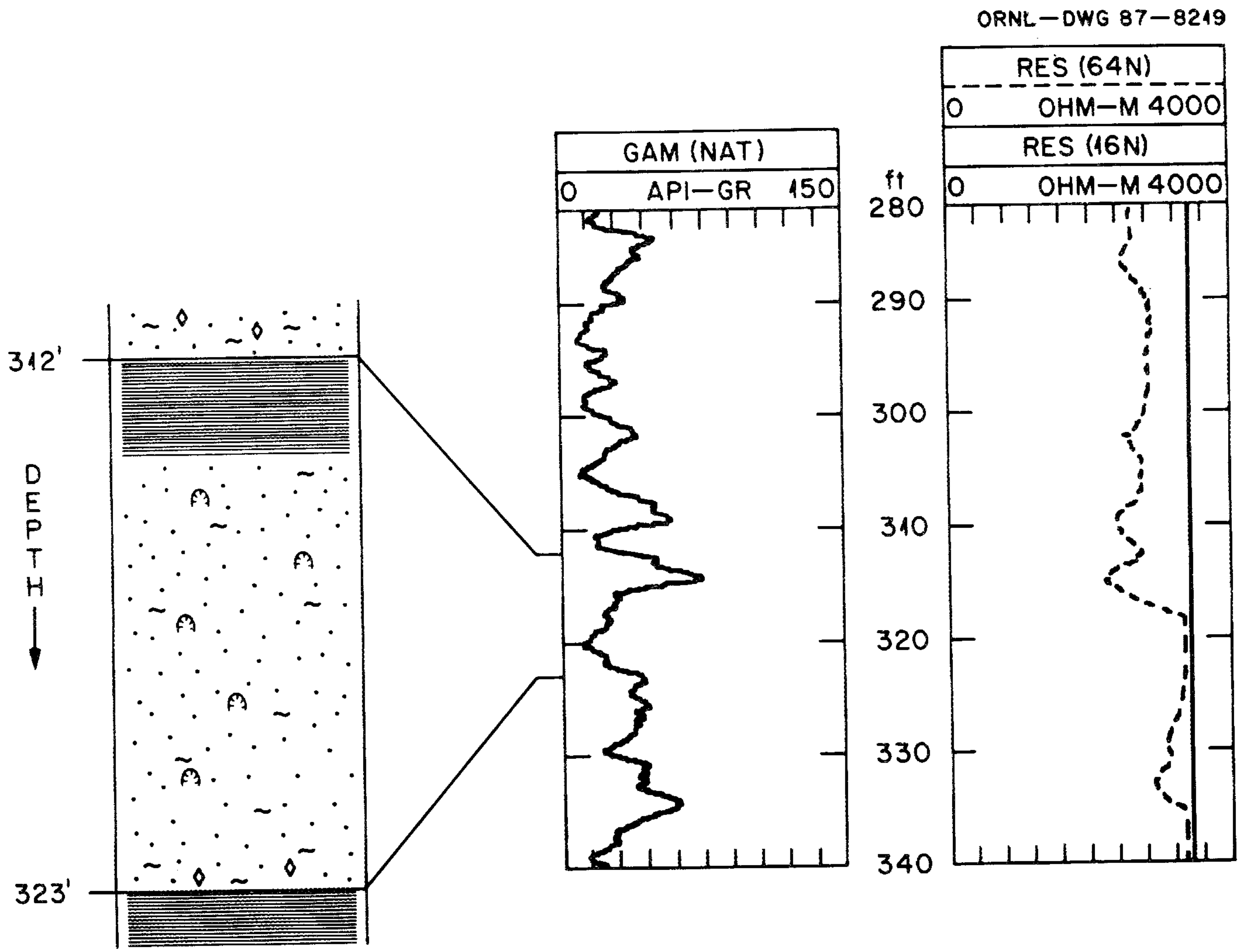

Fig. 7. Long/short normal resistivity anomaly; 334-284 ft in core hole 2.

distinctive lithologic sequence may be a good stratigraphic marker. Core hole locations are from 1.6 km (1 mile) to nearly 14.4 km (9 miles) northeast of the West Chestnut Ridge study area. Unlike core 2, the fine-grained, laminated facies at the top of the interval from two of these four cores are fractured and weathered. Depth comparisons of all five correlative intervals indicate that, with one exception, weathering is directly related to depth. This relationship suggests that deep weathering represents infiltration through the weathered/unweathered interface and that along strike flow may supercede or complement down dip flow.

Two abrupt long/short normal resistivity anomalies from 640 and 632 ft in hole 4 are shown in Fig. 8. The anomalies occur in medium-grained, current winnowed facies type 2 deposits at cycle tops exhibiting extensive fracturing now recemented with dolomite. Pyrite is abundantly incorporated around the recrystallized dolomite. The occurrence of these long/short normal resistivity anomalies is not fully understood. A similar dolomite and pyrite recrystallized fractured zone occurs at 655 ft but has no associated long/short normal resistivity anomaly. In addition, many bedding planes possess pyrite mineralization on disarticulated surfaces. It is anticipated that they too would exhibit long/short normal resistivity deflections when none exist. At this time we can only observe that geophysical logs do not indicate ubiquitous fluid invasion in fractured and dolomite/pyrite recrystallized facies type 2 deposits.

