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CORE FRACTURE ANALYSIS APPLIED TO GROUND WATER FLOW SYSTEMS: CHICKAMAUGA GROUP, OAK RIDGE, TENNESSEE

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ABSTRACT

The Chickamauga Group (CH) located in Bethel Valley on the DOE Oak Ridge Reservation is comprised of limestones and interbedded shales. Five core holes (CH 1-5), oriented across strike, provide a cross section of the CH and were mapped for fracture density, orientation and cross-cutting relationships as well as lithologic variations. Correlation of structural and lithologic features with downhole geophysical logs and hydraulic conductivity values shows a relationship between lithology, fracture density and increased permeability in an otherwise low-permeability environment.

Structures identified as influential in enhancing hydraulic conductivity include contractional bedding plane and tectonic stylolites and extensional fractures. Three sets of extensional fractures are indicated by cross-cutting relationships and various degrees of veining.

Hydraulic conductivity values (K) for the five wells indicate two ground water flow systems in the valley. A shallow system (up to 150 feet deep) shows a range in K from 10E-4 centimeters per second to 10E-6 centimeters per second. Shallow horizons show more open fractures than are observed at depth, and these fractures appear to control the enhanced K in the shallow system. A subhorizontal interface that is not defined by pre-existing structures or a stratigraphic horizon separates the two flow systems. The deeper system ranges in K values from 10E-9 centimeters per second to 10E-5 centimeters per second. The higher K values at depth correspond to increased fracture density at lithologic contacts, zones of tectonic stylolitization and partially veined extension fractures.

INTRODUCTION

A conceptual model of ground water flow systems is difficult to produce in a complex stratigraphic and structural terrane. Local and regional variations in hydraulic conductivity values are commonly a function of heterogeneities in the geologic media and the dominant processes that lead to variable conductivities vary between sites. In the Valley and Ridge province of the Appalachian fold belt in eastern Tennessee the ground water flow is not homogeneous but is influenced by fracture networks and stratigraphic layering.

The objective of this study is to correlate hydrologic properties with detailed geologic fabrics and to investigate the influence of a complex geologic setting on ground water systems. Our purpose

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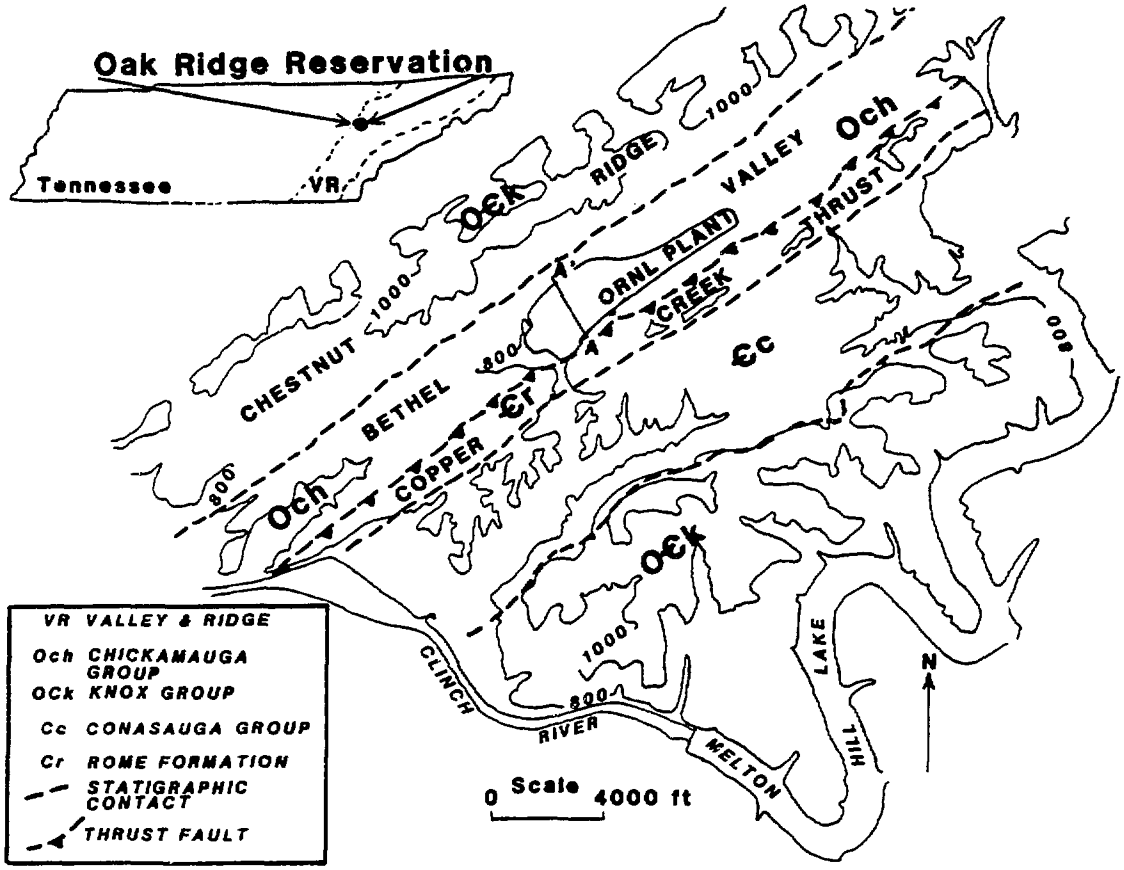