The last long/short resistivity anomalies, Fig. 9, are in hole 4 between 316 and 284 ft and include the lower portion of the stratigraphically overlapped interval with hole 5. These anomalies and their associated gamma spikes represent either 5 to 10-cm-thick shale beds or 5 to 10-cm-thick zones of densely arrayed thin shale partings in fine-grained facies type 1 deposits at cycle tops. In the cycle selected for illustration in Fig. 9, the fine-grained facies is weathered, buff-colored, and contains iron stained coatings on shaley partings and algal laminae. Mineralogical analysis indicates the iron staining results from the weathering of pyrite, presumed to occur throughout the section.

Of the forty-nine discrete long/short normal resistivity anomalies or anomaly clusters identified in this study, six occurred in facies type 3 deposits with well-developed vugs, and three were in facies type 2 deposits with dolomite/pyrite healed fractures. The remaining forty long/short resistivity anomalies were in fine-grained facies type 1 deposits with thin shale beds or densely arrayed shale partings, bedding plane fractures along thin shale partings, bedding-normal fractures, or offset fractures.

Preliminary examination of geophysical logs accompanying the four cores located northeast of the West Chestnut Ridge study area, mentioned earlier, revealed the presence of three prominent groups of long/short normal resistivity anomalies. The cores from these borings were examined to determine the stratigraphic continuity of the facies corresponding to the prominent anomalies.

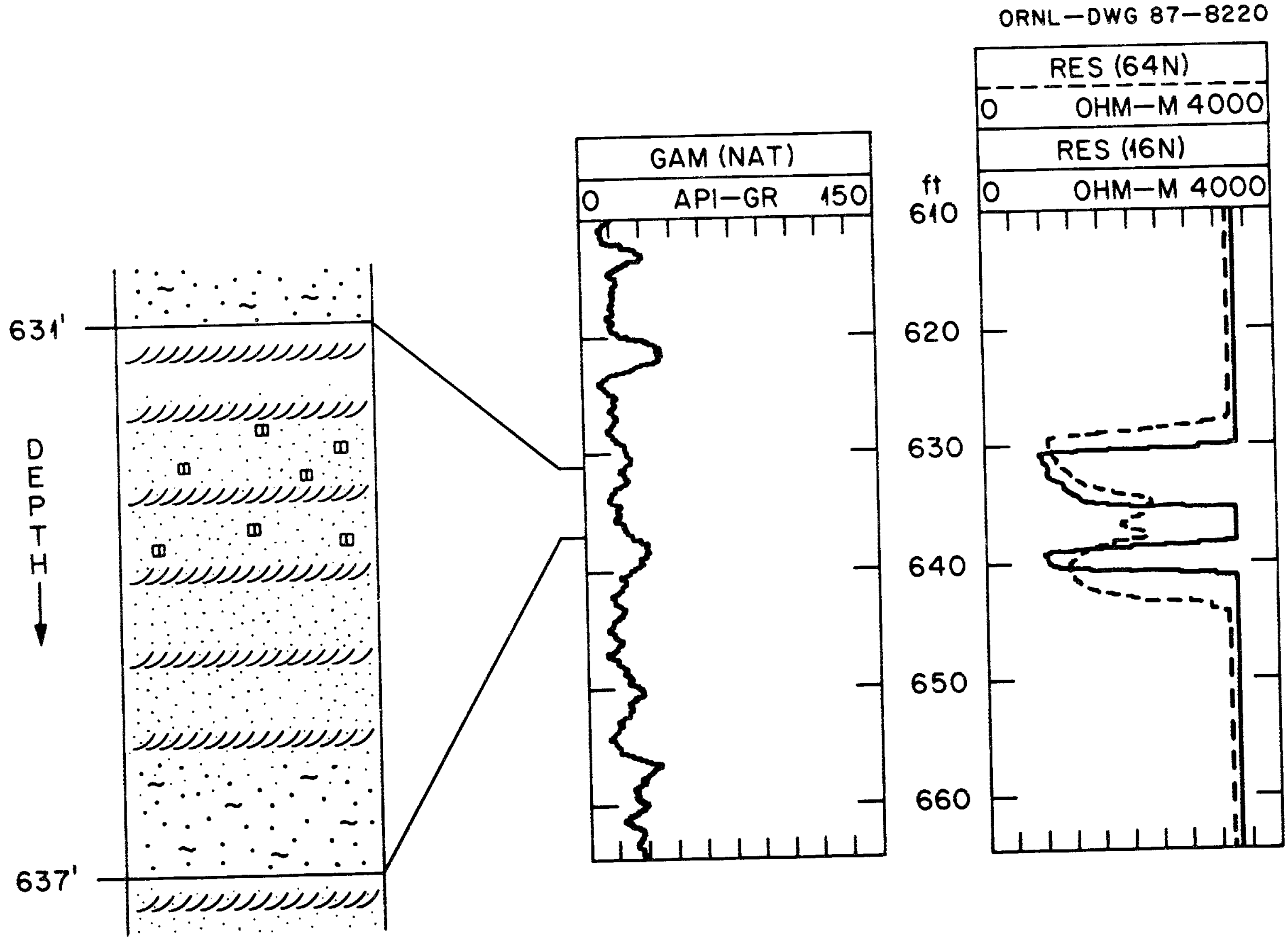

Fig. 8. Long/short normal resistivity anomalies; 640 and 632 ft in core hole 4.

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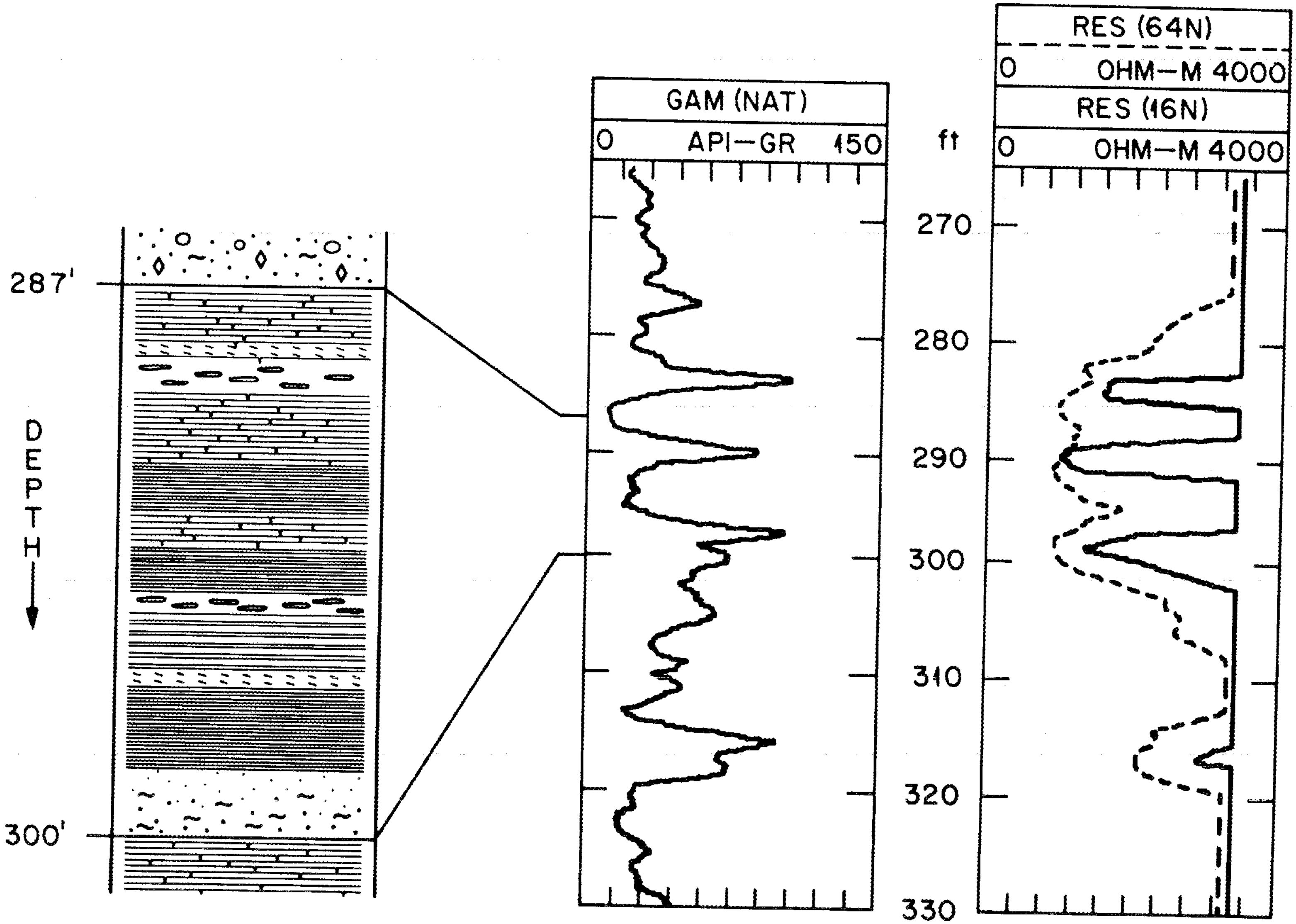

Fig. 9. Long/short normal resistivity anomalies; 316-284 ft in core hole 4.

The three long/short normal resistivity anomalies occur in the lower Copper Ridge at roughly 30 to 50 ft spacings. Their shallowest occurrence ranges from 310 to 550 ft in the four logs. The anomalies correspond to thin shale beds, densely arrayed shale partings, or disseminated shaley fine-grained facies type 1 deposits, similar to those illustrated in Fig. 9. These facies may be the asphaltic beds described by earlier workers. The core is fractured along bedding planes separated by shale partings, and some contain unremineralized, small-scale offset fractures. None exhibit evidence of weathering. Although the detailed characteristics of the shaley, fine-grained facies vary from core to core, as do the magnitude of the corresponding long/short normal resistivity anomalies, their lateral continuity is remarkable on geophysical log and supports the indications from this study that groundwater flow is confined to narrow stratabound pathways.

6.2.2 Fluid Resistivity Logs

Two major fluid resistivity anomalies were recorded during geophysical logging of the core holes. They are illustrated in Figs. 10 and 11 with the corresponding long/short normal resistivity and natural gamma traces for that portion of the interval. The apparently discontinuous fluid resistivity traces are an artifact of plotting and occur when the tracing pen recycles to accommodate values outside the range of the initial scale setting. The traces are in fact continuous, and actual ohm-meter values are included at selected locations in the figures for reference.

The first fluid resistivity anomaly, Fig. 10, begins at 490 ft and equilibrates at 522 ft in core hole 2. The log shows that fluid resistivity equilibrates immediately below the long/short normal resistivity anomaly minimum and the initiation of gamma trace maximum. The extreme negative deflection of the fluid resistivity trace suggests that the water below the 522 ft depth is a brine, and an interface exists that marks the bottom of fresh water at this core hole location.