Figure 1 - Location map and regional geologic map of the Oak Ridge National laboratory and plant. The trend of core holes CH 1 through CH 5 and the line cross-section is designated by the line A - A' that is oriented across strike of the ORNL plant. Geologic map taken from Lee and Ketelle, 1988.

is to illustrate the use of structural and lithologic variations, coupled with hydrologic properties, to construct a conceptual flow model in a complex terrane.

The study area is located on the Department of Energy (DOE) Oak Ridge Reservation (ORR) in eastern Tennessee (fig. 1). The area consists of Cambrian and Ordovician rocks that have been stacked and transported to the northwest along thrust faults that ramp up from a basement detachment. This study focuses on the Middle Ordovician Chickamauga Group that lies within the White Oak Mountain thrust sheet, below the Copper Creek thrust fault in Bethel Valley (fig. 1).

Stockdale (1951) identified specific units within the Chickamauga Group on the ORR and assigned an informal alphabetic classification to the units, A through H. The eight formations are subdivided into facies c through t (fig. 2). Units Aa, Ab, Ad, Ae, Af, C, D, E, and G are massive, nodular, ribbon, and mottled limestones with interlayered, thin terrigenous clastic facies and chert beds. Units Ac and d, B, and F are comprised of calcareous maroon shales with interlayered gray siltstone and gray stylolitic limestone.

Lozier and Pearson (1987a) proposed an overall flow pattern for the Chickamauga Group in Bethel Valley to be downward from the recharge areas of Chestnut Ridge and the exposed Copper Creek thrust and upward in Bethel Valley (fig. 1). The water table in Bethel Valley roughly follows the topography and ranges in depth from 1 foot to as much as 35 feet near a ground-water divide (Webster, 1976). Recharge is confined to the White Oak Creek drainage basin and occurs primarily

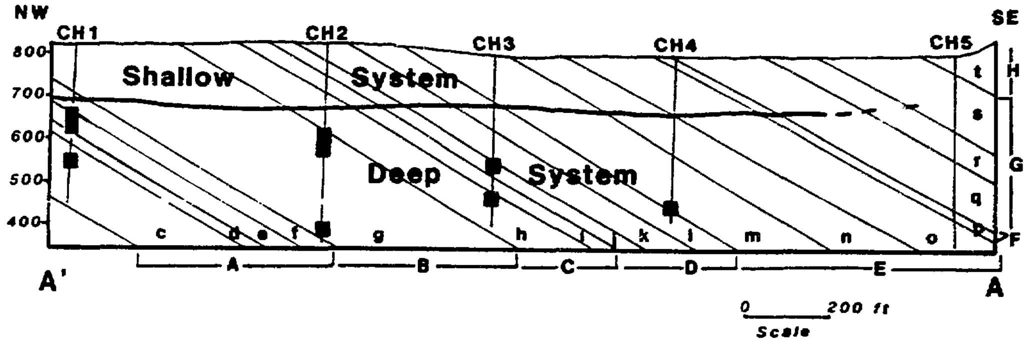

Figure 2 - Cross section A - A' of the Chickamauga Group from northwest to southeast across Bethel Valley. The cross- section shows depth of core holes CH 1 through CH 5 and the subhorizontal interface that divides the shallow system from the deep system. The shallow system represents hydraulic conductivities measured down each core hole of 10E-6 centimeters per second or greater. The deep system represents hydraulic conductivities ranging from 10E-5 centimeters per second to 10E-9 centimeters per second. Black squares located along core hole lines in the deep system represent high conductivities ranging from 1.7E-6 centimeters per second to 2.3E-5 centimeters per second (refer to table 1). The cross section also shows major units A through H and the unit facies subdivision (c through t). Figure modified from Lee and Ketelle, 1988.

by infiltration through the soil mantle and seasonally from the creek when the water table recedes below creek level (Webster, 1976).

The influence that the Chickamauga Group stratigraphy and structure has on ground water movement and storage was addressed by Webster (1976), and Dreier and others (1988). Webster noted that limestones of the Chickamauga Group are one of the major water-bearing units in the White Oak Creek Basin and therefore not desirable for the burial of waste. Dreier and others (1988) suggested that Bethel Valley as well as other parts of the ORR have two ground water flow systems, and that local variations in hydraulic conductivity within the flow systems are controlled by geologic structures and stratigraphy.

METHODS

Five core holes (CH 1 through CH 5) sample the Chickamauga Group in Bethel Valley in the plant area of Oak Ridge National Laboratory. The core holes are aligned across strike (fig. 1, trend of core holes A-A') and range from 370 feet to 470 feet in depth (fig. 2). Lithologic investigations of the core and geophysical logs acquired from the core holes enhanced Stockdale's classification of the Chickamauga Group (Lee and Ketelle, 1988). In addition, straddle packer tests were run in the boreholes to determine hydraulic conductivities and potentiometric head levels (Lozier and Pearson, 1987a and b).