Core examination offers no compelling lithologic explanation for the fluid resistivity anomaly. Cycles for roughly 40 ft above and below the anomaly are dominated by fine-grained facies type 1 deposits and are distinguishable only in that more clearly defined thin shale partings, identifiable on the gamma log trace, exist above the anomaly. The long/short normal resistivity trace indicates that the shale partings above the anomaly provide discrete horizons of fluid invasion within generally impermeable rock. Below the anomaly, diffusely distributed shale is represented by pervasive fluid invasion throughout the interval. This lower portion is the interval, too, where drilling fluid return was lost and which correlates with the most prominent of the three groups of long/short normal resistivity anomalies from the additional core and geophysical logs discussed earlier. If, as mentioned above, the beds below the fluid resistivity anomaly are the reported asphaltic beds, they may be responsible for the greatly reduced electrical resistance.

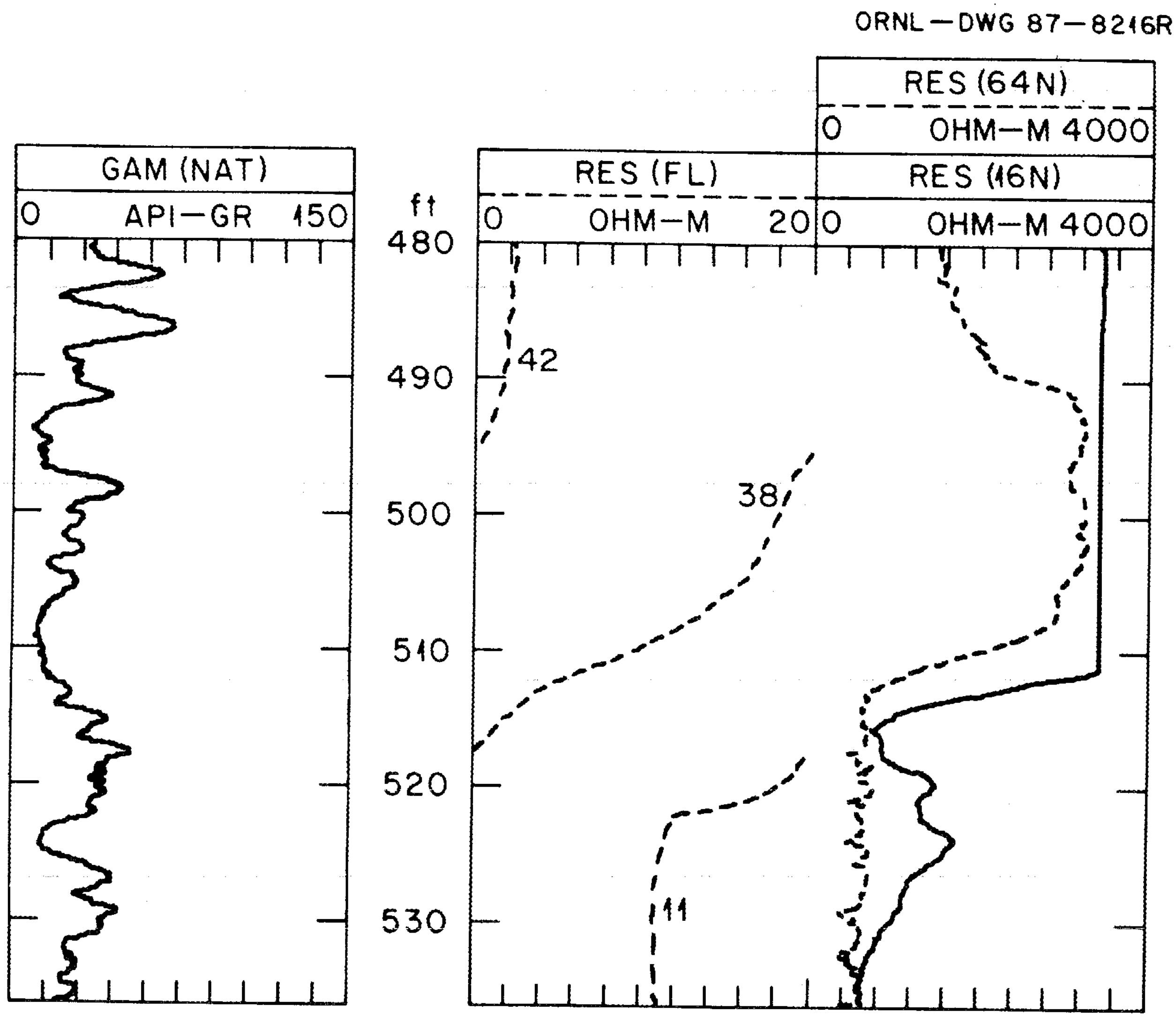

Fig. 10. Fluid resistivity anomaly; core hole 2--ohm-m values are included in reference.

The second major fluid resistivity anomaly reaches its maximum value at 522 ft in core hole 5 (Fig. 11). The anomaly occurs immediately below a group of long/short normal resistivity anomalies and gamma spikes corresponding to heavily fractured, weathered, finegrained facies type 1 deposits. The lower portion of this fractured interval correlates precisely with the top of core retrieval, at the weathered/unweathered rock interface, in core hole 4 described previously. It should be noted that core hole 5 used drilling fluid pumped from Grassy Creek and was geophysically logged six days after drilling was completed, when the lower portion of the core hole was filled largely with drilling fluid. The fluid resistivity anomaly appears to represent a stratigraphically bound interface between drilling fluid below and groundwater above. This suggests that groundwater is moving from the weathered/unweathered rock interface at a 158 ft depth in core hole 4 through cycles with well-represented, weathered, and fractured facies type 1 deposits to a depth of 522 ft in core hole 5.

6.3 STRATABOUND GROUNDWATER PATHWAYS

Figure 12 shows the gamma ray and long/short normal resistivity traces for the complete portion of the section for which stratigraphic overlap was achieved between holes 4 and 5. Correlation was achieved to the bedding plane level through observations of rock core conducted prior to geophysical log acquisition. For lack of a precise stratigraphic datum, the logs are hung near the middle of the overlapped section to more readily illustrate the correlative long/short normal resistivity anomalies. The lines connecting log sets represent correlative cycle boundaries (nondepositional surfaces) and are also included to discuss the long/short normal resistivity traces. Apparent section thickness differences are artifacts of slightly increased structural dip in hole 4. Notice, however, that within the overall structural complexity of the section, individual cycles differ in thickness.

The prominent long/short normal resistivity anomalies in the lower left portion of Fig. 12, between 316 and 284 ft in hole 4, occur in weathered, fine-grained facies type 1 deposits. These are the same anomalies described in detail in Section 6.2.1 and illustrated in Fig. 9. The correlative long/short normal resistivity anomalies in hole 5 correspond to facies type 1 deposits that are light gray and unweathered. These anomalies are less pronounced than those in hole 4 but suggest that down dip hydrologic communication exists between these core holes in stratigraphically correlative packages.

In the upper portion of Fig. 12, the thin shale lenses and fractured facies type 1 deposits in hole 4 occur close to the weathered/unweathered interface. The long/short normal resistivity trace suggests, and core examination confirms, that facies type 2 deposits have been incorporated in the fluid invasion and weathering. At greater depth in hole 5, however, the discrete, thin strata of preferred groundwater flow are readily identified and are limited to the facies type 1 deposits. This is the same stratigraphic interval in hole 5 which contains one of the fluid resistivity anomalies discussed in Section 6.2.2 and illustrated in Fig. 11.