As part of this study, a detailed core analysis of structural features and stratigraphic variabilities was conducted. Structural features such as fracture type, orientation, relative movement, spacing between like fractures, density, width, length, secondary mineralization, and cross-cutting relationships were documented for every 10 foot interval. Stratigraphic variabilities such as color changes, bioturbation and the visual percentage of limestone to shale per 10 foot interval were documented.

The down-hole hydraulic conductivity (K) and static head (H) values were determined by straddle-packer tests at selected 35 foot intervals. Thirty-eight packer tests were completed for core holes CH 1 through CH 5 by Golder and Associates. The packer assembly consisted of 2 sliding-end pneumatic packers, a downhole pneumatically activated shut-in valve and three downhole vibrating wire pressure transducers (for a complete description see Lozier and Pearson, 1987a). Packer placement was determined by geophysical logs and a cursory mapping of the core by Golder

Figure 3 - Photograph of a high angle reverse fault showing drag of the bedding.

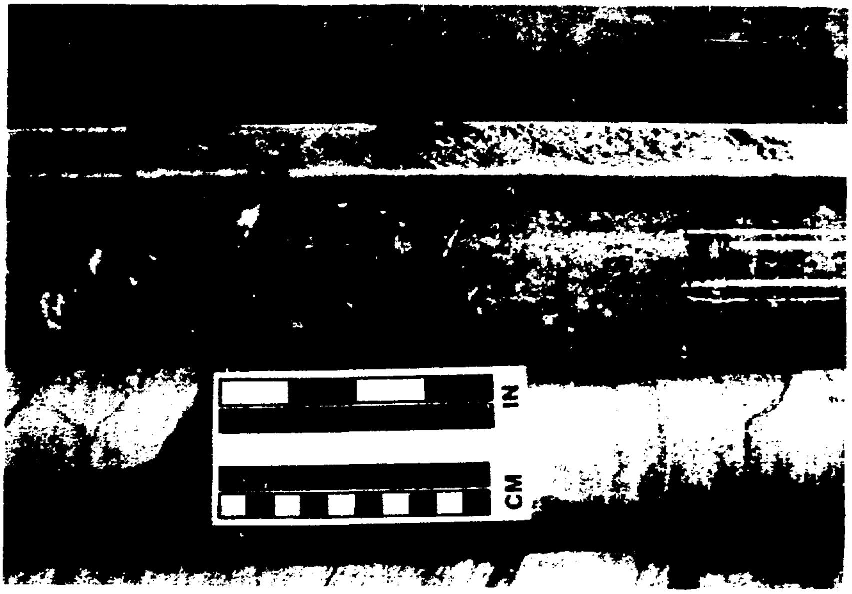

Figure 4 - Photograph of tectonic and bedding plane stylolites.

Figure 5 - Photomicrograph of a stylolite that has undergone extension and later filling of calcite. The growth of the calcite fibers from the stylolite walls towards the center of the fracture is clearly illustrated. Field of view is 3 mm x 2 mm.

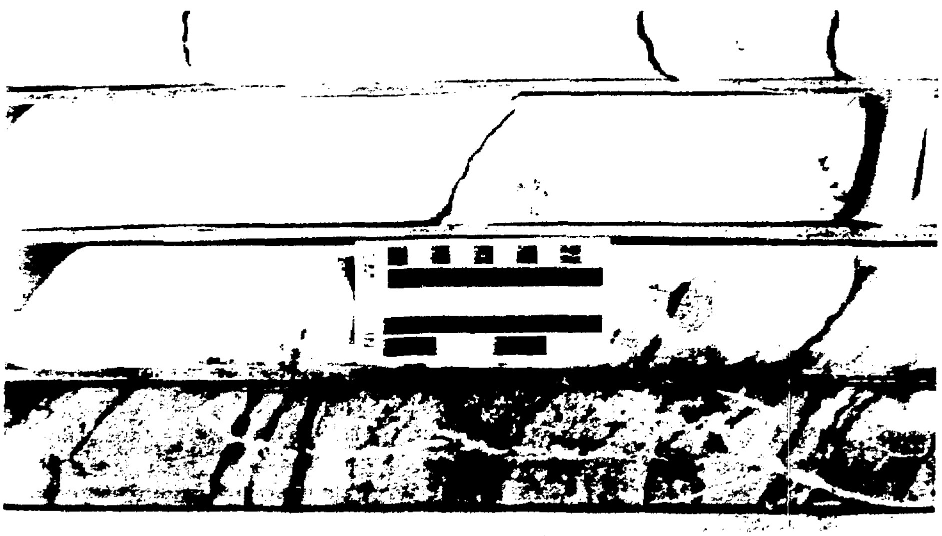

Figure 6 - Photograph of cross-cutting carbonate vein filled fractures.