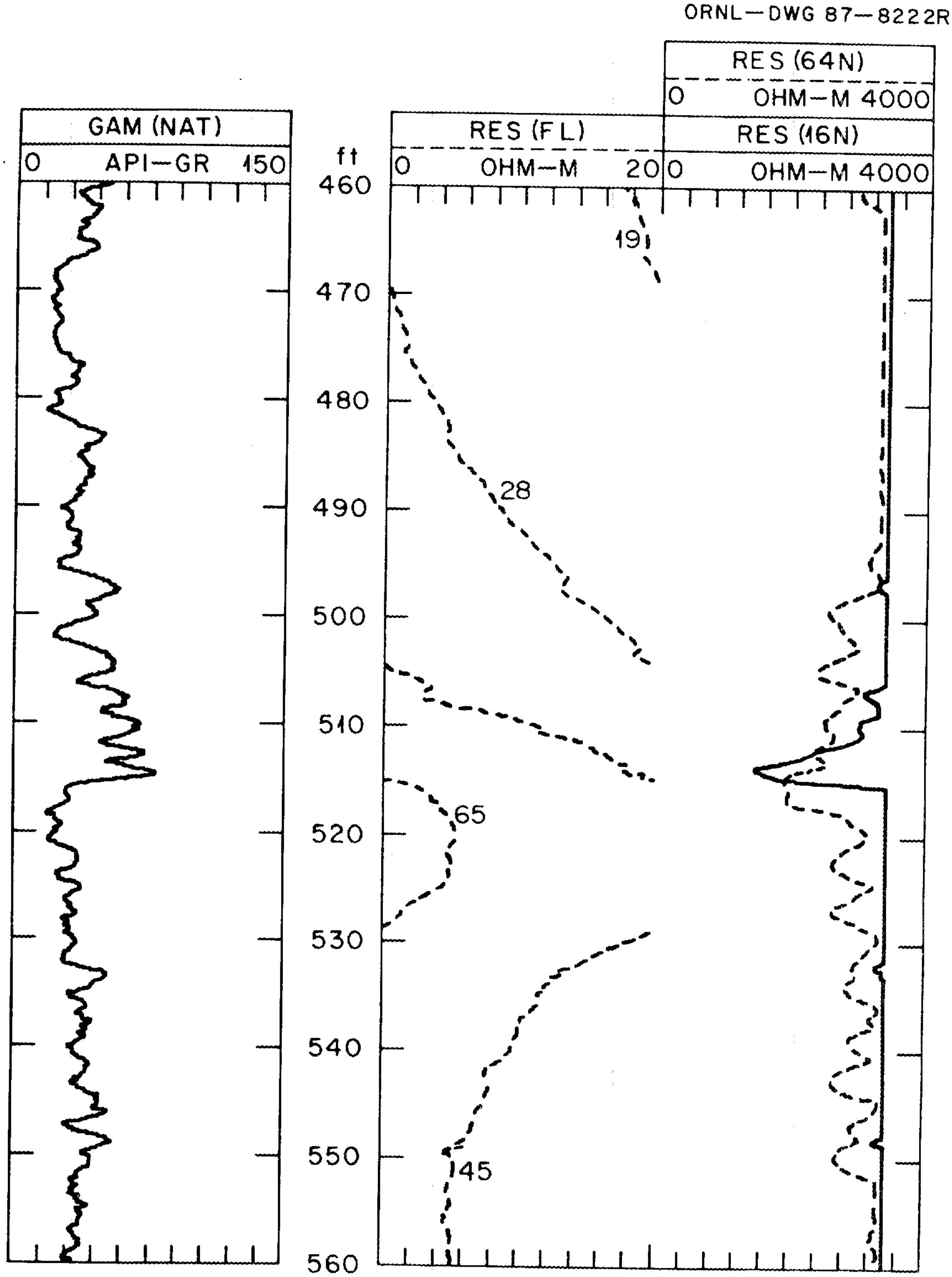

Fig. 11. Fluid resistivity anomaly; core hole 5--ohm-m values are included in reference.

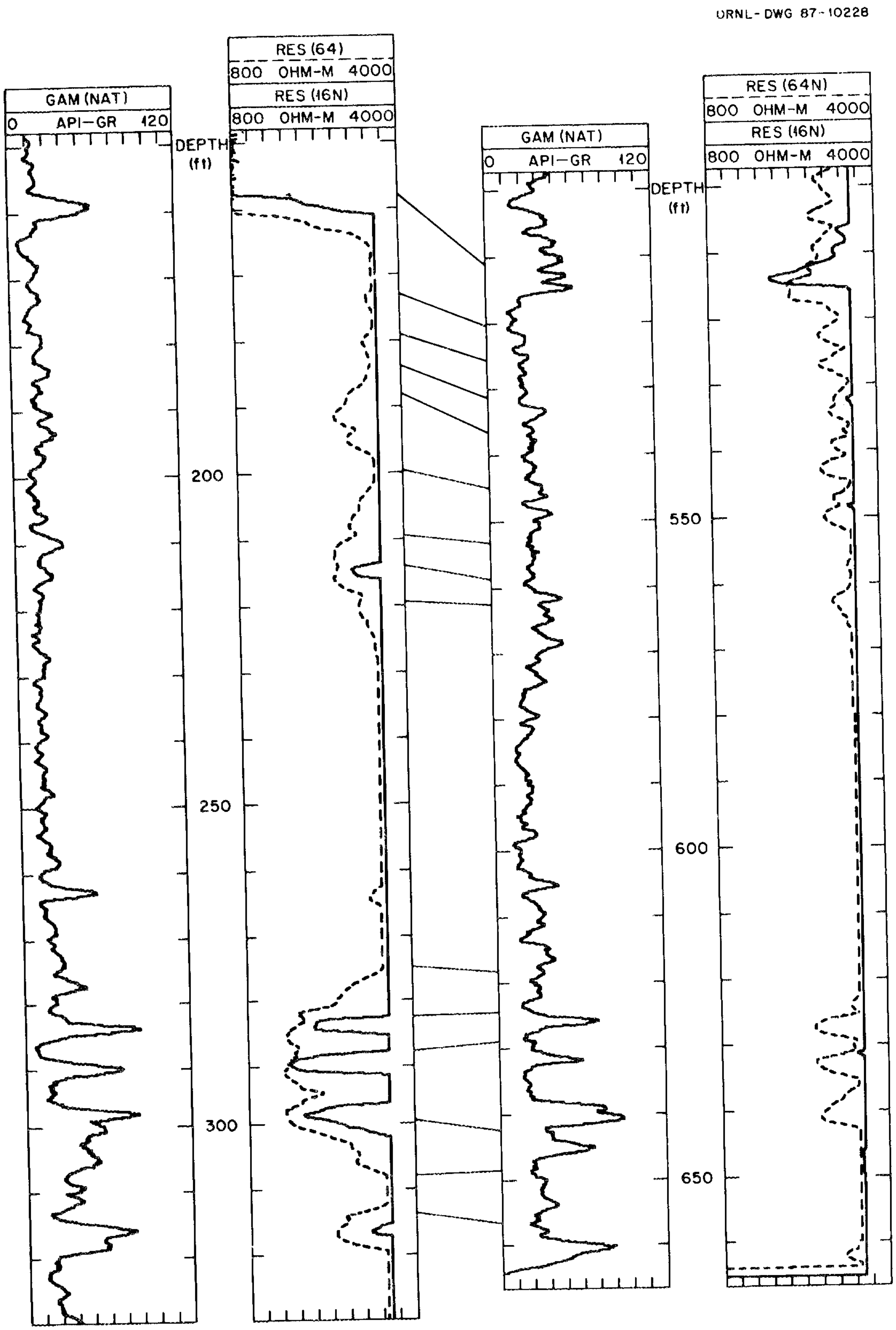

Fig. 12. Correlation of long/short normal resistivity anomalies; core holes 4 and 5. Lines connecting logs represent some of the cycle boundaries in this part of the section.

Clearly defined weathering characteristics in deep portions of the core are limited to narrow stratigraphic zones confined by the occurrence of well-developed, fine-grained facies type 1 deposits and are considered to be preferential groundwater pathways in the Copper Ridge. Four such pathway zones are identified in the upper Copper Ridge (Fig. 13). One, at the 284 ft depth in core hole 4, occurs at the bottom of the correlative interval between cores 4 and 5 illustrated in Fig. 12. (Reference to Fig. 9 shows one of the cycles in this groundwater pathway.) Another weathered facies type 1 groundwater pathway, at the 522 ft depth in core hole 5, occurs at the top of the overlapped interval illustrated in Fig. 12. (Reference to Fig. 11 shows the fluid resistivity trace immediately below this pathway.) Two additional weathered pathways occur in portions of the section in which no stratigraphic overlap was achieved at 440 ft in core 4, and at 405 ft in core 5.

Two zones of suspected weathering potential are included in Fig. 13. The first zone, at the 284 ft depth in core 2, was mentioned briefly earlier and illustrated in Fig. 7. Although unweathered, correlative weathered core from locations northeast of this study area makes it a potential weathering horizon. The second zone is at the top of core 2. This zone and its correlative interval from additional core are weathered, but their depth near the weathered/unweathered interface makes an interpretation of a deep weathering horizon unreliable. However, since the zones possess features nearly identical to those in the deeply weathered horizons, they too may be weathered at depth.

The three shaley fine-grained zones with prominent long/short normal resistivity anomalies from the other studies are in the lower Copper Ridge in Fig. 13. Although none of the zones are weathered, their occurrence in facies type 1 deposits, their bedding plane fracturing, pervasive stratigraphic continuity, and occurrence immediately below one of the fluid resistivity anomalies from this study make a compelling case for potential stratabound groundwater flow.

As suggested by Fig. 13, the subcropping of stratabound groundwater pathways at the weathered/unweathered interface appears to describe linear traces of preferred aquifer recharge. Infiltration is envisioned to be effectively funnelled from the weathered/unweathered interface down dip through these pathways to the underlying bedrock aquifer. In similar fashion, precipitation is envisioned to be effectively funnelled vertically from the ground surface to the weathered/unweathered rock interface above the pathways to describe linear surface traces of enhanced infiltration.

7. DISCUSSION

In the Copper Ridge, neither geophysical logs nor rock core independently provide adequate information regarding groundwater movement at depth. When rock core is weathered at depth, geophysical logs reliably corroborate a fluid invasion interpretation; however, in unweathered rock with characteristics suggestive of fluid invasion,