Figure 7 - Photographs of vugs formed (a) from the dissolution of carbonate veins along fractures and (b) formed from the incomplete filling of an extension fracture.

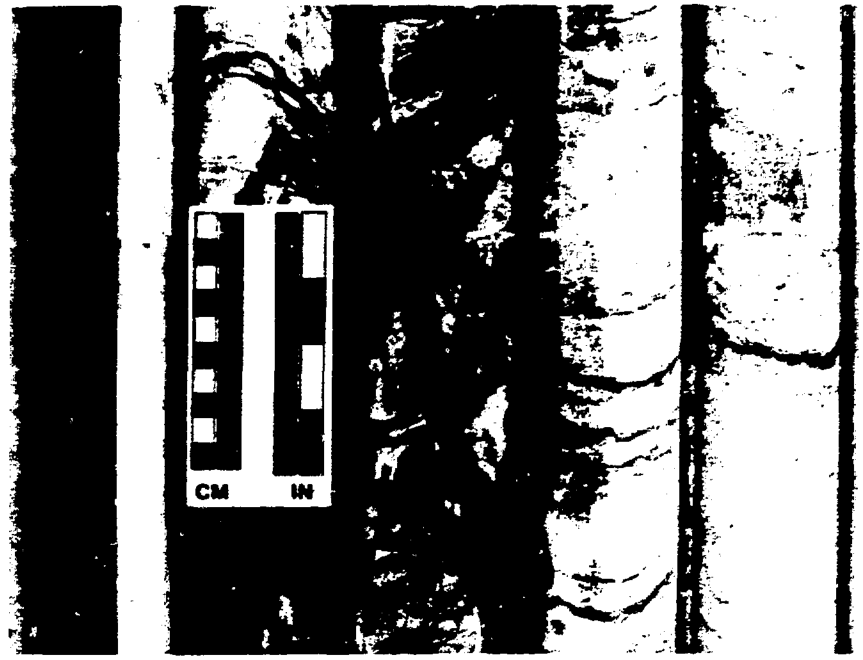

Figure 8 - Example of the extension fractures that cross-cut all other fractures and have a coating of carbonate crystals on the walls. The fractures are oriented parallel to strike and perpendicular to bedding.

Associates (Lozier and Pearson, 1987a). Natural gamma ray, spontaneous potential (SP), single point resistance, long-short normal resistivity, epithermal neutron and gamma-gamma compensated density logs were available for each hole. Both K and H were determined using the Horner Method. A variable head analysis was used to determine K when the interval recovered too rapidly to allow for sufficient data collection (Lozier and Pearson, 1987a and b).

RESULTS

Structure

Both extensional and compressional mesoscale and microscale deformational features are seen within the Chickamauga Group. Compressional features consist of a conjugate set of steeply dipping and subhorizontal faults and bedding plane slip surfaces. The bedding plane slip surfaces generally develop in thin clay/shale partings within the limestone. Slip is also noted along bedding plane partings of the maroon shales, although less frequently. Faults at a high angle to bedding show reverse slip and locally drag bedding (fig. 3). At shallow levels (less than 150 feet depth) the planes are commonly iron-stained.

Bedding plane and tectonic stylolites are pervasive throughout the limestone lithologies and exhibit variable cross-cutting relationships with respect to each other (fig. 4). Bedding plane-parallel stylolites are commonly reactivated and show shear strain. Some tectonic stylolites cut across bedding plane stylolites whereas other examples truncate at, or are offset by, bedding plane stylolites. Reactivation of the bedding plane stylolites has also caused dilation along some cross-cutting tectonic stylolites. Secondary mineralization subsequently filled the dilated stylolites (fig. 5).

Extensional features consist of strike-perpendicular, strike-parallel and oblique extension fractures. Early stages of deformation formed discontinuous fractures that are completely filled with calcite and cross-cut each other (fig. 6). Vugs and cavities are a result of dissolution (fig. 7a) or

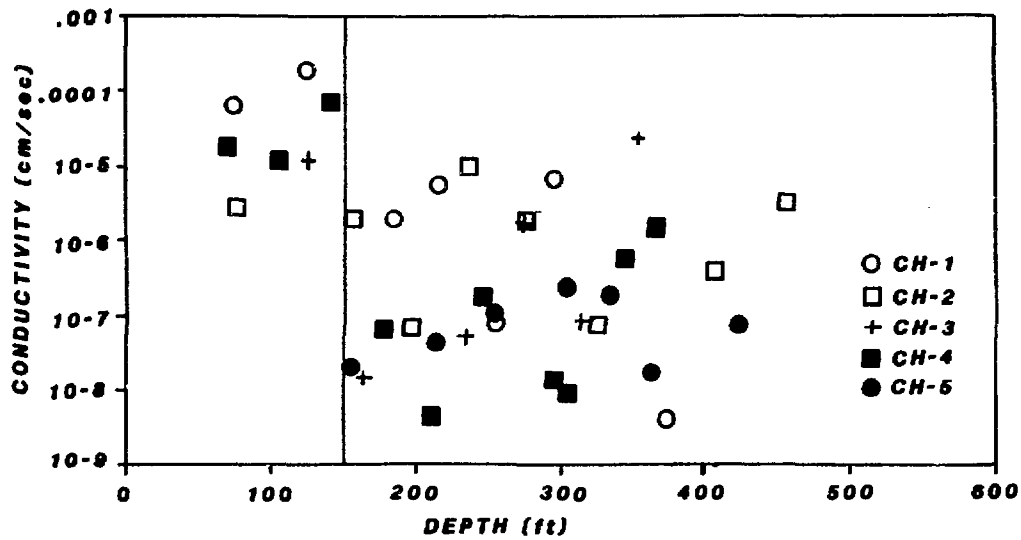

Figure 9 - Cross-plot of the hydraulic conductivity versus depth at 35 foot intervals down core holes CH 1 through CH 5. The vertical line at 150 foot marks the interface between the high conductivities of the shallow system and the variable conductivities of the deep system.

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incompletely filled fractures (fig. 7b) and are locally oil stained. The veins and shear surfaces are cut by high angle extension joints that parallel strike and are perpendicular to bedding (fig. 8). The high angle joints have a rough surface coating of calcite, local (secondary) pyrite, and are discolored by iron staining down to a depth of 100 to 150 feet.

Zones of combined fracture types occur along the core and are referred to as broken zones. These zones are a combination of bedding plane shear and high angle extension joints and locally include low angle fractures. The zones vary from 6 inches to 2.5 feet thick and show no relationship to either depth or lithology. The fractures and fragments of rock are locally filled and cemented with mud and clay (in most cases infiltrated drilling mud), but are mostly uncemented.

HYDROLOGY

Hydraulic conductivity values (K) for boreholes CH 1 through CH 5 indicate both a shallow and a deep ground water flow system in the valley (fig. 9). The shallow flow system extends to depths of approximately 150 feet and has K values that range from 10E-4 centimeters per second to 10E-6 centimeters per second. The flow systems are separated by a subhorizontal interface. Hydraulic conductivity values for the deeper system range from very low (10E-9 centimeters per second) to very high (10E-5 centimeters per second). Average K-values for the Chickamauga Group are considered to fall within the range 10E-7 to 10E-6 (see fig. 9).

The transition depth between the two flow systems was initially determined by visual inspection. However, in order to support this qualitative classification, a segmented curved fit test was conducted on the K vs depth data (fig. 9) to independently identify the transition depth. In the model, two zero-slope lines are joined by a sloping line. The conductivity intercepts of the zero-slope lines and the length and slope of the join segment are then allowed to vary in order to make a best fit to the data. The transition zone between flow systems is determined by the depth range of the sloping line. Results of this test are identical to the visual inspection. The join between the two plateaus (zero- slope lines) occurs between 141.8 and 131.9 feet, both of which are between two neighboring data points at depths of 141.6 and 154.6 feet. Hence the transition depth is approximately 147.5 feet. In addition the conductivity values assigned to each plateau, which are representative of the different flow systems, are significantly different from each other. The shallow system plateau conductivity is 1.8E-5 centimeters per second with a 95% confidence level between 9.9E-5 centimeters per second

Table 1 - Conductivity values for the deep system. Deep system grouped by average, high, and low K-values. Shale percent and the number of stylolites per 35 foot interval are listed. Lithology abbreviations are i = interlayered, sh = shale, ls = limestone, silt = siltstone, mot = mottled.

COREHOLE	UNIT	DEPTH (feet)	K (cm/s)	LITHOLOGY	% SHALE	STYLOLITES
AVERAGE K						
1	Ac/Ad	220-255	8.2E-8	ish-ls	45	6
2	Ch	161-197	7.2E-8	mot	45	45
2	B	291-327	7.7E-8	sh	90	31
2	B	372-408	3.9E-7	sh-silt	80	0
3	Dk	200-235	5.3E-8	mot-ls	30	83
3	C/Dj	280-315	8.3E-8	mot-ls	50	55
4	E2	140-175	6.8E-8	sh	80	5
4	E2/E1	210-245	1.7E-7	mot	25	3
4	E1	310-345	5.6E-7	mot-ls	40	62
4	E1/D	332-368	1.4E-6	ish-ls,mot	40	69
5	G2	179-214	4.3E-8	ls		310
5	Gq/Gr	219-255	1.1E-7	mot-ls	25	350
5	Gq	269-305	2.4E-7	ish-ls	15	283
5	Gq	299-334	1.9E-7	mot-ls	15	363
5	E3	389-424	7.7E-8	ish-ls	10	325
LOW K						
1	A2	340-375	4.1E-9	mot-sh	95	0
3	D1	129-164	1.4E-8	ils-sh		181
4	En	176-212	4.6E-9	sh-mot	> 55	0
4	Em	261-296	1.3E-8	mot-sh	> 50	2
4	Em	270-306	8.6E-9	mot	> 45	2
5	Gs	119-155	2.0E-8	ils-sh	40	176
5	Gq	329-364	1.7E-8	ils-sh	50	330
HIGH K						
1	Ae	180-215	5.6E-6	ls	0	20
1	A2	260-295	6.9E-6	silt-sh	22	0
1	Ae/Af	150-185	1.9E-6	ls	0	32
2	Ch	121-157	1.9E-6	ls	0	26
2	B/Ch	210-237	1.0E-5	ls	0	76
2	B	241-277	1.8E-6	ls-sh	45	0
2	B	421-457	3.1E-6	silt-sh		0
3	Bj/Dk	239-275	1.7E-6	ls	5	218
3	Ch/Ci	319-355	2.3E-5	ls	0	11