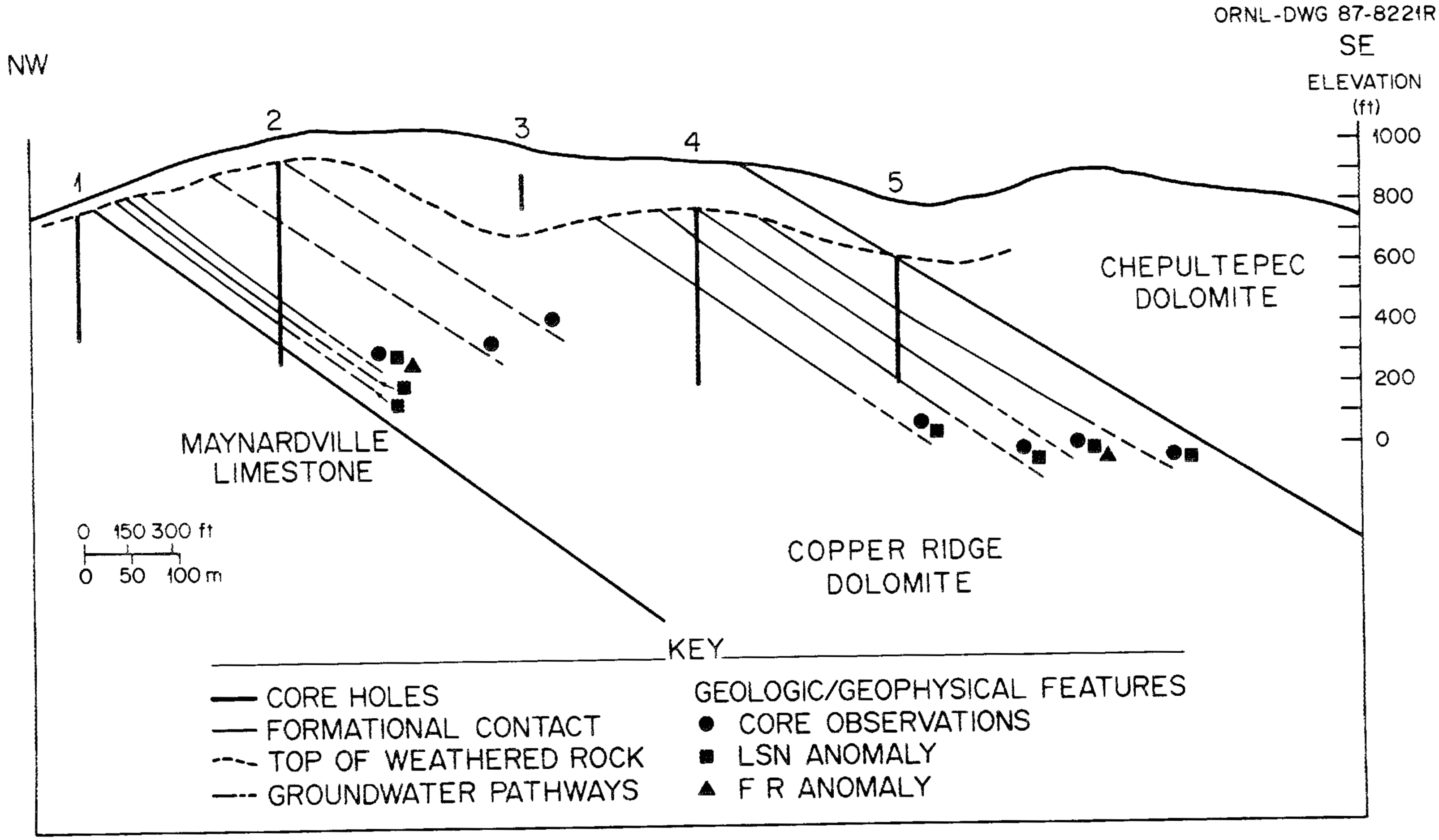

Fig. 13. Proposed groundwater pathways. Refer to Figs. 9, 11, and 12 for illustrations of representative geologic/geophysical features.

supportive geophysical evidence is less reliable. For example, several lithologically similar cycles, capped by well-represented facies type 1 deposits, are unweathered but possess unremineralized fractures with cm-scale offset. Normally, such offset fractures would be considered to indicate groundwater movement; however, not all of those identified in the Copper Ridge core exhibit notable geophysical evidence of fluid invasion. Significant fracture offset at 405 ft in core 2 and at 533 ft in core 5 exhibit only minor long/short normal resistivity spikes. Alternatively, significant long/short normal resistivity spikes are present at similarly offset fractured zones at the 368 and 443 ft depths in core 5.

Findings of this study have been developed inductively from rock core and geophysical log observations without the benefit of corroborative analyses from the acquisition of empirical data. As such, conclusions are considered to be preliminary working hypotheses. To be used in an evaluation of West Chestnut Ridge for suitability as a waste disposal site, these conclusions must be tested through the acquisition and analysis of empirical data. For example, the hydraulic conductivity of the weathered, shaley, unweathered but fracture offset, and vuggy zones should be compared both along strike and down dip. In addition, the fluid resistivity anomalies in core holes 2 and 5 are not fully understood. For example, it is not understood how the anomaly in core hole 5 varies with time, and we have no satisfactory lithologic explanation for the fluid resistivity anomaly in core hole 2.

Rigorous treatment of these uncertainties exceeds the limits of this study but is potentially important should the West Chestnut Ridge site continue to be considered as a waste disposal facility. The degree to which answers are required is directly related to the nature of the waste, the waste form, and the disposal unit design. However, results from this study can greatly focus additional site investigations to more specifically understand saturated flow and groundwater geochemistry on the West Chestnut Ridge site.

The combination of core observations, drilling conditions and difficulties, and geophysical logging has lead to increased understanding of groundwater flow in the Copper Ridge Formation on West Chestnut Ridge. The role of detailed stratigraphic analysis in predicting groundwater flow heterogeneities is a crucial component of future site investigations.

8. CONCLUSIONS

Discrete rock units in the Copper Ridge exhibit primary and secondary lithologic characteristics and weathering features considered to represent recent to ongoing groundwater movement at depth. Below the weathered rock zone, evidence of weathering is most clearly recognized in four horizons with cycles containing well-represented facies type 1 deposits and presumably coincident with the described locally mappable upper member. These horizons are considered to reflect preferred groundwater movement to drilled depths as great as 440 ft.

Based on physical correlation with weathered facies in core from other studies, unweathered facies type 1 deposits in the lower Copper Ridge are also considered to be potential avenues of preferred groundwater flow. Geophysical logs of these core holes strongly suggest that three correlative zones, occurring in unweathered facies type 1 deposits, possess pervasive evidence of stratabound fluid invasion. Geophysical evidence also suggests that the occurrence of facies type 1 deposits influences, and may significantly control, groundwater geochemistry at depth.

It is hypothesized that weathered facies type 1 deposits, in particular, operate as thin stratabound pathways of along strike and down dip preferred groundwater flow to depth and may act as conduits for aquifer recharge. Hydraulic conductivity, head, and groundwater geochemistry of these deposits are suspected to be significantly different from the immediately overlying and underlying rock. The recurrence of such pathways may affect previous contaminant transport and pathways analyses which assumed geohydrologic homogeneity. The ability to predict the locations of such discrete zones of groundwater movement enhances our ability to monitor and detect contaminant migration. In continued site characterization activities of the West Chestnut Ridge site, these strata will be targeted for quantitative downhole testing.

Conclusions from this study are as follows:

1. Core observations indicate the Copper Ridge is composed of 1 to 4-m-thick rock units interpreted to represent upward-shallowing depositional cycles.

2. Cycles exhibit remarkable lateral continuity over at least the 14.4 km from which core is available for study.

3. Nine zones with cycles containing well-developed, fine-grained facies type 1 deposits exhibit lithologic and geophysical evidence of preferred groundwater movement at depth.

4. The subcropping of these zones at the weathered/unweathered interface appears to define positions for preferential, stratabound funnelling of groundwater to depth and linear traces of preferred aquifer recharge.

5. Vertical projection from the weathered/unweathered rock interface to the surface may describe linear surface traces of enhanced infiltration.

6. Geophysical evidence suggests groundwater geochemistry may be controlled by the occurrence of weathered facies at depth.

7. Geophysical evidence suggests a fresh water/brine interface may exist in the lower Copper Ridge which is directly related to the lithologic characteristics of facies type 1 deposits overlying asphaltic beds.

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