and 3.2E-6 centimeters per second, whereas the deep system plateau conductivity is 2.2E-7 centimeters per second with a 95% confidence level between 4.9E-7 centimeters per second and 9.7E-8 centimeters per second.

Deep System

Average K-values for the deep flow system range from 4.3E-8 centimeters per second to 1.4E-6 centimeters per second (table 1). The values are primarily from units Eo/En (CH 4) and Gq/Gr (CH

Table 2 - Conductivity values for the shallow system. Shallow system K-values and units related to fracture density (that includes both extensional and compressional sets) and down-dip equivalent variables (starred rows). Two intervals in CH 4 do not have down-dip equivalent intervals available for comparison. Fractures measured as the number of fractures per unit depth interval.

CORE HOLE	UNIT	DEPTH (feet)	K (cm/s)	FRACTURES
1	B	40-75	2.2E-5	95
*2		375-410	3.9E-7	87
1	B	90-125	2.0E-4	75
*2		421-457	3.1E-6	100
2	Dj	40-75	2.7E-6	98
*3		240-275	1.7E-6	48
3	Em/D	190-125	1.2E-5	112
*4		332-368	1.4E-6	150
4	E3	36-71	1.8E-5	176
*5		390-425	7.7E-8	117
4		71-107	1.2E-5	140
4		107-142	7.0E-5	103

5) as well as from units B, Ch (CH 2), Dk/Dj (CH 3) and Ac/Ad (CH 1) (see fig. 2 for unit subdivision locations). Lithologic characteristics for these units range from massive shales with interbedded fine-medium grained limestone beds (unit B and Ac/Ad) to nodular olive gray limestone with shaley interbeds and partings that may include thick (0.10 to 0.25 inch) undulose stylolites (units Gq, Gr, Eo, En). The amount of shale in the intervals ranges from 15% to 80%.

In the deep system, the correlation of structural and lithologic features with downhole geophysical logs and hydraulic conductivity values shows a relationship between lithology, dissolution features, and increased permeability. A decrease in shale content and a relative increase in stylolite development can be roughly correlated with an increase in K (table 1). For example, the interval from 140 - 175 feet in core hole CH 4 has a shale content of approximately 80% and a K of 6.8E-8 centimeters per second. In the same borehole the K values increase to 5.6E-7 centimeters per second for the interval from 315-350 feet, which has an average shale content of 40%. Stylolite density also increases within these intervals from 5/interval at 140 feet to 62/interval at 315 feet.

Minimum K-values in the deeper system range from 4.1E-9 centimeters per second to 2.0E-8 centimeters per second. These low values are representative of shale rich facies (shale content ranging from 40% to 95%) of Ac (CH 1), Dl (CH 3), En/Em (CH 4) and Gs/Gq (CH 5) (table 1). The rocks consist of mottled limestones with dark shale layers (Ac, En, Em), gray nodular stylolitic limestones with thick black shale layers (Dl), and limestone layers interbedded with massive shale (Gs, Gq). Stylolite density in the low K intervals is generally low except for units Dl, Gs and Gq in which the density is moderate to high but consists of thick irregular undulose stylolites or closely spaced wispy laminae. The minimum K-value (4.1E-9 centimeters per second) is in a shale-rich mottled limestone that contains approximately 90% shale for half of the interval and has no stylolites.

The maximum K-values for the deep system range from 1.7E-6 centimeters per second to 5.6E-5 centimeters per second and are determined from units Ae/Af (CH 1), Ch, B (CH 2) and Dj/Dk, Ch/Ci (CH 3). With the exception of unit B in CH 2, the lithologies consist of massive nodular and laminated limestones with 5% to 22% shale content and a generally high percentage of stylolite development. Dissolution vugs developed in carbonate veins are also characteristic of these limestones. High values of conductivity are considered to be a function of the low shale content in addition

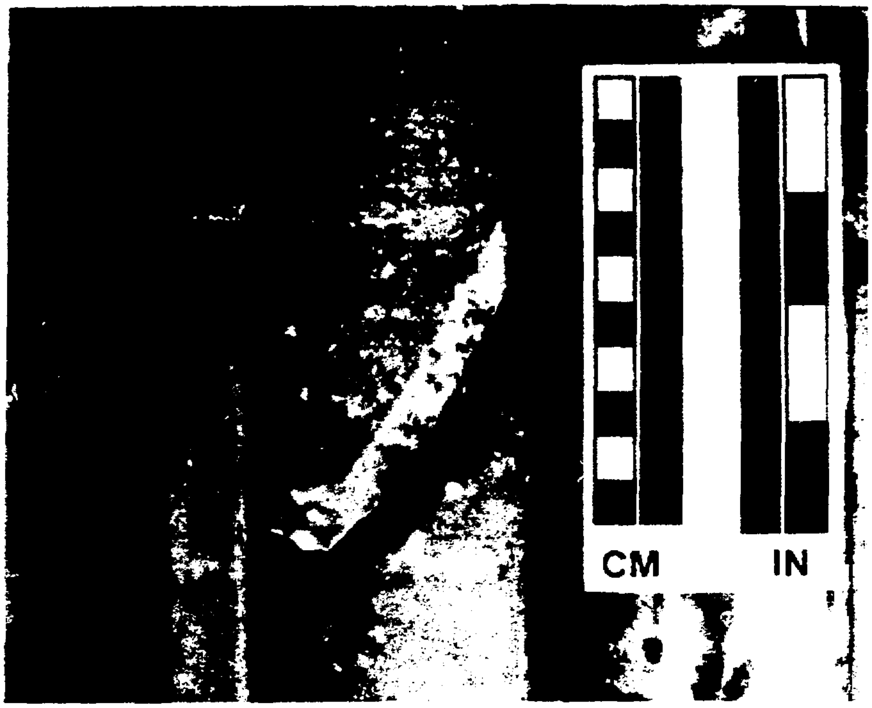

Figure 10 - Photograph of a recracked fracture after vein filling in the shallow system.

to a high stylolite density. For example, unit Ae (CH 1, 180-215 feet) and unit B/Ch (CH 2, 201-237 feet), both of which are stylolitic limestones with no shale, show K's of 5.6E-6 centimeters per second and 1.0E-5 centimeters per second, respectively (table 1). High permeability in unit B and A2 is a function of thick (5 feet to 10 feet thick) interbedded relatively pure calcilutite and stylolitic limestone layers within the maroon shales.

Shallow System

In the shallow system (less than 150 feet deep) the high conductivities are influenced not only by shale and stylolite density but also by the presence of open fractures. K-values measured from CH 1 - CH 4 range from 2.0E-4 centimeters per second to 2.7E-6 centimeters per second; CH 5 was not sampled at shallow levels (table 2). The packed-off intervals are correlative to stratigraphic horizons that showed either average or high conductivities at depth (table 2). The lithologies are primarily a stylolitic limestone such as Dj (Ch 2), Em/DI (CH 3), and E3 (Ch4), but also include massive shales of unit B (CH 1), which are interlayered with a calcilutite and limestone.

In addition to features observed in the units at depth, the shallow system shows a higher density of open fractures, separated stylolites, recracked veins and iron staining on fracture and bedding plane surfaces. The importance of open fractures or the amount of dilation of a fracture is shown in unit B (CH 1, 40 - 75 feet) and unit Em/DI (CH 3, 90 - 125 feet). Unit B, a massive maroon shale with a K value of 2.2E-5 centimeters per second, contains three broken zones in which there is a high degree of dilation. Bedding plane fractures, extension fractures and low angle shear fractures all contribute to the broken zones and show total separation of the fracture walls as well as iron staining on the fracture surfaces. The correlative unit at depth (CH 3, 375 - 410 feet) has approximately the same to slightly lower overall fracture density and a lower K value of 3.9E-7 centimeters per second. The fractures are not closely spaced or interconnected as is common in broken zones and less than 25% of the fractures show total separation. There is no iron staining on the fracture surfaces.

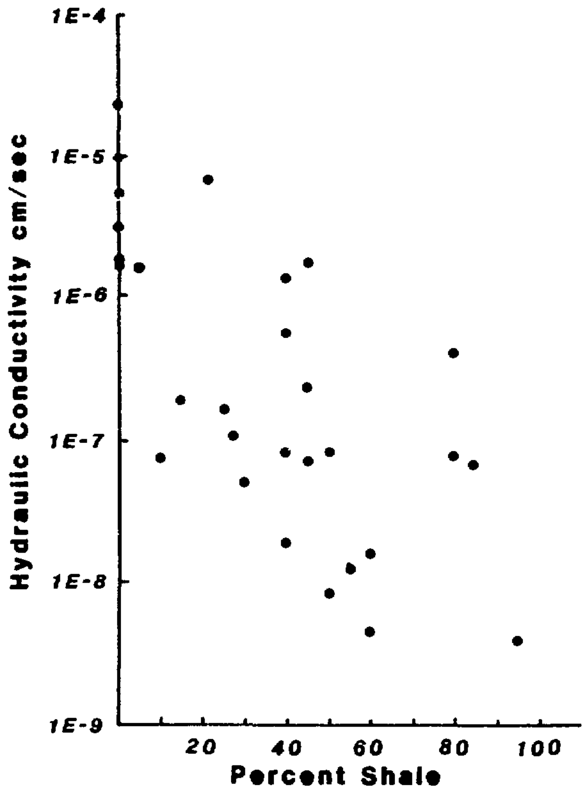

Figure 11 - Cross-plot of the deep system hydraulic conductivities versus the percent shale at 10 ft intervals. The plot shows an inverse relationship of conductivity versus shale percentage.

Em/Dl, a mottled to stylolitic limestone with a K value of 1.2E-5 centimeters per second, contains bedding plane, extension and low-angle shear fractures that show total separation of the fracture walls. The fractures occur both as broken zones and as bedding plane fracture zones. Irregular breaks also occur along bedding plane and tectonic stylolites. The correlative unit at depth (CH 4, 335- 370 feet) has a high density of fractures, however, few fractures show complete separation or significant dilation and the K value is 1.4E-6 centimeters per second or an order of magnitude smaller.

Units Dj and E3 have a higher density of fractures at shallow levels than the correlative intervals at depth. Dj (CH 2, 40 - 75 feet, K = 2.7E-6 centimeters per second) has approximately twice as many fractures as its down-dip equivalent in CH 3 (240 - 275 feet, K = 1.7E-6 centimeters per second: table 2). Contributing to the higher density is a broken zone (42.5 - 47.2 feet) made up of bedding plane and extension fractures. The fractures are iron-stained and recracking of previously formed fractures is evident at 70 feet where a vein has been broken away from the fracture wall and the new fracture surface subsequently iron stained (fig. 10). In unit E3 (CH 4, 35 - 70 feet, K = 1.8E-5 centimeters per second) the rock contains approximately a third more fractures than at deeper levels (CH 5, 390 - 425 feet, K = 7.7E-8 centimeters per second: see table 2). The shallower interval contains broken zones consisting of bedding plane, extension and shear fractures that cross-cut each other and show total separation or dilation. Stylolites are separated and give the appearance of irregular breaks that have a film of carbonate coating the surface of insoluble residue.

DISCUSSION

Deep System

Potential channels for fluid flow in carbonate rock include bedding planes, stylolites and fractures. Tectonic deformation or subsequent unloading can result in the formation of fractures. In addition, separated or open stylolite seams may later be partially filled with cement or act as an open conduit of flow (Bathurst and Land, 1986). A network of interconnected "opened" stylolites, vein openings and bedding planes will create a channelized flow path for fluids and a directional permeability in an otherwise low permeability and low porosity rock (Nelson, 1985; Rye and Bradbury, 1988).

Conductivities at depth in Bethel Valley are a function of both structure (eg., stylolite density) and lithology (ie., shale content). Conductivity is considered to be enhanced by the presence of both bedding plane and tectonic stylolites. The interconnectivity of cross-cutting stylolites and the coatings of insoluble residue provide pathways and a secondary permeability for fluid migration that has caused dissolution in veins.

The inverse relationship between shale percentage and conductivity for all the intervals within the deep system is shown in Figure 11. Bathurst and Land (1986) have noted that ten percent or greater clay content in a carbonate can inhibit stylolite formation. Therefore in the rocks with low and average conductivities the shale may serve the dual purpose of (1) a net reduction in permeability and (2) inhibiting the formation of stylolites. Without the stylolites the rock is essentially sealed and has few pathways along which fluids can flow.

Shallow System

Conductivities at shallow levels are a function of lithology and a higher density of fractures as well as recracking and dilation of previously formed fractures and stylolites. Conductivities that range from average to high at depth remain high for up-dip equivalent units in the shallow system and exceed the K-values for the deeper system. The increased K-values can be partly attributed to the same factors that affected the lower system (ie., stylolite density and shale content). Furthermore, the increased K- values in the shallow system reflect the correlation between fracture density and the degree of fracture and stylolite dilation.

The presence of dilated stylolites, recracked veined fractures and broken zones suggests a tensional stress that has reactivated previously formed features that were stable at depth. The subhorizontal interface that divides the deep system from the shallow system may represent the interface along which uplift and subhorizontal stretching occur during unloading (Suppe, 1985; Price, 1968).

Iron stains, found at a maximum depth of 150 feet in CH 1 and from 50 feet to 100 feet in CH 2 and CH 3, occur below the water table, which ranges from 1 - 35 feet below land surface. The presence of fresh pyrite (FeS_2) at depths below 150 feet (CH 1) or 80 feet (CH 4) indicates an insitu source for iron that may be carried in the ground water and precipitated upon mixing with oxidized water at shallow depths (less than 150 feet). Iron stain below the water table indicates mixing of reduced, iron saturated water (possibly from the deep system) in an oxidizing flow environment. The zone of mixing is marked by the shallow system interface and is a result of higher conductivities enhanced by a greater permeability from dilated fractures and stylolites.

SUMMARY

1. There are two ground water systems in Bethel Valley Chickamauga Group, a shallow and a deep system.
2. The interface between the shallow and deep system is not a function of stratigraphy or previously existing structures, but marks the depth of unloading structures and mixing between oxidized and reduced waters.

3. High conductivities in the deep system are a function of low shale content and stylolite formation in the pure limestones and are independent of fracture density or type.
4. High conductivities in the shallow system are a function of low shale content and fracture density in the form of recracked veins and stylolites.

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